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A method for economic optimization of energy performance and indoor environment in the design of sustainable buildings

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ABSTRACT

Future tightening of the energy requirements increases focus on design of new and better performing buildings with good indoor environment and only limited extra cost compared to new buildings today. This paper presents a method for economic optimization of the design of new low energy dwellings that takes into account the indoor thermal environment. By use of the criterion of cost of conserved energy implemented in a Microsoft Excel sheet, a cost optimal design according to a targeted energy frame can be found. The resulting indoor thermal environment is then evaluated based on parametric analysis in the dynamic simulation tool WinDesign. If any changes have to be made to ensure a good indoor thermal environment, iteration between the two programs must be performed. An example is used to illustrate this process. It indicates that the method can be used from the early design phases to ensure that an economic design solution with good indoor environment can be identified. The example also shows that in order to ensure that buildings have low energy consumption, at minimum extra cost, more appropriate products and solutions will have to become available on the market at a competitive price.

1. Introduction

According to EU (2010) residential and commercial buildings are responsible for about 40% of the total energy consumption and CO_2 emissions in Europe. Therefore ambitious targets for energy consumption of new buildings are being implemented, and by the year 2020 nearly zero energy buildings will become a requirement in the European Union. As a result, energy performance has become an important issue in the design of new buildings. Moreover, architects and engineers will face the challenge of designing these new buildings with only limited extra cost compared to new building today. Furthermore, the long-term solution is to eliminate the problems related to the use of fossil fuels by a combination of energy conservation and use of renewable energy. The economically optimal solution in building design is thus to find the balance between the cost of energy conservation and the cost of renewable energy. Various types of investment evaluation techniques can be applied for this optimization. The method used in this paper is called the cost of conserved energy (CCE) method (Meier, 1983).

Besides the aspect of cost efficiency, the indoor environment should also be taken into account in new building design. Many passive and low-energy houses today are designed with large window areas facing south, causing problems with overheating and extra investment in solar shading (Vanhoutteghem et al., 2011). The focus in their design is only on a reduction of energy consumption for heating and not on providing a good indoor thermal environment or efficient use of daylight. New low energy buildings should thus be designed in such a way that a low energy consumption is not obtained at the expenses of the indoor environment. This paper suggests a method for economic optimization of the energy performance and the indoor environment which is suitable for the early stages of building design.

The process in the method relies on finding a cost optimal building design, based on the implementation of the CCE method in Microsoft Excel, and the export of the solution to a program, named WinDesign, for evaluation of the resulting indoor thermal environment. If changes with regard to the indoor environment are needed, an iteration between the two programs can ensure a building design that is both cost-efficient and has good indoor thermal environment.

2. Using cost of conserved energy (CCE) for the economic optimization of a building design

2.1 Definition of the cost of conserved energy

The basic definition of cost of conserved energy (CCE) has been derived by Meier (1983), who outlined a method to evaluate the cost efficiency of an investment proposal. However, this basic definition of the cost of conserved energy requires the specification of a number of supplementary factors before it can be used to identify an appropriate design for new buildings. In order to determine if an energy-conserving building element would be cost-effective if used in the design of a new dwelling, information on its useful lifetime is required. Furthermore, since the useful lifetime of a building element can range from a few years to the entire lifetime of the designed building, a reference period must be introduced to the basic definition of CCE to ensure a fair frame of reference for comparing energy-conserving building elements with various useful lifetimes. An energy-conserving building element might also require a certain amount of maintenance and can for that reason have an associated cost for maintenance during its useful lifetime. To take account of this, the increase in annual maintenance cost (ΔM_{year}) is added to the annualised investment cost. Additionally, some energy-conserving building elements might consume energy for their operation, e.g. a mechanical ventilation unit.

This energy consumption ($\Delta E_{operation,year}$) must subsequently be subtracted from the energy conserved by the building element, see Eq. (1).

$$CCE = \frac{t \cdot a(n_r, d) \cdot I_{measure} + \Delta M_{year}}{p_1 \cdot \Delta E_{year} - p_2 \cdot \Delta E_{operation,year}}, \quad \text{with } a(n,d) = \frac{d}{1-(1+d)^{-n}}, \quad t = \frac{n_r}{n_u} \tag{1}$$

where $I_{measure}$ is the investment (or additional) cost of an energy-conserving building element (€), ΔE_{year} is the annual energy conserved by the building element (physical unit, e.g. kWh), $a(n,d)$ is the capital recovery rate (-), d is the real interest rate (%), n_r is the reference period (years), n_u is the useful lifetime of the building element (years), p_1 is the primary energy factor related to the conserved energy of the building element (-) and p_2 is the primary energy factor related to the energy consumed by the building element (-).

2.2 Economic optimization of building designs

The concept of CCE states that a building element is considered cost-efficient if the cost of conserved energy is lower than the price of primary energy (Meier, 1983). The price of primary energy can therefore be seen as the constraint in the economic optimization of a building design. However, as Pindyck (1999) and Poles (2010) have shown, it is almost an impossible task to credibly predict the future cost of primary energy. As a result, Petersen et al. (2012) and Hansen et al. (2011) suggested that it would be better to use the required energy performance as the constraint for economic optimization of a building design. The energy performance requirement is a well-known concept in the EU, expressed as energy use per heated m^2 floor area per year (kWh/m^2 year), in accordance with the Energy Performance of Buildings Directive (EPBD, 2010). Using the energy performance requirement, the economic optimization problem of a building design can be reduced to finding specific building elements that, when combined, yield the minimum cost and fulfil the energy performance requirement. In (Petersen et al, 2012) and (Hansen et al., 2011) it has been shown that the solution with the lowest cost that fulfils the energy constraint can be found where the marginal cost of conserved energy for each of the specific building elements is identical. Consequently, the combination of building elements with the same marginal cost of conserved energy will result in the economically optimal solution for a building design.

3. Energy use of building elements

In order to calculate the marginal CCE of each of the specific building elements, the energy use for each component has to be evaluated. The calculation of the energy use is different for the different specific building elements, and has been derived from EN ISO 13790 (2008). A distinction has, however, been made between calculation of energy use for building elements with continuous energy properties (i.e. walls, roof and floor) and building elements with discrete energy properties (i.e. windows and ventilation). Derivation of the calculation of energy use for the different types of building elements has been performed by (Hansen, 2011), and is briefly mentioned below.

3.1 Building elements with continuous energy properties

As mentioned previously, walls, roof, floor, and other construction parts, are building elements with continuous energy properties. Economic optimization of such building elements is a question of optimizing quantity, e.g. the amount of insulation material in the building element. When comparison needs to be made between building elements such as different wall compositions, important aspects like thermal heat capacity and extra material cost should also be taken into account.

According to (EN ISO 13790, 2008) the energy use per m^2 wall, roof and floor (Q_{constr}) can be determined as:

$$Q_{constr} = \frac{1}{R_{se,i} + \sum_{j=1}^{n} \frac{d_{j,i}}{\lambda_{j,i}} + R_{si,i}} \cdot (D_H - \eta_{C,Is} \cdot D_C) \tag{2}$$

where λ_j is the thermal conductivity for layer j (W/mK), d_j is the thickness of layer j (m), R_{se} and R_{si} are the surface resistances (m^{2}K/W), D_H is the number of degree hours calculated for the reference heating season and with reference thermal heat capacity (kKh), D_C is the number of degree hours calculated for the reference cooling season and with reference thermal heat capacity (kKh) and $\eta_{C,Is}$ is the utilization factor for heat loss (-).

By using information on the construction cost, a continuous function of the energy use (calculated according to Eq. 2) versus the marginal cost of conserved energy can be set up for different quantities of each of the building elements with continuous energy properties, see Fig. 1. These functions will be used later to find the optimal economic solution for the building design where the marginal cost of conserved energy should be the same for all building elements.

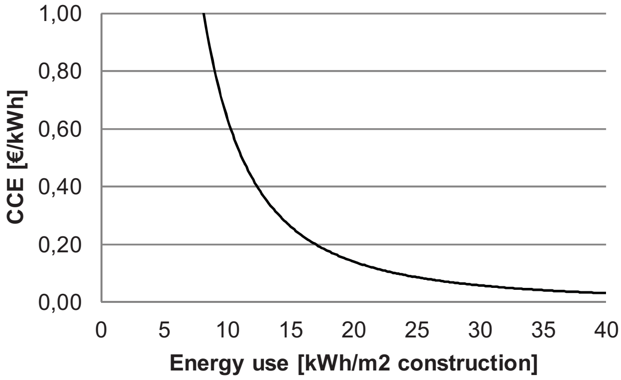

Fig. 1. Illustration of continuous function of energy use versus marginal cost of conserved energy

3.2 Building elements with discrete energy properties

Windows and ventilation systems are building elements with discrete energy properties. The optimization of such building elements is based on an evaluation of the quality of the building element, e.g. the window type or ventilation unit.

3.2.1 Windows

The energy use of the windows ($Q_{windows}$) is based on assumptions in (EN ISO 13790, 2008) and (Duer et al., 2002) and can be calculated as

$$Q_{window} = U_{window}\cdot(D_H - \eta_{C,Is}\cdot D_C) + F_s\cdot g\cdot(I_{C,korr} - \eta_{H,gn}\cdot I_{H,korr}) \quad (3)$$

where U_{window} is the heat transfer coefficient for the window (W/m^2K), D_H is the number of degree hours in the heating season (kKh), D_C is the number of degree hours in the cooling season (kKh), F_s is the shading factor (-), g is the total solar energy transmittance of the window (-), I_{korr} is the solar radiation during heating season, corrected for the dependency on the incidence angle (kWh/m^2) and $\eta_{H,gn}$ is the utilization factor for heat gain (-).

3.2.2 Ventilation

The energy use for ventilation (Q_{vent}) is calculated as energy use per m^3/s. The energy use for ventilation consists of electricity consumption and ventilation heat loss (ASHRAE, 2005) and is calculated according to Eq. (4).

$$Q_{vent} = SFP\cdot p\cdot k + \rho\cdot c\cdot(1-\eta)\cdot D_H - \eta_{C,Is}\cdot\rho\cdot c\cdot D_C \quad (4)$$

where SFP is the specific fan power (J/m^3), p is the primary energy factor for electricity (-), k is the ventilation time in use (kh), ρ is the density of air (kg/m^3), c is the specific heat capacity of air (J/kgK), η is the heat recovery efficiency (-), D_H is the number of degree hours in the heating season for ventilation (kKh), D_C is the number of degree hours in the cooling season for ventilation (kKh) and $\eta_{C,Is}$ is the utilization factor for heat loss (-).

3.2.3 From discrete to continuous function

The energy use against marginal cost of conserved energy of building elements with discrete energy properties forms a discrete function which can be approximated with a continuous function in order to select the economical optimal solutions. The continuous function can be created by following a procedure consisting of four steps (Hansen at al., 2011):

1. The annual energy use for building elements with discrete energy properties is calculated according to Eq. (3) or Eq. (4) and is listed according to the respective cost of the building elements. The component with the lowest cost is chosen as the reference.
2. The cost of conserved energy is calculated for each component with respect to the reference. All components with a negative cost of conserved energy will be rejected. As these components are more expensive than the reference and use more energy, they will never be economically efficient to apply.
3. The component with the smallest positive cost of conserved energy from previous calculation is set as a new reference. Step 2 and 3 are repeated until there are no components left.
4. All of the remaining components have their cost of conserved energy calculated based on the reference found in Step 1. The discrete dataset is then approximated with a continuous function, which can be used for treating the components with discrete energy properties as if they were components with continuous energy properties.

An illustration of following these four steps for the selection of windows in a building design is given in Fig. 2.

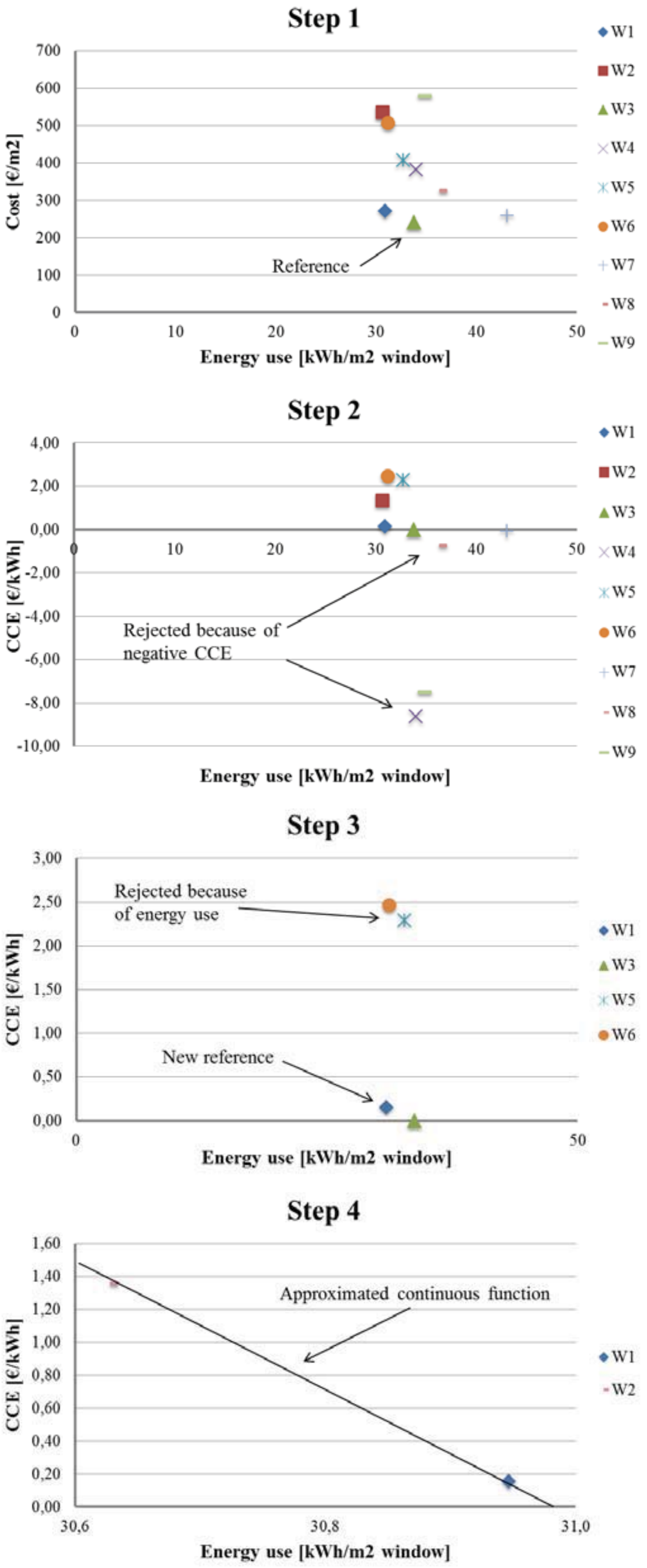

Fig. 2. Illustration of the four steps to approximate a discrete dataset of different windows with a continuous function

3.3 Other building elements

In the economic optimization of a building design, energy use and the cost of other building elements, like thermal bridges, lighting (for office buildings) and solar heating systems can also be included. Similar to the calculation of energy use for building elements in this article, the energy use of thermal bridges, lighting and solar heating systems can be defined with reference to (EN/ISO 13790, 2008), see (Hansen, 2011).

4. Optimal solution based on the cost of conserved energy and indoor environment

4.1 Optimization process based on the cost of conserved energy

As described above it is possible to generate continuous functions for all building elements in order to find the optimal solution for the building as a whole. A Microsoft Excel file was created where input about the quantity of each building element can be stated in the form of the area of the windows, wall, roof, floor, the ventilation rate etc. The Microsoft Excel file also includes a product database with typical composition and materials of building elements. In the product database, the building owner has the option to set certain constraints to the design of the building, e.g. maximum wall thickness, choice of materials, composition of building elements, etc.

Using the quantity of each building element allows the continuous functions generated for selected compositions and materials from the product database to be used to find the optimal distribution of the energy-conserving building elements in the building design. As mentioned previously, the building design solution with the lowest cost fulfilling the energy constraint can be found where the marginal cost of conserved energy is identical for all building elements.

This task is solved by using the standard numerical solver in Microsoft Excel. However the output is only a qualified estimate of an economically optimal energy solution for the building design, since the interactions between energy-conserving building elements are not taken into account. It nevertheless provides a good starting point for a further optimization which also takes into account the indoor environment.

4.2 Optimization process including indoor thermal environment

In order to take into account the indoor thermal environment, the program WinDesign is used (WinDesign, 2011). The program is a user-friendly program that performs calculations based on simple input data and can be used by architects and engineers during the design phase of new buildings as well as for the renovation of existing buildings (Svendsen et al., 2008). It has been developed in Microsoft Excel, using built-in and user defined functions in Visual Basic for Applications (VBA). The program is organised in four steps, which together represent an analysis of how a specific building design performs with regard to energy consumption, indoor thermal environment, and cost (Vanhoutteghem et al., 2011). The analyses in the steps are in accordance with the calculation methods in (EN ISO 13790, 2008) and gradually increase in level of detail to support the design decisions throughout the design process. In each step, a number of different scenarios can be defined where different parameters can be analysed. An overview of the calculations performed in the different steps in the program can be seen in Fig. 3.

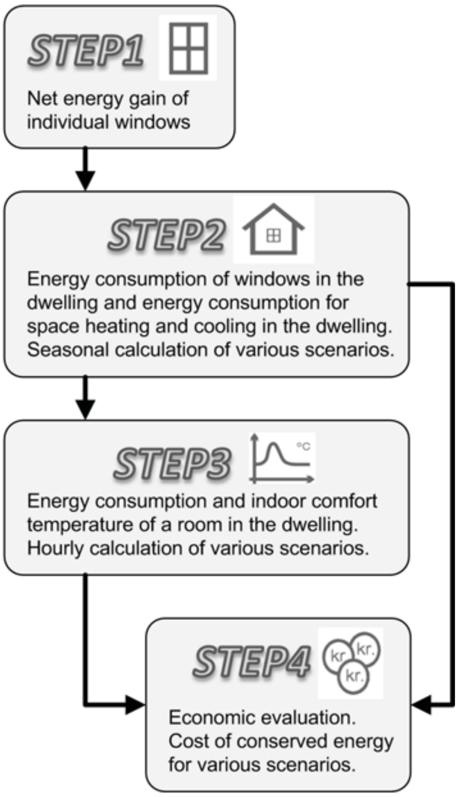

Fig. 3. Flowchart of the calculations performed in the different steps in WinDesign.

Within the context of this paper, step 3 (hourly calculation of energy consumption and indoor thermal environment at room level) will mainly be used.

Output data from the economical optimal solution found by using CCE calculations (i.e. U-values, quantity of building elements, ventilation rate, etc.) is imported in WinDesign, where a parametric analysis can be performed in order to make sure that a good indoor thermal environment is obtained, see Fig. 4. Parameters that can be varied are for example thermal mass, window type, configuration, size and orientation, use of solar shading devices and use of venting and night ventilation. In order to take into account the use of daylight, the authors suggest that the quantity of window area as input for the CCE calculation is chosen according to national guidelines as a reasonable starting point, and is providing enough daylight. If parameter analyses in WinDesign show that smaller windows, or windows with a lower visible light transmittance are required, an additional daylight analysis might be performed.

After analysis in WinDesign, the changes towards a design with good indoor environment can be implemented in the file containing the CCE calculations, see Fig. 4, as the changes might imply a change of economically optimal design.

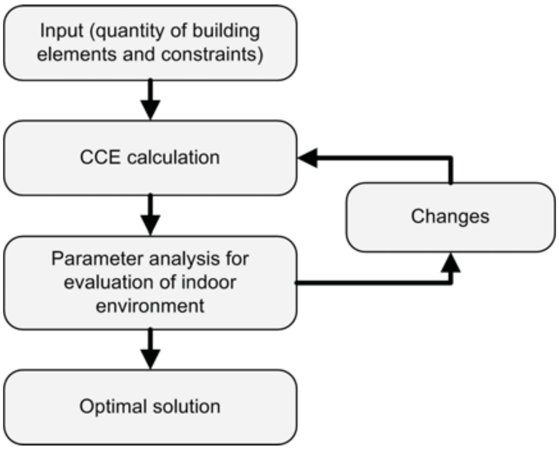

Fig. 4. Flowchart of the optimization process.

To ensure that the new economically optimal design has a good indoor environment, the solution should be imported in WinDesign once more. An example will now be used to illustrate the different steps in the process.

5. Example

The example used to illustrate the method presented in this paper is based on the optimization of the design of a typical Danish single-family house. The house has a heated floor area of 192 m^2 and a window area that is about 20 % of the floor area. The average mechanical ventilation rate is set to 0.5 h^{-1} and venting rate is set to 1.5 h^{-1}. The building must be designed to fulfil an energy frame of 20 kWh/m^2 year according to the Danish energy frame requirements for 2020 (BR10, 2011). Calculations of the CCE for the different building elements were performed with a discount rate set to 2.5%, a reference period set to 30 years and a primary energy factor for electricity set to 1.8.

Furthermore, the optimization of the insulation thickness in roof and floor was limited to a maximum thickness of 600 and 400 mm, respectively, and the total wall thickness was limited to 600mm. Optimizing without these constraints would result in unrealistic insulation thickness in wall, roof and floor since the cost of conserved energy is significantly lower for insulation in these building elements than for windows and ventilation units.

The optimization result for building envelope elements and the ventilation system can be seen in Table 1.

Table 1. Economically optimal solution for building envelope and ventilation system in the example.

Building element	CCE €/kWh	Measure
Wall	0.121	Wooden frame construction, 550 mm insulation with λ= 0.037 W/m^{2}K
Roof	0.158	500 mm insulation with λ= 0.040 W/m^{2}K
Floor	0.220	400 mm insulation with λ= 0.041 W/m^{2}K
Windows	0.018	Triple-glazed window with U-value = 0.78 W/m^{2}K, g-value = 0.5
Ventilation	0.018	VHR with SFP = 800 J/m^3 and η = 0.91

Results from evaluation of indoor thermal environment of the economically optimal solution in WinDesign, see Fig. 5, show that the indoor thermal environment of the economically optimal solution can be improved by an increase in thermal mass (replacement of wooden frame construction by brick-brick cavity wall), an increase in venting rate (from 1.5 h^{-1} to 3h^{-1}) and by application of solar shading (shading factor of 0.3) on south oriented windows (case 1-3 respectively). Increasing the thermal mass of the economically optimal solution is clearly the best solution; not only does an increase in thermal mass reduce hours of overheating more than the other suggestions for improvement, it also reduces the heating requirement in the single-family house.

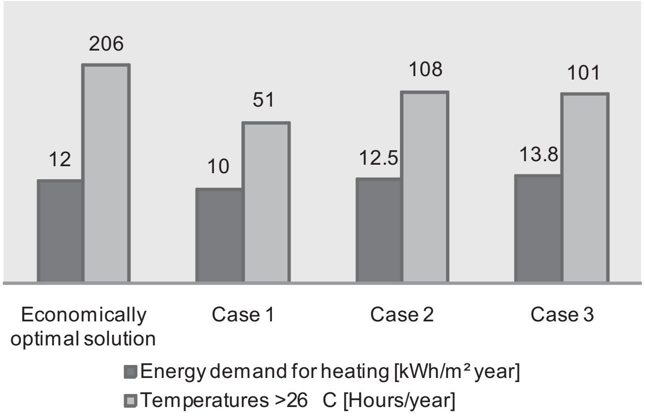

Fig. 5. Results from parameter analysis in WinDesign.

An iteration is therefore performed between WinDesign and the Microsoft Excel sheet containing the CCE calculations for a solution with increased thermal mass. The resulting economical optimal solution can be found in Table 2. Analysis of this solution in WinDesign confirms the previously found result that with the higher thermal mass, a better indoor thermal environment can be found. In addition, less insulation, but with a lower thermal conductivity, is needed in the new wall composition. However, even though more expensive insulation with a lower thermal conductivity is used, the new wall construction is still cheaper than original wooden frame construction for the wall.

Table 2. New economically optimal solution for building envelope and ventilation system in the case example.

Building element	CCE €/kWh	Measure
Wall	**0.084**	**Concrete wall, 400 mm insulation with λ= 0.034 W/m^{2}K**
Roof	0.158	500 mm insulation with λ= 0.040 W/m^{2}K
Floor	**0.276**	400 mm insulation with **λ= 0.038 W/m^{2}K**
Windows	0.018	Triple-glazed window with U-value = 0.78 W/m^{2}K and g-value = 0.5
Ventilation	0.018	VHR with SFP = 800 J/m^3 and η = 0.91

6. Discussion

6.1 Validation of the optimization based on the cost of conserved energy

The method was used for design optimization of several Danish single family houses and the energy use of the optimized result was compared with results in Be10. Be10 is the program used to document whether or not a building design complies with the energy performance requirements in Denmark (SBi, 2008). The comparison showed that the energy use of the optimization result overestimates the energy use by 2.3-8.3% compared to the calculation of energy use with Be10, which is reasonable considering that energy use for the different building elements was not calculated by taking into account their interactions on the total energy balance in the building.

6.2 Validation of the calculation of indoor environment

Results obtained from calculations in WinDesign were validated both in accordance with (ANSI/ASHREA, 2007) and (EN 15265, 2007). For a set of basic and in-depth test cases defined in (ANSI/ASHREA, 2007), the comparison showed that WinDesign provides estimates of the heating and cooling requirements and the indoor thermal environment that are comparable to the results obtained by using well-known building energy simulation programs, such as TRNSYS (Klein et al., 1990) and ESP-r (Clarke et al., 1991).

The results for heating and cooling demand obtained in WinDesign also comply with accuracy level A or B (relative difference in heating or cooling demand respectively $\leq$ 5% or $\leq$ 10%) compared to the reference results from the informative test cases in (EN 15265, 2007).

6.3 Limitations

The method for economic optimization has several advantages but also some limitations. As costs of building elements vary across regions and countries and are influenced by local costs of energy, labour and materials, the method should have access to an extensive and updated product database. As mentioned previous, such a database has been developed for buildings elements in Denmark, but this must be replaced with a database from other countries in order to give realistic building design solutions in these countries.

Nevertheless, results in the example illustrate that even if a product database is included in the program, it can be hard to reach a solution where the marginal CCE is the same for all building elements. This could be due to the fact that only limited far-reaching energy saving measures exist and are included in the database. However, the method can be used to illustrate the economic efficiency of the individual building elements, making it possible to identify the potential for further product development (i.e. insulation with lower thermal conductivity, development of sandwich panels of high performance concrete etc.).

The method for economic optimization is also a simplified method, and as such the solution found with the method should only be seen as a starting point for the whole design process. The use of only a few input parameters also makes the method more suitable for the design of residential buildings than for office buildings.

In addition, data exchange between the method for economic optimization and evaluation of indoor thermal environment in WinDesign must still be performed manually. In the future, this could be made automatically or the method for economical optimization could be extended to take indoor environment into account.

7. Conclusions

In this paper, a method is presented for the economic optimization of the energy performance and the indoor environment of a building design. Based on CCE calculations in a Microsoft Excel sheet for different building elements, an economically optimal design solution could be found according to a certain targeted energy frame.

Evaluations of the indoor environment in the economically optimal design solution are based on parametric analysis in WinDesign. If any changes have to be made to ensure a good indoor environment, an iteration between the two programs must be performed.

In other words, the method can in a simple and transparent way integrate both economic optimization and considerations with regards to indoor environment into the decisions made in the early design phases. A case example featuring the optimization of a typical single-family house illustrates this and shows how the method is able to generate a qualified estimate of an economically optimal solution, which can be used as a starting point for detailed optimization and iterative design with other advanced simulation tools. Results in the example also show that in order to ensure that buildings reach low energy consumption, at minimum extra cost, a further development of appropriate products and solutions for different building elements is required and that they will have to be made available on the market at competitive prices.

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