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Economical optimization of building elements for use in design of nearly zero energy buildings

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ABSTRACT

Nearly zero energy buildings are to become a requirement as part of the European energy policy. There are many ways of designing nearly zero energy buildings, but there is a lack of knowledge on how to end up with the most economical optimal solution. Therefore this paper present a method for finding the economical optimal solutions based on the use of the cost of conserved energy for each main building envelope part and building service system and cost of produced energy for each energy producing system. By use of information on construction cost and developed models of the yearly energy use for each component, a function is set up that represents the relation of the marginal cost of conserved energy and the energy use for different quantities and qualities of the components.

The optimal mix of solutions for the whole building is found by selecting building parts with the same cost of conserved energy. The constraint is that the total energy performance of the building is fulfilling the requirements. A case example shows how the method with success can find the solution for a typical single family house with the energy performance requirement for 2020.

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. 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 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 method (Meier, 1983). Currently, the method has been used to post-assess the economic efficiency of energy-conserving building elements in both new and retrofitted buildings based on measured energy savings (Cohen et al., 1991) and (Piette et al., 1995). The method has also been used to assess and optimize the economic efficiency of potential design decisions in the retrofit of buildings (Martinaitis et al., 2004) and (Gieseler et al., 2004). Most recently (Petersen et al, 2012) and (Hansen et al., 2011) have showed that the method can be used to find an economically optimal solution, if the method is limited to a few main building elements and if the considered energy use is for the heating season only. This paper suggests a simple and transparent method for economic optimization which is able to handle more types of building elements, even energy-producing elements, and is based on the energy use all year round. The method is suitable for the early stages of building design and the aim of the method is to provide a good starting point for a process with the purpose of finding the optimal economical combination of the building elements.

2. Using cost of conserved energy for the economic optimization of building design

2.1 Cost of conserved energy for design of new buildings

The basic definition of cost of conserved energy (CCE) is derived from the paper by (Meier, 1983) where a method to evaluate the energy conservation investment proposal is outlined.

$$CCE = \frac{a(n,d) \cdot I_{measure}}{\Delta E_{year}} \quad , \quad a(n,d) = \frac{d}{1-(1+d)^{-n}} \quad (1)$$

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 (shares of unit), and n is the useful lifetime of the building element (years).

This basic definition of cost of conserved energy needs a number of supplementing factors in order to be appropriate for design of new buildings. One needed supplementing factor is the useful lifetime of the energy-conserving building element. The useful lifetime of a building element can be from a few years to the entire lifetime of the designed building. A reference period is therefore introduced to ensure a fair frame of reference for comparison of energy-conserving building elements with various useful lifetimes. The useful lifetime n in equation (1) is consequently replaced by the reference period n_r (also in years) and a factor t is introduced as the ratio between useful lifetime (n_u) of the building element and the reference period and thereby only the proportion of the investment cost is depreciated during the reference period. If the reference period is lower than the useful lifetime, a remaining value of the energy-conserving measure arises as $(1 - t) \cdot I_{measure}$. However, if the reference period is greater than the useful lifetime, a replacement of the

energy-conserving building element is needed within the reference period, but only the fraction *(t – 1)* of the reinvestment cost is depreciated in equation (2).

An energy-conserving building element might require a certain rate of maintenance and will therefore have an associated cost. The increase in annual maintenance cost (ΔM_{year}) is added to the annualised investment cost, see equation (2). If the maintenance cost occurs in an interval smaller or greater than one year, this maintenance cost should be distributed as an annual maintenance cost.

Some energy-conserving building elements might consume energy in 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. If $\Delta E_{operation,year}$ and/or ΔE_{year} are in units of electricity, the difference between energy content in one unit of heating and in one unit of electricity should be taken into account by multiplying with a primary energy factor in accordance with the national standard. Some of the energy might be converted into a heat gain for the building and this gain could be reflected by a reduction of the primary energy factor.

With these supplementing factors in order to make the cost of conserved energy appropriate for the design of a new building, the complete definition of cost of conserved energy is

$$CCE = \frac{t \cdot a(n_r,d) \cdot I_{measure} + \Delta M_{year}}{p_1 \cdot \Delta E_{year} - p_2 \cdot \Delta E_{operation,year}} \quad , \quad t = \frac{n_r}{n_u} \quad (2)$$

Where 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 consumed energy of the building element.

2.2 Economic optimization of building designs

The original formulation of the cost of conserved energy concept states that a measure (i.e. building element) is considered economically efficient if the cost of conserved energy is lower than the price of primary energy from the energy supply system (Meier, 1983) and therefore that the price of primary energy is the constraint in the economical optimization. Establishing a reasonable price of primary energy for comparison is a nearly impossible task, even with the use of sophisticated forecasting models, which take potential phase-out of the conventional energy sources into account (like (Pindyck, 1999) and (Poles, 2010)), as it will always relies on assumptions about energy price evolution. As a result, (Petersen et al, 2012) and (Hansen et al., 2011) suggested to use the requirement for 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), according to the Energy Performance Building Directive (EPBD, 2010).

According to (Friedman, 2007) the most effective allocation of resources is to maximise the contribution margin through marginal optimization. This implies that the optimization of energy-conserving building elements can be formulated as a constrained optimization problem where the total cost of the energy-conserving building elements is the objective function. The constraint to the objective function is the sum of the

energy use of the building elements equal to a specific requirement (e.g. the energy performance requirement). However it is assumed that the total energy use of different building elements can be calculated as the sum of their individual energy use well-knowingly (Crown et al., 1993) have shown the presence and importance of energy-conserving building elements interactions, but the simplification is allowed in order to generate an appropriate starting point. The optimization problem is thus reduced to finding the specific building elements that give the minimum cost and fulfil the constraint of the energy use.

The energy constraint states that the sum of the energy use has to be constant. Consequently, a small positive change in energy E_1 always has to be equal to a similar small negative change in energy E_2 for the different building elements. Furthermore, the corresponding changes in the cost of the energy-conserved building elements, P_1 and P_2, have to be equal with opposite signs at the minimum point. This argument can be expanded to cover n different building elements as described in (Hansen, 2011), and can therefore be expressed as

$$\frac{dP_1}{dE_1} = \frac{dP_2}{dE_2} = ... = \frac{dP_n}{dE_n} \quad (3)$$

where the differential quotient *dP/dE* is analogous to the definition of cost of conserved energy. The solution with the lowest cost that fulfils the energy constraint can thus be found where the marginal cost of conserved energy is identical.

2.3 Cost of produced energy

In nearly zero energy building it will often be considered to make use of energy-producing elements, e.g. a solar heating system. Therefore, it is in this paper suggested to extent the above mentioned method with a definition of the cost of produced energy, CPE.

$$CPE = \frac{\frac{n_r}{n_u} \cdot a(n_r,d) \cdot I_{measure}}{p_1 \cdot \Delta E_{produced,year} - p_2 \cdot E_{operation,year}} \quad (4)$$

where *CPE* is the cost of produced energy (€/kWh), $I_{measure}$ is the investment (or additional) cost of an energy-producing element (€), $\Delta E_{produced,year}$ is the annual energy production by the element (kWh) and $\Delta E_{operation,year}$ is the energy consumption of the energy-producing element (kWh).

The CPE will make it possible to calculate what it will cost to produce 1 kWh. If the marginal CCE is greater or equal to the marginal CPE for an energy-producing element, it will be the economical optimal solution to include the energy-producing element in the building design compared to adding more insulation or using a better and more expensive ventilation system.

3. Cost of conserved energy and energy use of building elements

In order to calculate the cost of conserved energy as a part of the process of finding the combination of the building elements with the same marginal cost of conserved energy, the energy use for each component has to be calculated. The calculations of the energy use will differ for the different building elements. In the following, the calculation method of the energy use for the building elements will be described in

the context they will be used in the later case example. The calculation method of the energy use for the building elements can be divided in two types: buildings elements with continuous energy properties and building elements with discrete energy properties.

3.1 Constructions

The construction parts, walls, roof and floor, are building elements with continuous energy properties and the optimization of such a building element is a question of optimizing quantity, e.g. the amount of insulation material in a construction.

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

$$Q_{constr} = \frac{1}{R_{se,i} + \sum_{j=1}^{n} \frac{d_{j,i}}{\lambda_{j,i}} + R_{si,i}} \cdot (D_H - \eta_{C,Is} \cdot D_C) \qquad (5)$$

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 (kKh), D_C is the number of degree hours calculated for the reference cooling season (kKh) and $\eta_{C,Is}$ is the utilization factor for heat loss (-).

By use of information on construction cost, the marginal cost can be set up as a continuous function of the energy use (calculated according to Eq. 5) for different quantities of each of the building elements with continuous energy properties, see Fig. 1. These functions can then be used to find the optimal economical solution for the building design where the marginal cost of conserved energy should be the same for all building elements.
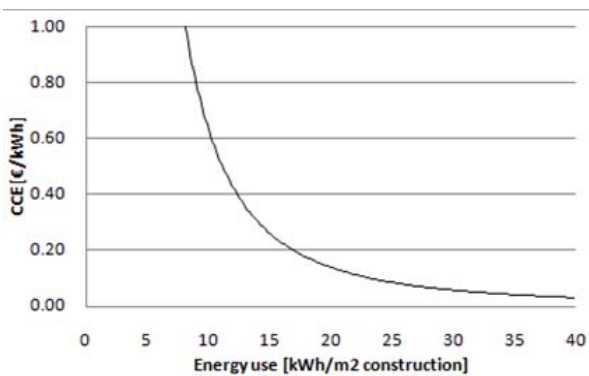

Fig. 1. Illustration of the marginal cost of conserved energy as a continuous function of the energy use.

If different wall types, and not just the insulation thickness, are included in the optimization (e.g. both brick and concrete wall types are considered), the variations of the construction parts will have to be considered as building elements with discrete energy properties, in order to find the optimal solution for a given insulation thickness and wall type before optimizing the quantity.

However it is worth mentioning that the investment cost for the building elements have a predominant effect on the CCE, so it is important that the investment cost used is updated and from the relevant region/country. This mean that the method is valid all over, but the input in form of a product database has to be set up regionally in order to produce an economical optimal solution, which is valid in the specific region.

3.2 Windows

The windows (as well as the ventilation system) are building elements with discrete energy properties and the optimization of such a building element is about evaluating the quality of the measure, e.g. the window type or a ventilation unit.

The energy use of the windows ($Q_{windows}$) is depending on the orientation of the window because of the solar radiation dependence on orientation, and is based on (EN ISO 13790, 2008) and (Duer et al., 2002). The energy use can be calculated as

$$\begin{aligned} Q_{window} = U_{window} \cdot (D_H - \eta_{C,Is} \cdot D_C) \\ + F_s \cdot g \cdot (I_{C,korr} - \eta_{H,gn} \cdot I_{H,korr}) \end{aligned} \qquad (6)$$

where U_{window} is the heat transfer coefficient for the window (W/m^{2}K), 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 (-).

The data of building elements with discrete energy properties form a discrete function which can be approximated with a continuous function during a procedure consisting of four steps:

1. The annual energy use for the windows is calculated according to equation (6) and is listed with their respective cost. The component with the lowest cost is chosen as reference.
2. The cost of conserved energy is calculated for the components with respect to the reference. All components with a negative cost of conserved energy will be rejected, since it will never be economically efficient, because they are more expensive than the reference and use more energy.
3. The component with the smallest positive cost of conserved energy 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 components with continuous energy properties.

An illustration of following these four steps for selection of windows in a building design is given in Fig. 2.
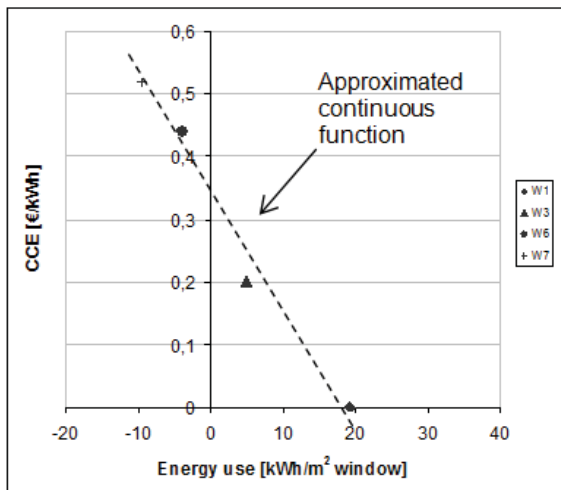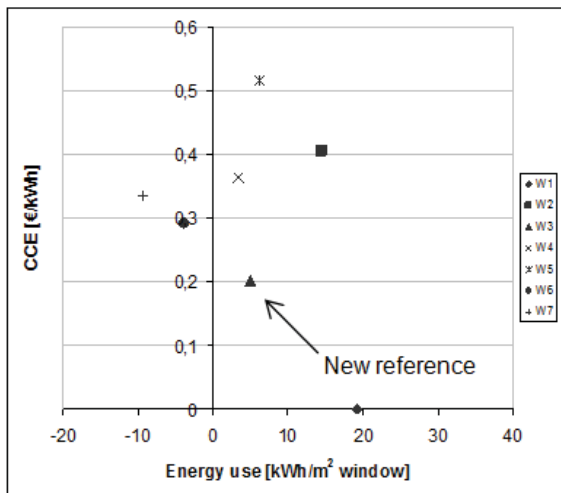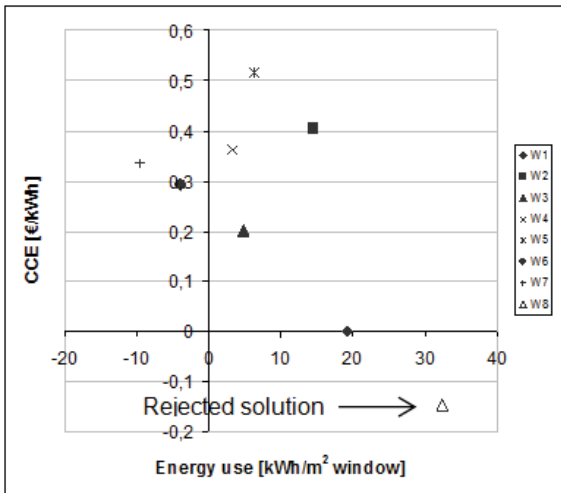
Fig. 2. Top: Step 2, rejecting of solution with negative cost of conserved energy. In the middle: Step 3, finding a new reference. Bottom: Step 4, continuous function generated based on cost of conserved energy of the remaining components.

3.3 Ventilation

The ventilation systems have, as the windows, discrete energy properties, and the creation of a continuous function is again performed by the procedures five step as described for the windows.

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. (7)

$$Q_{vent} = SFP \cdot p \cdot k + \rho \cdot c \cdot (1 - \eta) \cdot D_H - \eta_{C,Is} \cdot \rho \cdot c \cdot D_C \qquad (7)$$

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 (-).

3.4 Expansion of the method

The method also includes the energy use of other building elements, like thermal bridges, lightning (for office building) and solar heating systems, however they are for the sake of simplicity excluded here. Furthermore the method can be expanded to include different length of heating and cooling season (dependent on the building design), the impact of thermal mass, hot water consumption and internal heat. Similar to the calculations of energy use for the building elements in this paper, energy use of thermal bridges, lighting and solar heating systems can be defined with basis in (EN/ISO 13790, 2008), see (Hansen, 2011).

4. Building optimization

In order to find the optimal solution for the building as a whole, continuous functions for building elements are generated as described above. The quantity of each building element is then stated, e.g. in the form of the area of the constructions and windows, the ventilation rate etc. The continuous functions are then used to find the optimal distribution of the energy-conserving building elements for the building design accordingly to the criteria that the solution with the lowest cost fulfilling the energy constraint can be found where the marginal cost of conserved energy is identical.

This task can be facilitated by using the standard numerical solver in Microsoft Excel (Excel, 2003). However if the optimized building design contains building elements which do not match a known solution (a discrete value), it is necessary to either search for a solution that matches the optimization output, or choose the discrete value closest to the optimization output.

The task can also be facilitated by using a graphical method, where it is possible to optimize the cost of conserved energy based on the continuous function for the separate building elements (diagram 1-3 on Fig. 3) and a accumulated continuous function for all the building elements (diagram 4 on Fig. 3). On diagram 4 the national given energy performance requirement is located and the corresponding cost of conserved energy is found. Then the matching cost of conserved energy for the building elements can be used to find the optimal building elements. The requirement that the cost of conserved energy for all the building elements have to be equal can then be viewed as a way to force the optimization to find a balance between all building elements.
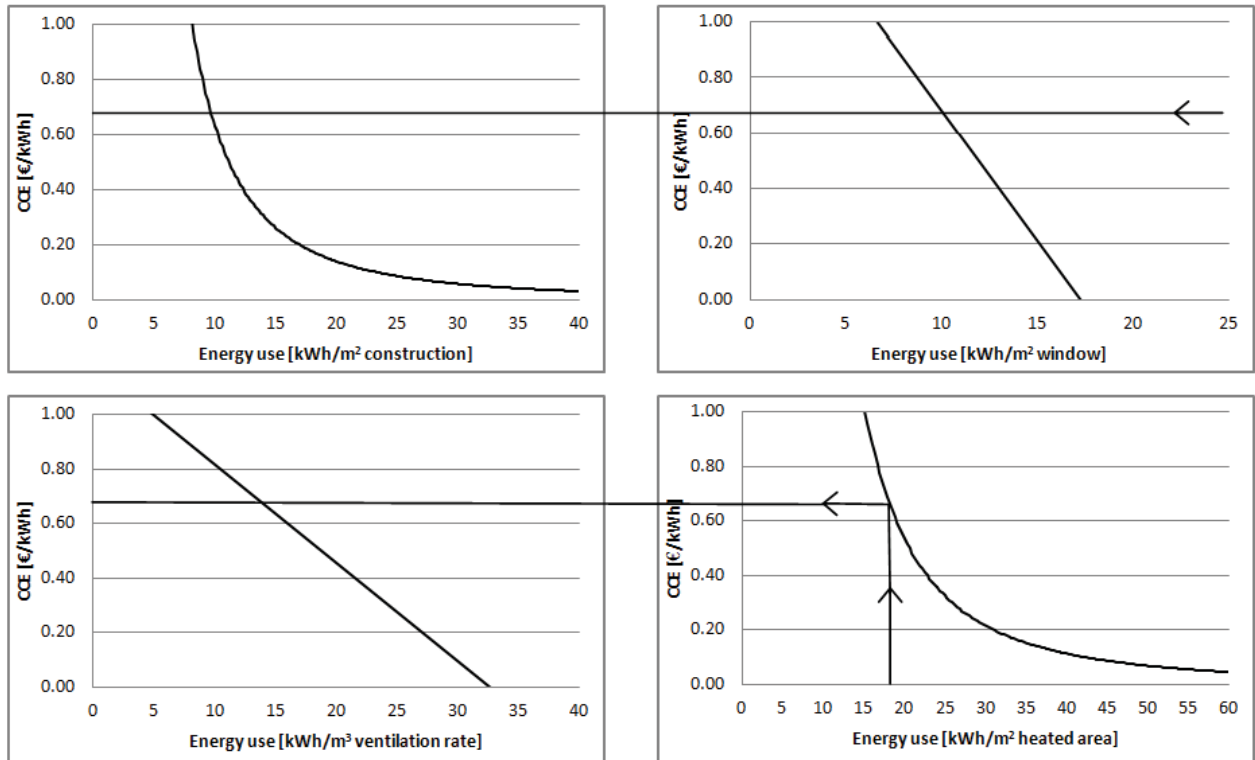
Fig. 3. Optimized building design based on the lowest cost of conserved energy for each building element to fulfil the energy frame.

However, the output from the building optimization is only a qualified estimate of an economically optimal energy solution, since the dynamic behaviour and interactions between energy-conserving building elements are not taken into account. The qualified estimate is, nevertheless, a good starting point for a process with the purpose of finding the correct optimal solution.

5. Comparison of output with Be10

Be10 is the program used in Denmark to document the energy performance requirement and calculate the energy use for construction cases on the design stage (SBi, 2008). The method described in this paper has been applied to a typical Danish single family house and compared to the energy use calculated with Be10. The examination showed that the method overestimates the energy use with 2-5 % compared to the calculation of energy use with Be10. The overestimation is reasonable since the method does not include the interactions of the energy-conserving building elements.

6. Case example

The following case illustrates how a simple version of the method can be applied on a typical Danish single family house. The heated floor area is 192 m^2 and the window area contributes 14% of the facade. The average mechanical ventilation rate is 0.3 ls^{-1}m^{-2}. The building has to be optimized to fulfil an energy performance requirement of 20 kWh/m^2 year (the Danish requirement for 2020 (BR10, 2011)). For the sake of simplicity, the optimization is limited to the constructions (wall, roof and floor), windows and mechanical ventilation. Furthermore, all maintenance costs are neglected. The basic data needed for calculating the CCE in accordance with equation (2) is given as: The discount rate is 2.5%, the reference period is 30 years and the primary

energy factor for electricity is 1.8. Table 1-3 contain data for possible energy-conserving building elements based on prices from Danish market conditions.

Table 1. Data assumption for insulation in wall, roof and floor. Lifetime is 100 years.

Building Element	Material	Thermal conductivity W/(m K)	Cost €/(cm m^2)
Wall	Mineral wool	0.034	1.23
Roof	Mineral wool	0.040	1.01
Floor	EPS	0.038	1.39

U-value and g-value in Table 2 are calculated for a window size of 1.23 x 1.48 m.

Table 2. Data assumption for windows. Lifetime is 20 years.

Windows	U-value W/(m^2 K)	g-value -	Cost €/m^2
W1	0.87	0.32	241
W2	0.85	0.44	381

Various heat recovery efficiencies affect the pressure loss of the ventilation system and thus the average specific fan power (SFP). However in Table 3 SFP is kept constant by sizing other ventilation components (dust system, fillers etc.) The sizing will have an effect on the price, but is neglected.

Table 3. Data assumption for mechanical ventilation systems. Lifetime is 30 years.

Mechanical ventilation	Average SFP J/m^3	Heat recovery %	Cost € per m^3/s
V1	600	0.92	83825
V2	800	0.88	22068

On the basis of the data assumption in Table 1-3, it is possible to calculate the continuous function describing the cost of conserved energy as a function of the energy use for the respective building elements. The standard solver in Microsoft Excel (Excel, 2003) is used to find the optimal distribution of the energy-conserving building elements in order to reach the energy performance requirement. Furthermore, the optimization of the insulation thickness in wall, roof and floor was constrained to a maximum thickness of 400, 600 and 500 mm, respectively. Optimizing without this constrain would result in unrealistic insulation thickness since the cost of conserved energy is significantly lower for insulation than for windows and ventilation units. The optimization result can be seen in Table 4.

Table 4. Economically optimal solution for case example.

Building element	CCE €/kWh	Measure
Wall	0.20	400 mm insulation
Roof	0.45	500 mm insulation
Floor	0.45	450 mm insulation
Windows	0.25	Between W1 and W2
Ventilation	0.25	Between V1 and V2

The solution does not fulfil the constraint that the cost of conserved energy for all the building elements should be equal. The reason for this is the constrain on the maximum insulation thickness and the few available and suitable ventilation units.

The optimization result shows that the optimal window and the optimal ventilation unit are located between two of the available building elements. This indicates a potential for economically efficient energy savings in the development of more energy efficient windows and ventilation systems. However, until they are developed the optimized solution will be the window and ventilation unit closest to the optimization output.

7. Analysing the method

The method 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, it is necessary to have access to an extensive and updated product database. In order to test the method such a database has been developed for buildings elements in Denmark (CCE Calc, 2011), but this must be replaced with a database from other countries in order to give realistic building design solutions in these countries.

Nevertheless, the results from the case example illustrate that even if a product database is included in the program, it can be hard to reach a solution where the marginal cost of conserved energy 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 thus enabling the identification of potentials for further product development. One of the obvious potentials for further product development would be to develop sandwich panels of high performance concrete or to have insulation with a lower thermal conductivity available on the market in order to avoid the constraint on insulation thickness in e.g. the walls, which, as it is shown in the case example, will have the lowest cost of conserved energy. Furthermore, the case example points in the direction that ventilation units with lower SFP and windows with a larger net energy gain would help reach the nearly zero energy performance requirement with building elements which have the same marginal cost of conserved energy and consequently force the optimization to find the economically optimal balance between all building elements.

8. Conclusions

The presented method can in a simple and transparent way integrate economic optimization into the design decisions made in the early stages of design, which is of increasing interest due to the increasingly low energy requirements. It has been justified that an economic optimum can be found where the marginal cost of conserved energy is identical for all energy-conserving building elements and that the whole building will fulfil the given energy performance requirement. In this way, the method using the marginal cost of conserved energy can identify the economically optimized combination of various energy-conserving building elements needed to fulfil the national given energy performance requirement. In addition, the method can be used to illustrate the economic efficiency of the individual building elements enabling the identification of potentials for further product development.

A case example featuring the optimization of a typical single family house has been given to illustrate the feasibility of the method. The example illustrates 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.

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