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DEFINING ENERGY- AND COST-SAVING POTENTIALS AND THEIR APPLICATION IN OPTIMAL BUILDING REFURBISHMENT

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Abstract

In this paper, we develop a rigorous theoretical framework and a practical implementation for the evaluation of the energy- and cost-saving potential of buildings. The goal is to promote sustainability in the context of building energetics by achieving the most efficient, optimal exploitation of the financial resources available for refurbishments. The practical realization of this concept requires the evaluation of the optimal refurbishment cost that maximizes the net energetic or financial savings during the life cycle of the building. On the one hand, too small a refurbishment cost might lock-in a substantial amount of energy and cost savings potential. On the other hand, refurbishment costs that are too high due to unnecessarily implemented energy-saving measures are likely to waste financial resources. The key concept behind the theory is the novel definition of the reference value used for the computation of the energy- and cost-saving potentials. From a mathematical point of view, the reference value is obtained by two subsequent optimizations. First, a constrained, single-objective optimization is used to evaluate the best energetic state of the building as a function of the refurbishment cost. Second, a simple unconstrained search must be performed to obtain the minimum value and the minimum place of the one-dimensional cost function. The proposed framework automatically provides personalized solutions corresponding to the actual technical characteristics of the building. These solutions are optimal under the given circumstances of the actual refurbishment, resulting in either the highest possible energy- or cost-saving amounts during the life cycle of the building.

Key words: efficiency, energy saving, cost saving, potential, optimization

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1. Introduction

In 2010, the total primary energy consumption of Hungary was 1 085 PJ. Currently, 40% of this energy is consumed by the operation of buildings (434 PJ). Two-thirds of the operational costs are attributed to the heating and cooling of buildings, resulting in an annual energy consumption of 289 PJ. According to the National Energy Strategy 2030 (MND, 2012), by 2030, Hungary intends to achieve a 30% decrease in this building energy consumption. Thus, 87 PJ of energy must be saved by the energetic improvement of the Hungarian building stock. Because the new buildings must follow high energy standards and the building rate is quite low, most of this energy must be saved by the appropriate refurbishment of the existing building stock. Approximately 70% of the 4.3 million buildings in Hungary do not conform to the modern technical requirements; as a result, 3 million buildings are potential subjects of refurbishment.

Because the European, national and household resources available for the refurbishment of buildings is quite limited, they have to be exploited in the most efficient, i.e., optimal, manner. The refurbishment design of an actual building is a highly complex procedure. Frequently, the retrofit is based on the architect's practical expertise. In the more

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sophisticated cases, a low number (often three) refurbishment designs are created, allowing the customer choose the one that best fits the actual needs. Clearly, this approach might be quite sub-optimal, i.e., due to the high complexity of the design process, the energy saving achieved by the refurbishment can be considerably less than the technically possible ideal limit (i.e., the energy-saving potential) of the particular building.

The term energy-saving potential refers to the largest amount of energy that can be saved by the appropriate refurbishment of a building under certain conditions. Although it is a key concept, the literature is quite vague regarding an exact definition. In a particularly relevant reference, Joosten et al. (2006) addresses the calculated energy savings by Passive House construction in different countries. In the study, the energy-saving potential per country is calculated by comparing energy uses per applied energy source for new-to-build dwellings and refurbished dwellings with those of the Passive House. The authors use the following definition for the energy-saving potential of refurbished buildings per country (Eq. 1):

$$\Delta Q_i = \sum \left(Q_{REFURBISHED} - Q_{PH}\right)_i, \qquad (1)$$

where $Q_{REFURBISHED}$ and Q_{PH} stand for the heating energy requirement of refurbished building *i* and of its alternative refurbishment satisfying the passive house standards, respectively.

Joosten et al. (2006) states: “The energy saving is calculated by subtracting the energy use of a Passive House from the energy use of a typical new dwelling and from the energy use of an average existing dwelling. The energy saving potential is calculated by multiplying energy savings by the expected numbers of Passive Houses and Passive House refurbishments.”

Although this definition adequately handles the basic idea, it considers passive houses as reference points. However, a passive house might not always be an optimal solution in regard to the refurbishment of a building. It is obvious that some buildings are easier to be refurbished to the passive house level than others. If the surface-to-volume ratio is low and the windows are well oriented, reaching the passive house level can be a reasonable objective. However, for buildings with complex geometry and unfavorable characteristics, the passive house level is most probably an unrealistic choice. In the latter case, the energy-saving potential definitely should not be calculated based upon the passive house requirements.

The key issue behind the definition of the energy-saving potential is the definition of the reference value. In the present paper, the intention is to establish the foundation of a rigorous approach for defining (i) the reference value; (ii) the energy-saving potential of an arbitrary building; and (iii) the intrinsically linked concept of the cost-saving potential. The main goal is to present a theory that can be easily implemented in practical work. The benefits of the approach are two-fold. First, the analysis provides personalized solutions corresponding to the actual technical characteristics of the building. These solutions are optimal under the given circumstances of the actual refurbishment. Second, the accuracy of the model is based on the available technical and economic information. The more data that are fed into the model, the more accurate the answer will be, without the need to change the background theory.

The outline of this paper is as follows. In section 2, the applied model of building optimization is introduced. The concepts of energy- and cost-saving potentials are defined in section 3. The practical implementation of the theory is described in section 4. In section 5, a test case is presented involving the optimal refurbishment of a residential dwelling. Finally, in section 6, concluding remarks and a preview of future research are presented.

2. A basic model for optimization

2.1. Basic definitions

To simplify the adopted formulations, we make the following two assumptions:

- We are only interested in the optimization of building envelopes, i.e., the HVAC system is not modified.
- We assume that the building is heated by a single source of energy, i.e., by using natural gas.

Although these simplifications might be limiting in some practical applications, they make the presentation considerably clearer. Moreover, the main results of this paper retain their validity even when these assumptions are broken. Because our aim is to improve the envelope of the building, the energetic quality of the building is represented by the value of the specific heat loss coefficient *q* (including the transmission heat loss coefficient of the building minus the solar gains per heated volume, expressed in units of W/m^3K).

Consider a building subject to refurbishment, with an estimated remaining life cycle of *T* years. In the context of optimization, we distinguish three different states of the building. The initial state is the one to be improved by the refurbishment process. The refurbished state is obtained by the actually realized retrofit that is designed by human experts. Finally, the optimally refurbished state or the optimal state depends on the technical limitations posed by the following factors:

- the technical characteristics of the building,
- the costs, physical properties, and the gray energy content of all materials that can be potentially applied in the refurbishment process,
- salary tables for the possible work types,
- the economy of energy sources and predicted future trends,

• in some types of optimizations, the prescribed budget or the targeted energy performance.

Note that the optimal state is in fact a priori unknown, and in practical applications, most likely it can never be exactly determined. The refurbishment transforming the initial state to the optimal state is referred to as the optimal refurbishment or design. Thus, the optimal refurbishment expresses the best possible improvement on the initial state under the prescribed circumstances. In principle, no human expert can design a better state than the optimal state. In the rest of this paper, the following labeling conventions will be used exclusively: quantities describing the initial, refurbished and the optimal states will be denoted by subscripts *I*, *R* and *O*, respectively.

One of the most important aims of the refurbishment process is to decrease the annual heating energy consumption e^H of the building in terms of delivered energy. Note that e_I^H and e_R^H can be considered as two different constant quantities, before and after the refurbishment, respectively. In contrast, the c_t^H annual cost of unit heating energy is a function of time, where subscript *t* represents the *t*-th year. The cumulated heating energy and the corresponding cost over the life cycle of the building are given by Eqs. (2, 3), respectively.

$$E^H = e^H T \tag{2}$$

$$C^H = e^H > C_R^H \tag{3}$$

We define the total life cycle (LC) energy consumption of the building as given by Eq. (4).

$$E^{TLC} = E^R + E^H + E^M + E^{DA} \tag{4}$$

where E^R, E^M and E^{DA} and are the gray energy content related to the components applied during the refurbishment, the possible reparations and maintenance work during the life cycle of the building, and the disassembly of the building at the end of its life cycle, respectively. A similar equation (Eq.5) can be formulated for the total LC cost function.

$$C^{TLC} = C^R + C^H + C^M + C^{DA}, \tag{5}$$

where C^R, C^M and C^{DA} are the refurbishment cost, the cost of possible reparations and maintenance work during the life cycle of the building, and the cost of disassembly of the building at the end of its life cycle, respectively.

2.2. Problem statement

In this paper, we consider the following two levels of optimization scenarios:

• Level 1: what is the best technically available energy quality of a particular building (i.e., the smallest possible *q*-value) if the total budget of the refurbishment is prescribed?

• Level 2: what is the optimal refurbishment budget C_O^R that minimizes the total LC cost function C_R^{TLC} ?

The level 1 type optimization is a typical scenario, e.g., when a family has a certain amount of capital to refurbish their house. In this case, the desire is to obtain the refurbishment design leading to the smallest possible annual heating bill, i.e., to minimize $e_R^H \cdot c_t^H$ under the constraint of a fixed refurbishment budget. Using mathematical terminology, this is a single objective optimization problem that can only be solved by sophisticated scientific tools (Bichioua and Krarti, 2011; Caldas and Norford, 2003; Csík et al., 2012; Tuhus-Dubrow and Krarti, 2010). Here, we use the state-of-the-art ENERGOPT expert system developed by the authors of this paper (Csík et al., 2012). In relation to the level 1 optimization problem, the following questions naturally emerge:

• Does e_R^H decrease considerably if C^R were somewhat higher?

• Would e_R^H not change considerably if C^R were somewhat smaller?

What is the optimal refurbishment cost that minimizes either E_R^{TLC} or C_R^{TLC} ? The more cost (gray energy) we invest into a refurbishment, the less the heating bill (heating energy consumption) will be. The main goal of this paper is to introduce a rigorous framework to determine the optimal refurbishment cost C_O^R for a particular building. Thus, the computation of C_O^{TLC} is supported by a sound analysis of the technical limitations (listed in subsection 2.1).

2.3. The state vector of a building

Consider a building subject to refurbishment. From an energetic perspective, the actual state of the building can be described by a set of numbers reflecting the properties of its components (e.g., thickness of façade wall, its λ-value etc.). Some of these components can be changed during the refurbishment process (e.g., wall insulation), whereas some other components cannot (e.g., in many cases, the base area of the building). Note that it is always case dependent which components are adjustable, i.e., can be changed, modified, or replaced.

Let us gather all of the quantities describing the adjustable components of the building into a one-dimensional array. We refer to this array as the optimization state vector of the building (or simply the state vector) and label it *W*. Thus, the state vectors corresponding to the initial, refurbished and the optimal states are labeled as W_I, W_R and W_O, respectively. In a simple test case, when the refurbishment can target only the wall insulation and five windows, *W* has the following 7 components: the type of insulator, the thickness of the insulation and the types of the five windows.

3. Saving potentials of a building

3.1. The energy-saving potential

Assume that the initial building was not refurbished. During time *T*, the cumulative heating energy is given by Eq. (6).

$$E_I^H = e_I^H T \quad (6)$$

The total LC energy requirement is expressed as Eq. (7).

$$E_I^{TLC} = E_I^H + E_I^M + E_I^{DA} \quad (7)$$

Considering the renovated scenario, during the life cycle of the building, the cumulative heating energy is given by Eq. (7).

$$E_R^H = e_R^H T \quad (8)$$

The total LC energy required for the refurbishment process and for the operation of the refurbished building for time period *T* is given by Eq. (9).

$$E_R^{TLC} = E^R + E_R^H + E_R^M + E_R^{DA} \quad (9)$$

From an energetic perspective, the goal of the refurbishment is to decrease E_R^{TLC} as much as is possibly allowed by the technical limitations. Clearly, given the available technological, economic and financial background, there exists the smallest value for E_R^{TLC}, denoted by Eq. (10).

$$E_O^{TLC} = min \;\; E_R^{TLC} \quad (10)$$

This ideal limit is achieved by the energy-optimal refurbishment, leading to the energy-optimal refurbished state W_{EO} of the building. This state has the technically possible smallest amount of total LC energy requirement. Thus, we propose to use E_O^{TLC} as the reference point in the definition of the energy-saving potential. The cost of the energy-optimal refurbishment is called "energy-optimal refurbishment cost" and is denoted by C_{EO}^R.

The energy saving potential Φ^E of the initial building represents all total energy requirements that can be saved under the given technical limitations by the optimal refurbishment (Eq. 11):

$$\Phi^E = E_I^{TLC} - E_O^{TLC} \quad (11)$$

3.2. The cost-saving potential

The energy-optimal state of the building leads to the smallest cumulated total LC energy consumption during its life cycle. However, this state may not lead to the smallest total LC cost. In the following, we put the above considerations in perspective with respect to costs. Without refurbishment, the total LC cost of the initial building during its life cycle is given by Eq. (12).

$$C_I^{TLC} = C_I^H + C_I^M + C_I^{DA}. \quad (12)$$

Let us focus on the financial aspects of the refurbished building. The total operating cost during its life cycle is according to Eq. (13).

$$C_R^{TLC} = C^R + C_R^H + C_R^M + C_R^{DA} \quad (13)$$

The goal of the cost-optimal refurbishment is to determine the smallest possible value of C_R^{TLC}, labeled by (Eq. 14):

$$C_O^{TLC} = min \;\; C_R^{TLC} \quad (14)$$

This ideal limit is achieved by the cost-optimal refurbishment (Csík, 2013, 2014), leading to the cost-optimal refurbished state W_{CO} of the building. This state has the technically possible smallest amount of total LC cost requirement. Following the ideas expressed above, we propose to use C_O^{TLC} as the reference point in the definition of the cost-saving potential. The cost of the cost-optimal refurbishment is called "cost-optimal refurbishment cost" and is denoted by C_{CO}^R.

The cost-saving potential of the initial building (Csík, 2013) defining the total LC cost that can be saved during its life cycle is given by Eq. (15):

$$\Phi^C = C_I^{TLC} - C_O^{TLC} \quad (15)$$

4. Practical implementation

The main novelty of this paper is the method enabling the approximate computation of C_{EO}^R and C_{CO}^R. The value of C_{EO}^R leads to the energy-optimal refurbishment and the corresponding value of E_O^{TLC}. Thus, the energy-saving potential of the initial building can be readily computed from Eq. (11). Similarly, the value of C_{CO}^{R} leads to the cost-optimal refurbishment and the corresponding value of C_{O}^{TLC}. Thus, the cost-saving potential of the initial building can be readily computed from Eq. (15).

In this section, we provide the main details of the computations of C_{EO}^{R} and C_{CO}^{R}. For brevity, we only describe the evaluation of C_{CO}^{R} and the cost-saving potential; the computation of C_{EO}^{R} and the energy-saving potential can be obtained by following the same pattern.

4.1. Basic assumptions

To establish a well-posed optimization problem, we make the following basic assumptions:

1. The initial state vector of the building is known.
2. There exists a mathematical model to compute all quantities that are important from energetic and financial points of view.
3. There is a known database containing all physical properties, gray energy content and costs of the components available for implementation during the refurbishment process, so the total cost of the installed materials can be calculated.
4. There is a known database containing the costs of all types of work emerging in the renovation process, so the total cost of the man-power can be calculated.
5. The gray energy and the cost of the maintenance works during the life-cycle of the building are given in a database.
6. The gray energy and the cost of the disassembly of the building at the end of its life-cycle are given in a database.
7. The price of unit energy as the function of time is available by some economical estimations, i.e., c_t is known for all $1 \le t \le T$.

With these assumptions, we obtain a well-posed optimization problem. In practice, there is an infinite (very large) number of possible renovations that can improve the energy quality of a building. Our goal is to find the single one leading to the smallest total LC costs C_{O}^{TLC}. The corresponding cost-optimal refurbishment cost C_{CO}^{R} can be obtained in the following two steps:

1. Determine function $q\left(C^{R}\right)$,
2. Determine function $C_{R}^{TLC}\left(C^{R}\right)$ and find its minimum value C_{O}^{TLC} and minimum place C_{CO}^{R}

4.2. Step 1: Determine function $q\left(C^{R}\right)$

Now, let us fix the total cost of refurbishment C^{R} related to the energetic improvements of the building to a specific value, say 12 000 EUR. Many different refurbishments can be financed from this cost, leading to different qualities of the building envelope. In the context of sustainability, we must find the one providing the best energy quality with the smallest specific heat loss coefficient.

The solution of this complex problem requires computer-aided state-of-the-art mathematical methods. Indeed, the refurbishment design is a highly complex process involving the evaluation of a large number of expressions depending on excessive data sets. In addition, a subtle balance has to be maintained between the quality of the implemented components and the corresponding costs. From a mathematical point of view, the building optimization is equivalent to finding the global extremum of the objective function defined in a space with as many dimensions as the number of components of the state vector. Due to the prohibitively large optimization spaces occurring in real life, classical methods for exact optimum finding are not feasible.

This problem can be solved by modern optimization techniques based on heuristic approaches. In this paper, we use the EnergOpt expert system (Csík, 2013, 2014) to obtain the smallest possible (optimal) value of *q* for a fixed total refurbishment cost. The optimization problem is solved in the following three steps.

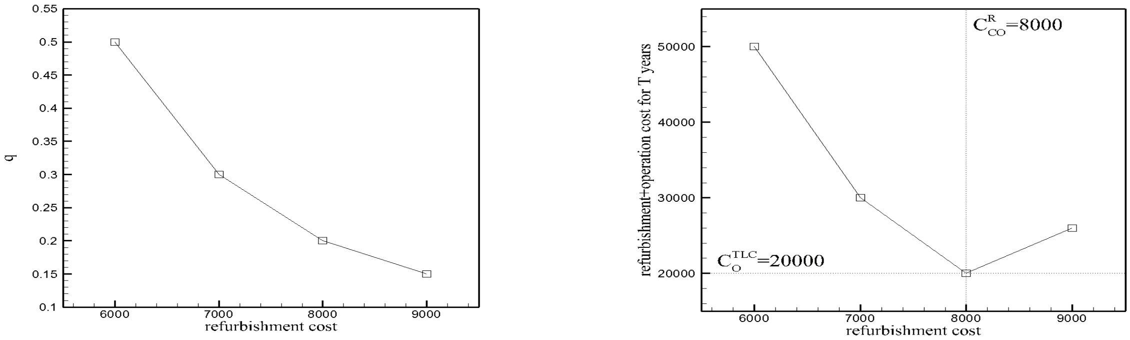
1. All data affecting the status of the energy use of the building are entered into the energy evaluation module, and the energy category of the building is computed.
2. The total cost of the refurbishment is set (e.g., 12 000 EUR).
3. The optimization module provides the optimal state of the building and the corresponding optimal value of *q*.

Let us change the value of refurbishment cost C^{R} over a realistic interval $\left[C_{\min}^{R}, C_{\max}^{R}\right]$ with a step size of ΔC^{R}. For every value of C^{R}, we obtain the corresponding value of $q\left(C^{R}\right)$. This way, we can obtain the discrete $q\left(C^{R}\right)$ function with any desired resolution ΔC^{R} (see the left panel of Fig. 1).

4.3. Step 2: Determine function $C_{R}^{TLC}\left(C^{R}\right)$

Based on the $q\left(C^{R}\right)$ function, the total heating LC energy consumption $E_{R}^{H}\left(C^{R}\right)$ can be calculated, yielding the $C_{R}^{H}\left(C^{R}\right)$ function. Next, we can evaluate $C_{R}^{TLC}\left(C^{R}\right)$ from Eq. (13). Finally, the minimum value and the minimum place of function $C_{R}^{TLC}\left(C^{R}\right)$ can be numerically evaluated to obtain C_{O}^{TLC} and C_{CO}^{R}, respectively. This procedure is illustrated on the schematic plots of Fig 1.

On Fig 1a. the monotone decreasing specific heat loss coefficient function $q\left(C^{R}\right)$ is plotted as the function of the refurbishment cost C^{R}. On Fig 1b. the corresponding total life cycle cost function is presented. Its minimum value and minimum place defines the cost-optimal total life cycle cost and the cost-optimal refurbishment cost, respectively.



a **b**

Fig. 1. The discrete functions of $q\left(C^{R}\right)$ (a) and $C_{R}^{TLC}\left(C^{R}\right)$ (b) (the optimal renovation cost C_{CO}^{R} and the total *LC* cost C_{O}^{TLC} are indicated as the minimum place and the minimum value of function $C_{R}^{TLC}\left(C^{R}\right)$, respectively)

5. The test case

5.1. Description of the building

In the test case, we consider the refurbishment of a family house situated in Budapest, built in 1950. The building has three floors. There is a cellar bellow the ground floor. The first floor is partially composed of a heated living area that is insulated by 15-cm-thick fiberglass insulation. The other part of the first floor is without roof insulation and is connected to an unheated attic above. The total heated floor area is 164.64 m^{2}. The specific heat loss coefficient of the original building is q_{I} = 1.14 W/m^{3}K, and the total primary energy consumption is EP_{I}=326kWh/m^{2}a. The energy category of the building is F on the energy certificate. The source of heating is natural gas.

In the test computation, only the optimization of the building envelope is performed, i.e., the heating system is unchanged. Four different types of insulations (façade walls, attic, cellar slab, and attic slab), six windows and a door were optimized. Thus, the problem is equivalent to finding the optimal solution in a 14-dimensional search space.

5.2. Simplifications

To keep the focus on the main concepts of this paper, we make the following simplifications:

1. The maintenance cost during the life cycle of the building is not considered: $C_{I}^{M}=C_{R}^{M}=0$.
2. The cost of the disassembly of the building at the end of its life cycle is not considered: $C_{I}^{DA}=C_{R}^{DA}=0$.
3. We take a simple static energy price model, i.e., $c_{t}^{H}=c_{1}^{H}=c^{H}$ for all $1\leq t\leq T$.

Note that these assumptions do not affect the generality of the theory described so far. All three elements can be easily added to the optimization procedure without any considerable technical modifications, provided the corresponding information is available. As a result, we seek the balance between the refurbishment cost and the cost of the total LC heating energy. The total LC cost and the cost-saving potential reduce to:

$$C_{R}^{TLC}=C^{R}+e_{R}^{H}c^{H}T \tag{16}$$

$$\Phi^{C}=\left(e_{I}^{H}-e_{O}^{H}\right)c^{H}T-C^{R}. \tag{17}$$

5.3. Calculation of the heating energy cost and the refurbishment cost

At the date of writing, in Hungary, up to 11 400 kWh annual energy usage of natural gas costs 0.043 EUR/kWh, and above this limit, the price is 0.050 EUR/kWh. There is also a base charge of 48.51 EUR/a. Because we use a static model, these energy prices are not modified. The refurbished building has an anticipated life cycle of T=20 years.

The cost of the refurbishment process is obtained by using the database of the EnergOpt expert system. The value of C^{R} is the sum of the cost of the installed components and the corresponding cost of manpower.

5.4. Optimization results

The optimization results were obtained by the EnergOpt expert system. The initial building was optimized by fixing the refurbishment cost and minimizing the specific heat loss coefficient as the objective function. The refurbishment cost was changed from $C^R_{\min} = 1\,000\,000$ HUF (~3 400 EUR) to $C^R_{\max} = 4\,000\,000$ HUF (~ 13 800 EUR) in steps of $\Delta C^R = 100\,000$ HUF (~ 340 EUR). For every value of C^R, the best possible building envelope was obtained, represented by the value of the specific heat loss coefficient q The results are plotted in Fig. 2. The horizontal dotted line at the top of the figure represents the $q_I = 1.14$ W/m^{3}K value of the initial building (original state). The two vertical dotted lines represent the cost-optimal range of 7 500 EURO $\leq C^R \leq$ 11 000 EURO to be discussed later. The two horizontal lines at the bottom represent the corresponding q-values (0.16 W/m^{3}K $\leq q \leq$ 0.28 W/m^{3}K).

The asymptotically converging shape of q implies that the envelope of the building cannot be improved beyond limit with the available materials in the database. Thus, it is not worth investing in the improvement of the envelope above a given cost because the effect of continuously decreasing energetic improvements does not justify the invested extra financial resources. The aim of the refurbishment process is to minimize the total LC costs C^{TLC}_R. To find the cost-optimal refurbishment cost C^R_{CO}, in Fig. 3, different cost-related quantities are presented as a function of C^R. The straight dashed line has a slope of unity, representing the refurbishment cost C^R itself. The cumulated LC cost of the heating energy C^H_R for 20 years is plotted by a dash-dotted line. The sum of these two quantities, i.e., the total LC cost $C^{TLC}_R\left(C^R\right)$ is plotted by a thick solid line.

According to the expectations for smaller refurbishment costs, C^{TLC}_R is decreasing, implying that the cost of the invested money pays off in the long run. At approximately 7 500 EUR, the curve reaches its lower bound; it stalls and exhibits small, practically negligible variations until 11 000 EUR. Above this limit, the C^{TLC}_R curve starts to rise, implying that the additional money spent on the refurbishment results in miniscule energetic improvements that are not paying off financially. The cost-optimal domain is represented by two vertical dotted lines (7 500 EURO $\leq C^R \leq$ 11 000 EURO) in Fig. 2. Any refurbishment cost in this interval leads to practically identical $C^{TLC}_O \approx 19\,000$ EUR of total LC cost (bottom dotted horizontal line). The dotted horizontal line at the top of the figure represents the $C^{TLC}_I \approx 43\,000$ EUR cumulated heating costs of the initial building for 20 years.

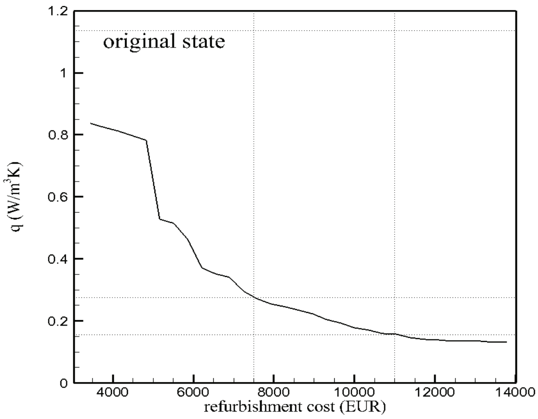


Fig. 2. The optimal specific heat loss coefficient of the refurbished building as a function of C^R (the horizontal dotted line at the top represents the q=1.14 W/m^{3}K value of the initial building; the vertical dotted lines bound the cost-optimal results)

(7 500 EURO $\leq C^R \leq$ 11 000 EURO)

6. Discussion and conclusions

In the present paper, we introduced rigorous definitions for the energy-saving potential and the cost-saving potential of an arbitrary building subject to refurbishment. In addition, we provided the appropriate methodology and technical background to implement the theory in practical applications. The method provides an exact framework for answering the following questions:

- What is the largest amount of energy that can be saved by the energy-optimal refurbishment of a particular building during its life cycle?
- What is the corresponding energy optimal refurbishment cost?
- What is the largest amount of money that can be saved by the cost-optimal refurbishment of a particular building during its life cycle?
- What is the corresponding cost optimal refurbishment cost?

Based on the presented theory, virtually any building can be analyzed, provided all necessary information is available. The information required by the model is arranged into a modular structure, with each module representing some type of information in the generic main framework (energy evaluation module, salary database, material database, reparation cost database, disassembly database). Note that the last three databases contain the relevant gray energy content as well. The first three modules are absolutely essential for the optimization of building energy use. The more the other modules are filled with information, the more accurate the output of the theory will be.

In particular, the energetic evaluation module can either be based on a complex thermodynamic model or on a simplified algebraic model. In most related papers, the authors employ the thermodynamic model to simulate the energy performance of buildings.

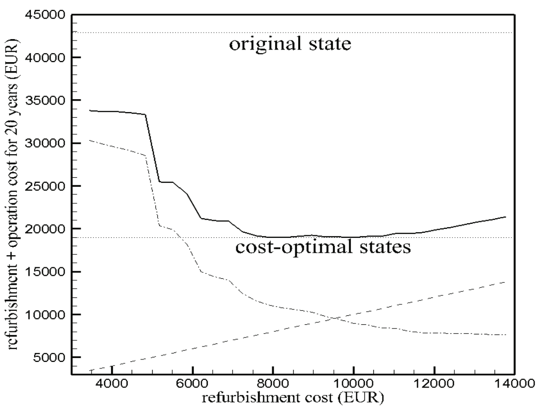


Fig. 3. Different costs as a function of the refurbishment cost C^R (dashed line: refurbishment cost C^R; dash-dotted line: cost of heating energy C_R^H for a 20-year-long life cycle; solid line: sum of the refurbishment cost and the cost of heating energy for a 20-year-long life cycle: $C_R^{TLC} = C^R + C_R^H$; the horizontal dotted lines represent the total operational costs for the initial (original) and the cost-optimal states)

Although this approach can be very accurate, it requires highly detailed technical information on the building subject to investigation. In the present paper, we considered a simplified model (i.e., the national building code of Hungary) that uses only the information that is required to evaluate the energy category of buildings. Although this approach is less accurate, it requires considerably less information than the thermodynamic approach. Thus, it can be easily implemented into the work flow of large companies and governmental agencies working with a very large number of buildings on short time scales.

The cost optimum analysis has recently become a political priority as well. According to the EPBD recast (2010/31/EU directive on the energy performance of buildings), member states should set their energy performance requirements to the cost optimal level. The determination of the cost optimal level of the energy performance of the buildings is based on a common EU methodology that has been applied individually by all member states. This fact highlights the political importance of cost optimization in general. However, the EU method is not designed for determining the cost optimal refurbishment for actual construction projects because the national cost optimal studies are based on sets of typical or characteristic buildings. The ENERGOPT expert system is developed for such applications, when the subject of cost optimality is considered from the point of view of individual buildings.

In the presented test case, we investigated the cost-optimal refurbishment of a family house. The analysis revealed that in this particular case, the refurbishment cost should be in the range of 7 500 EURO $\leq C^R \leq$ 11 000 EURO to minimize the sum of the refurbishment costs and the heating costs for 20 years of anticipated life cycle. Aspects of the initial capital cost or CO_2 emission could be considered to select the actual refurbishment cost from this interval. Clearly, smaller vales result in higher heating costs and higher CO_2 emission during the life cycle, while higher refurbishment costs decrease both quantities. Obviously, the width of this interval is case dependent, so it should be computed for each building before starting any refurbishment process. The optimal (minimal) value of the total LC cost is $C_O^{TLC} \approx$ 19 000 EURO. Because the cumulated heating cost of the initial building is $C_I^{TLC} \approx$ 43 000 EUR for 20 years, the cost-saving potential of the original house is $\Phi^C =$ 24 000 EUR. This figure means that for a 20 years of predicted life cycle no more money can be saved by any refurbishment than Φ^C. If the refurbishment of the building is performed from a lower budget than the smallest value of the cost-optimal domain $C_{min}^R =$ 7 500 EUR, a considerable amount of cost-saving potential (and energy-saving potential) becomes locked into the building for the rest of its life cycle. For example, the refurbishment cost of $C^R =$ 6 000 EURO yields $C_R^{TLC} = 23\ 000$ EURO, resulting in 4 000 EURO of locked-in cost-saving potential for 20 years. However, if the refurbishment cost is too high, the money invested into the higher energetic level does not pay off, i.e., the increase in energy quality becomes negligible and the invested money is wasted. For example, $C^R =$ 14 000 EURO refurbishment cost yields $C_R^{TLC} =$ 22 000 EURO, resulting in 3 000 EURO of locked-in cost-saving potential during 20 years.

These figures may not seem striking in the case of a single building; however, on a national level, the decrease in the cumulated energy consumption, CO_2 emission and operation cost may reach substantial levels. Moreover, the cumulated financial resources allocated for the refurbishment of the national building stock can be significantly decreased by more than 20%. Obviously, no general conclusions should be drawn from the results of a simple test case. The presented methodology must be evaluated on a large set of buildings to derive some statistical information on the expected saving potentials.

It is clear that the predicted life cycle of the building is a free parameter in this model. Accordingly, all results are prone to change if the length of the life cycle is modified. It is also essential to recognize that determining the optimal refurbishment cost in itself does not guarantee the desired energy quality. After fixing the total LC cost, the refurbishment still must be optimized by an available building optimization tool, such as the ENERGOPT expert system.

The research plan for the future follows four paths. First, all ignored databases and modules should be included in the framework for increasing the accuracy of the model. Second, more information must be gathered by the operation of the system by optimizing a large set of buildings. Third, in addition to the building envelope, the optimization process should also integrate the improvement of the HVAC system. Finally, the localization of the system in other countries with different regulation systems is an exciting option for the future.

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