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An approach for holistic energy retrofitting based on assessment of economic viability and durability of energy saving measures

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SUMMARY
The majority of renovation projects are driven by the possibility of reducing energy consumption of buildings. This, however, might result in retrofitting projects that neglects the longevity of the building. Furthermore, many evaluation techniques only consider the profitability of the energy saving measures and forget to consider, whether it is more prudent to demolished the building and erect a new building.

An evaluation approach is presented to assess whether to retrofit an existing building or to demolish and replace it. The primary concept of the method is to develop a retrofitting proposal with a profitably combination of energy saving measures. The cost of the combination of energy saving measures is evaluated against the cost of demolishing the existing building and erecting a new building including consideration of maintenance costs and operational costs. The energy price is used as constraint to determine the amount of building retrofitting for implementation. The approach includes also durability assessments of the energy saving measures.

An example is carried out to illustrate the application of the approach. The example highlights the importance of including risk assessment and durability evaluation of the energy saving measures when performing holistic energy retrofitting of buildings.

1. Introduction

In recent years, major focus is addressed to building renovation given that new buildings add at most 1% a year to the existing building stock. The stimulus for carry out building renovation is reducing the energy consumption of buildings. In Denmark the government has adopted a long-term policy, implying that Denmark should be independent of fossil fuels by 2050, and by 2035 energy supply to buildings should be from renewable energy sources (Danish Government, 2011). To meet this objective, it is of significance to improve the energy efficiency of the existing building stock, but also to invest in and convert the supply network to renewable energy sources. Ideally, a balance must be found between the costs for improving energy efficiency of the existing building stock and the costs of buying energy from heating and power plants based on renewable energy sources.

Several approaches exist for optimisation of building renovation, where the commonly used economic techniques are simple payback time and net present value (NPV) (Verbeeck and Hens, 2005; Tommerup and Svendsen, 2006). Both techniques, as well as their limitations, are described by Martinaitis et al. (2004). A method derived from NPV is cost of conserved energy (CCE), which gives the cost to save 1 kWh of energy and is directly comparable to the cost of supplied energy. This makes the CCE technique more transparent and practicable for understanding the profitability of the measures as compared to the monetary result obtained using e.g. the NPV method. The CCE method was applied in building renovation by Martinaitis et al. (2004; 2007) and for design of new buildings by (Petersen and Svendsen, 2012). In common, the methods focus on energy consumption and not the durability of the energy saving measures (ESMs). The stimulus for saving energy neglects the fact that the longevity of the building could be challenged due to changed hygro-thermal conditions. Therefore, it is important to include both an assessment of the whole building as well as ESMs in the retrofitting approach.

The presented approach determines the viability of various ESMs including an assessment whether to renovate the existing building or to replace it with a new building. Furthermore, the approach evaluates the durability of the ESMs. The first part of the method is adapted to building retrofitting from the method presented by Petersen and Svendsen (2012), and the energy price is used as constraint to determine the amount of building retrofitting for implementation. The durability of the measures is evaluated based on hygro-thermal measurements and experiences in a test apartment of a multi-family building.

2. Approach for holistic energy retrofitting

The approach for holistic energy retrofitting is shown in Figure 1, which consider both the profitability of the retrofitting project and the durability of the ESMs. First step was to determine the needed retrofitting and whether the retrofitting should be executed or the building should be demolished and rebuild. Second step was to investigate the ESMs regarding their durability.

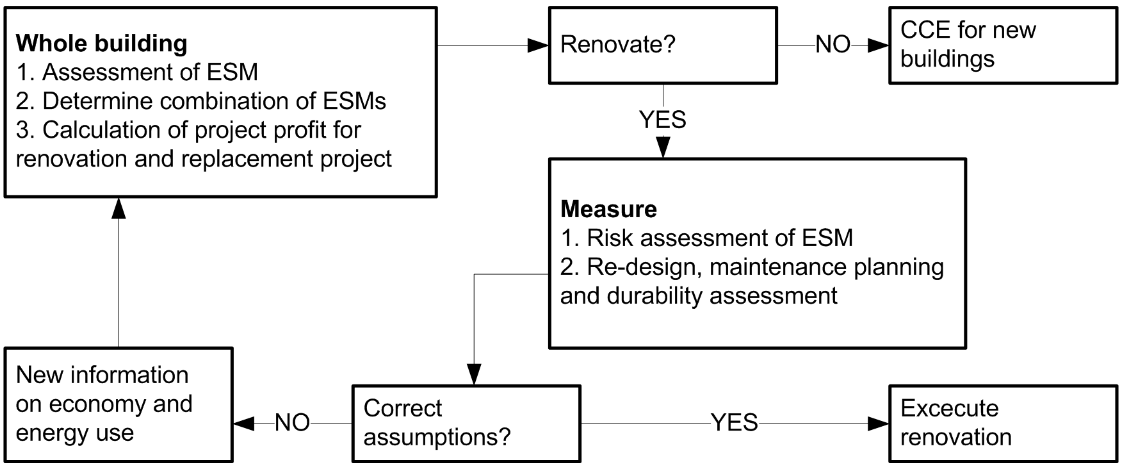

FIG. 1. Holistic energy retrofitting from whole building to energy saving measure (ESM)

2.1 Whole building

The profitability of the whole building retrofitting is based on the cost of conserved energy (CCE) concept described by Morelli et al. (2014) and in the following bullets 1-3. This concept allows for a decision-making on whether to invest in ESMs or buying energy, as the CCE results are directly comparable with the energy price.

1. Assessment of ESM and determining the inter-relationship between the CCE_R (€/kWh), which is the marginal CCE for the different measures. From Eq. (1) the energy use can be expressed as a function of the CCE_R which enable a direct comparison of the ESMs.

$$CCE_R = \frac{t \cdot a(n_r, d) \cdot I_{measure} + \Delta M_{year} + \Delta E_{operation,\,year} \cdot P_{energy\ type}}{\Delta E_{year}} \quad (1)$$

where, t is a reference period that enables a comparison of measures with different service life and is defined as the ratio between the reference period, n_r (years), and the useful lifetime, n_u (years); $a(n_r, d)$ is the capital recovery rate, for which d is the real interest rate (absolute number); $I_{measure}$ is the marginal investment cost (€), where $a(n_r, d)$ I is the marginal* *annualised investment cost(€); ΔM_{year} is the change in annual maintenance cost (€); $\Delta E_{operation,year}$ is the annual change in energy consumption during operation of the measure (kWh); $P_{energy\ type}$ is the energy price for the energy type used for operational energy (€/kWh); ΔE_{year} is the annual change in annual energy conserved by the measure (kWh).*

This, however, is easily applicable for continuous ESMs e.g. insulation materials, but not for discrete measures e.g. windows and ventilation. Therefore, a five step algorithm was formulated to rank the discrete ESMs (Morelli et al., 2014).

A. A first reference is determined among a number of components based on their investment cost and annual energy use. The components are ranked according to investment cost, and the component with lowest cost is chosen as reference. If the investment cost is identical for two or more components, the component with lowest energy use should be chosen as reference, and the other components should be omitted due to the higher energy use. For existing components the investment cost will be the refurbishment cost, thus the component performs as when it was newly installed.
B. The marginal CCE_R for each component is calculated applying Eq. (1) using the reference component determined in step A. Components with negative values of CCE_R are omitted because they use more energy combined with a higher investment than the reference component determined in step A.
C. A new reference is determined based on the marginal CCE_R derived in step B. The component with the smallest positive marginal CCE_R is chosen as a new reference to form a curve. From the remaining components, those with an energy use equal or higher than the new reference are omitted as they are not ESMs compared to the new reference
D. The marginal CCE_R for each component is calculated applying Eq. (1) using the reference component determined in step C and its respective investment cost and energy savings. Step C and D are repeated until there are no more components to consider.
E. The reference component found in step A and those determined in step C are listed in the order they are determined. These discrete components are thereby transformed in to a continuous CCE_R function by calculating the marginal CCE_R according to Eq. (1).

2. The method suggest that the determination of a combination of ESMs is defined as the energy weighted average marginal CCE_R of the measures ($CCE_{R,average}$ [€/kWh]) equal to the energy price, Eq. (2). First the discrete measures must be chosen as close to the energy price as possible, and thereafter adjusting the $CCE_{R,average}$ by choosing the continuous measures, thus the $CCE_{R,average}$ equals the energy price.

$$CCE_{R,average} = \frac{\Delta E_1 \cdot CCE_{R,1} + \Delta E_2 \cdot CCE_{R,2} + \ldots + \Delta E_n \cdot CCE_{R,n}}{\sum_1^n \Delta E_i} \leq P_{energy\ \ type} \qquad (2)$$

where, E_n is the energy consumption for the ESM n (kWh); $CCE_{R,n}$ is the cost of conserved energy for the ESM n (€/kWh);and, $\sum_1^n \Delta E_i$ is the sum of the individual energy consumptions of all ESMs (kWh).

3. Calculation of the economic project profit considering whether to renovate the building or replace it with a new building. The profit of any given project is determined on the basis of the market value (MV) for the retrofitted building, or a newly erected building, minus the investment cost (I),which can also including the transaction costs, and the discounted (1/capital recovery rate) maintenance and operational (M&O) costs, as given in Eq. (3). If a new building is erected at the exact same location as the existing building, the cost for demolishing (D) the existing building must also be included. The building project that should be undertaken in economic terms will be the one having the highest profit.

$$Profit = MV - \left(I + D + \frac{M\&O}{a(n_r, d)} \right) \tag{3}$$

2.2 Measures

Two types of ESMs were investigated, i.e. 1) two types of interior insulation and 2) four different measures to improve the windows. These measures were investigated in full scale in the test apartment.

The risk of failures was identified for an interior insulated masonry-wooden beam assembly applying Failure Mode and Effect Analysis (FMEA) (Stamatis, 2003). The critical points, found in the FMEA, were investigated by full scale measurements of temperature and relative humidity behind the interior insulation and in the wooden beam embedded in the masonry.

The four window measures were installed in the test apartment and their energy performance was calculated based on the energy balance (Morelli et al., 2012).

3. Multi-family building – a case study

A typical building in Copenhagen, Denmark, dated from the period 1850-1930 was used as case. The building with 30 apartments had six storeys with a floor to floor height of 2.6 m and a gross floor area at each storey of 453 m^2. The solid masonry facades were deemed worthy of preservation and the windows constituted 27% of the overall façade area. The windows were with a single pane; however, the windows on the street façade had a secondary glazing installed. The un-insulated floor divisions were constructed with wooden beams and clay pugging. The building was natural ventilated by opening windows, infiltration and ventilation ducts located in the kitchens and bathrooms. Furthermore, the building employed central heating produced from district heating. A detailed description of the building is given in (Morelli et al., 2012) where the pre-renovation energy consumption for the building was determined to approx. 160 kWh/(m^2 year).

3.1 Description of energy saving measures

Two interior insulation materials were tested. i) A combination of aerogel and stone wool fibres with a gypsum board mounted on the surface, hereafter referred to as MiWo-Aero, which has a thermal conductivity of 0.019 W/(m2 K). ii) Vacuum insulation panel (VIP) having a thermal conductivity of 0.005 W/(m^2 K) for a thickness of 20 mm under 1 mbar pressure. The four window measures are briefly described in Table 1 where the numbers of panes refer to the total amount of panes in the window (Morelli et al., 2012).

TABLE 1. Energy data for window measures

#	Window type and retrofit measure	U_W [W/(m^2K)]	g_w [-]	E_{ref} [kWh/(m^2 year)]
	Ref. with 1 layer normal pane	4.05	0.51	-266
	Ref. with secondary pane (2 panes)	2.20	0.45	-109
1	Refit with secondary pane (3 panes)	1.09	0.38	-24
2	Refit with secondary pane (2 panes)	1.62	0.44	-59
3	Refit with sash on casement (2 panes)	1.76	0.44	-72
4	New with coupled frames (3 panes)	0.96	0.33	-21

3.2 Whole building assessment

For the economical assessment of the whole building retrofitting, a reference period of 30 years was considered, which corresponds to a typical loan period for building investments but also the approximated service life of many building components. The real interest rate was set to 2.5% and expresses the amount that the nominal interest rate is larger than the rate of inflation. The energy price in 2040 for heat based on renewable energy sources was determined to 0.15 €/kWh by Morelli et al. (2014), whereas todays energy price was 0.09 €/kWh. The graphs in Figure 2 for interior insulation and window measures are based on Eq. (1). Similar figures were developed for each ESM. Applying Eq. (2) and choosing discrete ESMs before continuous ESMs the amount of ESMs in Table 2 were obtained, which correspond to an energy consumption for the building of about 45-50 kWh/(m^2 year) depending on the energy price (Morelli et al., 2014). The measures implemented were: demand controlled ventilation, new windows, insulation towards basement and attic as well insulation on the inside and outside of the walls.

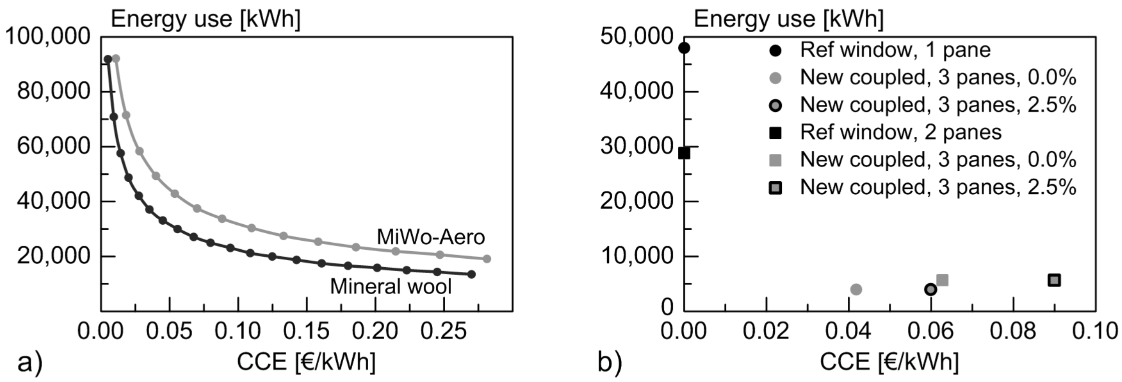

FIG 2. Energy use as a function of CCE_R for a) 2 types of interior insulation and b) windows with single pane and single pane with secondary pane (Morelli et al., 2014)

TABLE 2. Amount of energy saving measures in relation to energy price and interest rate of 2.5%

Energy price	0.09 €/kWh		0.15 €/kWh	
Measure #	CCE [€/kWh]	Type [-]	CCE [€/kWh]	Type [-]
Mechanical ventilation	0.22	Central DCV	0.22	Central DCV
Windows – yard	0.06	New 3 panes	0.06	New 3 panes
Windows – street	0.09	New 3 panes	0.09	New 3 panes
Floor to basement	0.06	50 mm	0.14	105 mm
Floor to attic	0.06	260 mm	0.14	435 mm
Wall- interior insul.	0.06	80 mm	0.14	140 mm
End wall – exterior insul.	0.06	50 mm	0.14	90 mm

The evaluation of whether to renovate the building or build a new, according to Eq. (3), was based on presumptions of market values, renovation cost of the building and theoretically energy consumption (Morelli et al., 2014).

In connection with the building renovation new bathrooms and kitchens would be installed, which was included in the investment cost of the renovation given in Table 3. The retrofitted building was compared to a new building fulfilling the Danish Building Regulations in 2015 corresponding to a total energy consumption of approx. 30 kWh/(m^2 year).

TABLE 3. Economic evaluation of retrofitted and new building

Energy price	0.09 €/kWh		0.15 €/kWh	
	Refit [€/m^2]	New [€/m^2]	Refit [€/m^2]	New [€/m^2]
Market value	3100	4000	3100	4000

Expenses:				
Investment	695	2200	745	2200
Demolish		90		90
Heat	11	6	18	11
Electricity	3	3	3	3
Profit ±	**2391**	**1701**	**2334**	**1696**

3.3 Experiences with interior insulation from a test apartment

The FMEA conducted on the interior insulated masonry and wooden beam assembly focused on the three main structural parts; masonry, wooden beam, and insulation including vapour barrier. The results were as given below in prioritised order (Morelli & Svendsen, 2013).

1. Collapse of the wooden beam due to moisture penetration into the structure.
2. Loss of adherence between the brick and mortar.
3. Mould growth behind the interior insulation.

The first and last failures were investigated by measurements of temperature and relative humidity in the beam and behind the insulation. Figure 3 shows the results for insulation installed to a northeast facing wall and placed between the ground and first floor. After dismantling the MiWo-Aero product on first floor no visible signs of mould growth were present, which was documented through Mycrometer surface tests (measurements on bio-mass from a swap).

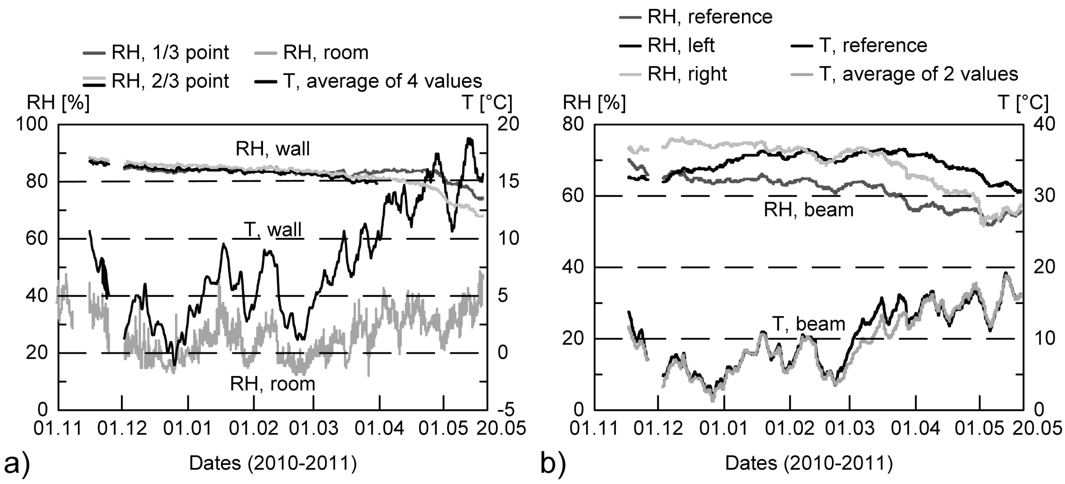

FIG 3. Temperature and relative humidity a) behind inside insulation and indoor relative humidity; and b) in the wooden beam and temperature in the exterior climate (Morelli et al., 2012)

The MiWo-Aero product was reasonably easy to work with, but the product could not take up any deviations on the surface of the wall. Consequently, the preparation of the wall ensuring a relatively smooth surface was very important, thus the applied insulation likewise provided an even, flat surface. However, the mineral fibers in the MiWo-Aero product did not have enough adhesion to keep the gypsum board fixed to the surface of the insulation resulting in a gap between insulation and gypsum board. In comparison to the MiWo-Aero product, the VIP product was a challenge to work with. Specifically, the VIP product needed to be ordered in specific sizes, given that no on site changes could be made, if incorrect sizes were delivered. Furthermore, the VIP product needed special care as the VIP panels were easily punctured; thereby increasing their thermal transmittance from 0.005 W/(m^2 K) to 0.019 W/(m^2 K).

4. Discussion

The economical assessment can be used by decision-makers to determine whether to renovate their building or demolish it and thereafter erect a new building. The approach can be applied at different stages of projects, and for a comparison of different ESMs. The method is easily adjustable to different energy prices, what on the one hand is an advantage of the method, because the energy price is difficult to forecast. On the other hand, this implies that care must be taken using the method, because the energy price strongly influences the optimised combination of ESMs. However, the study showed that doubling the energy price did not change the buildings energy usage significant. This could indicate that an upper limit for implementing ESMs is reached regarding insulation measures. Nevertheless, other measures might further reduce the building's energy consumption, e.g. technical installations excluding mechanical ventilation, as technical installations were not considered in this study. A reduction of approx. 70% in energy consumption is achieved after retrofitting, which is close to the expected requirement for nearly zero energy buildings.

The economical assessment, in the twofold holistic energy retrofitting approach, relies on two main assumptions, i.e. maintenance cost and operational costs. A verification of these assumptions is needed for the holistic energy retrofitting method before making the final decision whether to retrofit or replace the building. Installing interior insulation on solid masonry walls with embedded wooden beams, the wooden structure becomes critical parts, due to the outer wall's changed moisture balance. This could cause premature deterioration of the beam. However, the measurements are about 5-10% RH higher as compared to the reference measurement. A RH below 75% does not pose a risk for the durability of the beam end. These measurements were performed in a northeast facing wall that received, given its orientation and location on the building (between ground and first floor), a limited amount of wind driven rain and direct exposure to sunlight. Based on Isopleths information provided in (Sedlbauer, 2002) a risk for mould growth could be present when interpreting the measurements. The temperature is around 10 °C and the RH is 85%; in such instances under these conditions the germination time is about 2 days. However, there were no visible signs of mould growth on the wall after dismantling the MiWo-Aero product. In case, the measurements indicated risk for wood rot or mould growth, new retrofit measure should have been suggested, installation of monitoring devices or planning maintenance including economically considerations. These new assumptions should then be included in a second round of calculation according to Figure 1 determining an optimised retrofitting.

The two critical points related to mould growth and wood rot reveal, in this study, no expected increase in maintenance or operational cost for the ESM. However, the durability of the MiWo-Aero product itself did not show the expected service life, as the gypsum board and insulation material could not stay fixed. This would increase the maintenance cost, if this insulation material was to be used. Relying on the VIP product a significant cost for planning had to be included, thus the needed sizes of VIP panels are ordered and installed in the building. In worst case, this could lead to many poor assemblies and together with a potential increased thermal transmittance by punctured VIP panels this would result in overestimations of the energy savings or increases in operational cost.

Through these two simple examples of insulation materials the significant of the durability is shown when approaching a holistic energy retrofitting in an early project stage. Especially, when considering new materials such as the MiWo-Aero and VIP products. In instances, where either the MiWo-Aero or VIP products are the only materials considered as interior insulation, one could have entailed a significant increase in cost for maintenance, operation or even installation. A more difficult parameter to appraise is the loss of living space due to installed interior insulation, which also should be accounted for in the holistic energy retrofitting approach.

5. Conclusion

An approach for holistic energy retrofitting is developed that consider both the economical profitability of the energy saving measures (ESMs), whether to retrofit the building or demolish it and build a new building, and the durability of the ESMs. The economic assessment integrates methods of component-based optimisation and evaluation of the project economy for building renovation measures. A trade-off between investing in ESMs and buying energy is established entirely on the predicted future renewable energy price. The method uses the marginal cost of conserved energy (CCE) to identify an optimised combination of ESMs having the energy weighted average marginal CCE_R equal to the energy price. The profit of the project is determined as the market value deducting the cost for renovation/new building (including demolishing), maintenance and operation. The building with highest profit must be chosen. In cases where replacement of buildings is not an option because of preservation value on facades, not heritage buildings, the method can be used to evaluate, whether it is reasonably to preserve these buildings. Furthermore, the holistic method includes and risk assessment and durability evaluation of the ESMs, thus the energy savings are not the only stimulus for executing the building renovation.

The holistic energy retrofitting approach for building renovation developed is highly relevant to and useful for the many future retrofitting projects.

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