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Methodology for Evaluation and Development of Refurbishment Scenarios for Multi-Story Apartment Buildings, Applied to Two Buildings in Denmark and Switzerland.

Yovko Ivanov Antonov [1,*], Per Heiselberg [1], Flourentzos Flourentzou [2] and Michal Zbigniew Pomianowski [1]

[1] Department of the Built Environment, Aalborg University, 9220 Aalborg Ø, Denmark; pkh@build.aau.dk (P.H.); mzp@build.aau.dk (M.Z.P.)
[2] ESTIA SA, 1015 Lausanne, Switzerland; flourentzou@estia.ch
* Correspondence: yia@build.aau.dk

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Abstract: Renovation of existing buildings is an indispensable part of achieving European efficiency and environmental targets. This paper applies different assessment methodologies to find optimal renovation, given different evaluation criteria. The performed literature study identifies the cost-optimal methodology employing Life Cycle Cost (LCC) calculation as one of the most common assessment methods. This paper proposes a new renovation assessment method targeted to the early design phases of specific building projects. The method has a simple structure, and can be used as a roadmap of necessary activities for obtaining solid building knowledge and required energy and cost calculations. The methodology is based on linking economic and energy efficiency parameters into defined cost-effective value, calculated for all investigated renovation actions. The cost-effectiveness value is used for ranking and selecting the most appropriate single renovation actions to form renovation packages, which can be further examined in detail (for example, with LCC). To demonstrate the method, evaluate the strengths, and identify the weaknesses, it is applied to case study buildings in Denmark and Switzerland. The results show that, in the initial stage, the proposed cost-effectiveness representation can be used successfully to compare and evaluate different envelope elements and systems. Cost-effectiveness also provides rational results on a package level. Further work is still required in the area of evaluation of energy supply and renewable energy production systems.

Keywords: renovation methodology; cost-effective; cost-optimal; residential renovation; energy efficiency

1. Introduction

Buildings have been identified as one of the main contributors to energy use and CO_2 emissions [1]; therefore, policies in the European Union (EU) have been driving towards high efficiency standards for both new and renovated buildings [2–4]. As a result, Member States have tightened national energy efficiency requirements for performance of buildings and building elements, and nowadays new buildings use much less energy than existing buildings [5]. Considering that the demolition and construction of new buildings account for less than 2% of the building stock and that 90% of the buildings in the EU are older than 30 years [5], renovation is vital to achieving environmental and energy efficiency targets in the EU.

Since the implementation of Directive 2018/844 [6], Member States are also demanded to develop and regularly update long-term renovation strategies expediting cost-efficient transformation of existing buildings to nearly Zero Energy Buildings (NZEB). The main characteristics of an NZEB are high-energy efficiency and healthy indoor environment. To meet those requirements, transformation of existing buildings to NZEB demands integration of active renewable energy systems and passive design solutions. Evaluation of those typically requires dynamic calculation methods, which can be complex and costly.

A method for calculation of cost-optimal renovations on a national level has been established by the EU Directive 2012/244 [7]. Even though the EU methodology concerns cost-optimal calculation for minimum energy performance on a national level, it has been successfully adopted to assess single [8] and multiple buildings [9]. The methodology consists of assessment of packages/scenarios based on Life Cycle Cost (LCC), where achieved energy savings and their respective LCC are the criteria used to find a cost-optimal scenario.

The existing EU cost-optimal methodology is on a package level, which means that selection of what a renovation package consists of is arbitrary to the designer. While required by the cost-optimal EU method, LCC calculations for renovation of buildings require uncertain forecasted parameters as lifetime of elements and products, energy price development, and inflation rate. Challenges and shortcomings of the methodology are presented in [10,11], while examples of its application in three EU countries are shown in [12]. Despite the uncertainties, LCC calculations are well established for evaluation of building renovation as they have been part of the EU Commission directives since 2010 [2], and remain unchanged in 2019 [4].

Other renovation methodologies have also integrated criteria types beyond energy saving and economy to solve renovation optimization problems. In [13], the authors also considered comfort, building lifespan, and environmental impact. In [14,15], the authors integrated risk assessment parameters, whereas the methodology presented in [15] integrates architectural value, technical, and social evaluation criteria, besides energy savings and economy. Environmental and social criteria are used in [16]. As expressed by the referenced literature above, multi-criteria methodologies are useful for evaluation of renovation packages (compilation of single actions) as they typically affect multiple aspects of the building (energy use, occupant comfort, operation and maintenance cost, property value, etc.). However, the increased complexity requires time and expertise, and it is applied only for specific client needs or research purposes. In practice, the decision of "what to renovate?" is often based on the available budget and specific project characteristics. For specific building projects, there is a need for evaluation of applicable renovation alternatives on a component level. This would support the selection of the most effective actions to comprise a renovation package with respect to the available budget [17].

In some projects, multiple renovation solutions per building element are applicable, while, in others, only certain elements can be renovated due to building specific reasons (limited space for insulation, preservation of architectural elements, etc.). In principle, multi-criteria methods can be applied to single renovation actions in order to select which actions should be included in a package. However, such approach can be too complex and workload heavy for evaluating each renovation action separately. There is a need for a reliable, yet simplified method to evaluate the possible renovation variations for a building part and compare it against other building parts considered for renovation.

Few authors perform a comparison of the contribution of each separate part for a given criterion [13,18–20]. The authors of [13] evaluated two envelope and three system renovation measures by selected qualitative and quantitative sustainable criteria. Detailed energy models in combination with LCC calculations are done in [18,19], while the authors of [20] compared single actions based on energy savings, CO_2 reduction, and simple payback period. In [17], allocation of the budget is evaluated based on achieved energy savings of each envelope element. Where available, investigation of multiple alternatives for renovation of the same building part are performed in terms of variations in insulation thickness, U-values of windows or different system types [9,19]. The applied methods vary in number and type of evaluation criteria, as well as scope of applied energy calculation models and considered cost levels. This makes it difficult to deduct a common specific methodology for evaluation of single renovation measures.

The objective of this paper is to present a new renovation assessment methodology for evaluation of separate, single renovation actions based on project specific criteria. The method provides an overview of applicable renovation alternatives for different building parts and their combination into optimal renovation scenarios for specific projects. The scope of the method covers the early design stages from initial start-up until the detail design of renovation packages, targeting multi-family dwellings. The approach can be considered as a pre-step to cost-optimal (LCC) and multi-criteria methods for assessment of renovation on package level. Therefore, an aim for the methodology is for it to be simplified in a way that designers can apply it using building information with which they are already familiar. Thus, the method is limited to energy saving and economic evaluation criteria. While simplified, the proposed process allows for gathering of essential building data and accounts for lifespan, cost, and energy savings of each element.

This paper presents a literature review of renovation assessment methodologies, classified by targeted building type, number and type of evaluation criteria, and how renovation packages are composed. Following the literature study, the proposed methodology is described in a seven-step approach and applied to two multi-story apartment buildings situated in Denmark and Switzerland (consisting of 66 and 15 apartments, respectively). The paper finishes with a discussion of the strengths and weaknesses of the methodology and concludes on applicability and further development.

2. Materials and Methods

The proposed methodology is based on a literature review presented in Section 2.1. The developed methodology is presented in Section 2.2. To demonstrate the method and identify strengths and weaknesses, it is applied to two existing buildings in need of renovation.

2.1. State of the Art of Renovation Assessment Methodologies

The following review of academic papers is done in order to gain insight into different ways of assessing and selecting renovation alternatives. The review aim is to identify both common and unique evaluation criteria comprising the different methodologies. Moreover, the review serves as a possibility to identify gaps within assessment methodologies for residential buildings presented in literature. While the main target for the review is multi-family dwellings, other building types are not ultimately excluded in order to achieve higher comprehensiveness and understanding of current assessment methodologies. The review focuses on characterization of the methods according to the following main areas:

- Stage of the renovation that the methodology supports. Distinguishing between pre- and post-renovation stage. Pre-renovation considers all activities until the physical site implementation of the renovation, whereas post-renovation considers activities after implementation of the renovations of the building.
- The scope of the building stock that the methodology concerns. Identified if the method is applied to a single building, multiple buildings, or large building stock—district wide or on a national level.
- The building type for which the methodology is developed or applicable. Distinguishing among dwellings (single-family and multi-family, respectively, identified as SF and MF in Table 1), office, and public buildings.
- The type of criteria that the methodology integrates. For the purpose of the classification presented in this paper, the evaluation criteria applied in the reviewed articles are classified according to the sustainability areas, social, economic, and environment. Evaluation criteria, used in the methods, are further divided into sub-criteria for each main area. The reviewed methodologies often employ a different number of parameters and to different depth within the sustainability areas; therefore, the following general sub-classification within each area is made:
    a) Social (SOC)

    - i. Indoor comfort (IC). Methodologies dealing with evaluation of one or more parameters related to indoor comfort i.e., thermal, atmospheric, visual, or acoustic comfort.
    - ii. Occupant behavior (OB). Methodologies investigating effect of occupant behavior on renovation results or such where occupants are part of the methodology directly as part of the process, or indirectly as part of education on efficiency of building operation.
    - iii. Additional renovation effects (ARE). This is a broad subcategory comprised of methodologies integrating criteria such as architectural preservation and quality, qualitative co-benefits, home quality parameters, renovation duration, etc.
  - b) Economic (ECO)
    - i. Life Cycle Cost (LCC). Methodologies integrating LCC calculations, not strictly following the EU cost-optimal method. Furthermore, methodologies investigating building renovation by net present value (NPV) measure are also considered within this classification but shown independently.
    - ii. Cost-optimal (CO). Methodologies strictly following the EU cost-optimal method.
    - iii. Simple payback (SP). Methodologies integrating basic payback calculations.
    - iv. Investment cost (INV). Methodologies considering only investment cost.
  - c) Environmental (ENV)
    - i. Life Cycle Analysis (LCA)
    - ii. Reduction of carbon dioxide (CO_2)
    - iii. Primary energy (PE)
- Composition of renovation scenarios. How the methods deal with selection of renovation actions included in a renovation package. Here, three subgroups are identified: on single component level, single and package level, or complete renovation package (scenario) only.

Table 1 shows an overview of all reviewed papers and their classification according to the categories described above. As evident in Table 1, all reviewed methodologies support the pre-renovation phase of building renovation by assessing the renovation based on multiple evaluation criteria. Three of the reviewed publications also provide activities in the post-renovation stage [14,21,22]. The most represented building type is dwellings, where most of the methodologies are developed and/or applied to a single building. The investigated building is either case specific or identified as representative for certain share of the building stock.

A large share of the reviewed methods integrates multiple criteria in order to find an optimal renovation package. Authors have successfully applied the EU methodology of cost-optimality for different building types [8,23–25]. Moreover, authors have also expanded the cost-optimal EU method by combining additional criteria as LCA [26,27], CO_2 reduction [28–30], thermal comfort [31], and various co-benefits [30]. This indicates that the methodology is quite flexible and robust.

Optimal renovation scenarios have also been determined by multi-criteria methodologies not following the EU cost-optimal approach. Such methodologies focus on two or more criteria for evaluation of renovations. For example, Terez et al. [18] focused on a single energy and economic criteria, [32] employs energy and the effect of occupant behavior for decision support, while the authors of [33] focused mainly on economic and social criteria.

In nearly all cases, reduction of energy demand and economic criteria are considered at one or another detail level. In addition to energy and economic related criteria, authors have integrated environmental criteria [13], comfort criteria [31], home quality improvements [34], and CO_2 reduction [17,20]. Selection of renovations have also been done via evaluation of multi-criteria in steps, where the optimum is reached by exclusion, given certain constraints at each step [16]. In [15], the authors described a detailed methodology integrating selection and weighting of solutions by different stakeholders in the renovation case where architectural preservation is of high importance. In this case, the selection is based on different risk groups and technical, architectural, economic, and social criteria.

Table 1. Classification of applied renovation methodologies in accordance to evaluated criteria.

Ref.	Phase	Building Scale	Building Type	Evaluation Criteria			Renovation Level
				SOC	ECO	ENV	
[8]	Pre	Single	MF		CO, NPV	PE	Single spec. and Package
[9]	Pre	Multiple	MF		CO	PE	Single spec. and Package
[13]	Pre	Single	MF	IC, ARE	PB, NPV	CO_2, PE	Single spec. and Package
[14]	Pre / Post			-	-	-	
[15]	Pre	Single	MF	IC, ARE	PB, INV	CO_2	Single spec. and Package
[16]	Pre	Single	MF	OB.	LCC	CO_2	Single and Package
[17]	Pre	Single L. stock	MF		LCC	CO_2	Single spec.and Package
[18]	Pre	Single	MF		PB, NPV	PE	Single spec. and Package
[19]	Pre	Single L. stock	MF		CO	PE	Single spec. and Package
[20]	Pre		Public		PB	CO_2, PE	Single spec. and Package
[21]	Pre / Post		Public		PB, NPV	CO_2, PE	Single and Package
[22]	Pre / Post	Single	MF	IC			-
[23]	Pre	Multiple L. stock	SF, MF, Office, Public		CO	PE	Package
[24]	Pre	L. stock	Public		CO	PE	Single and Package
[25]	Pre	Multiple L. stock	SF, MF		CO	PE	Single and Package
[26]	Pre	Single	Office		LCC	LCA, CO_2, PE	Package
[27]	Pre		MF		LCC	LCA	Single and Package
[28]	Pre	L. stock	MF		CO	CO_2, PE	Package
[29]	Pre	Multiple	MF		CO	CO_2, PE	Single and Package
[30]	Pre	Multiple	MF, Public		CO	CO_2, PE	Single and Package
[31]	Pre	Single	MF	IC	CO	PE	Single spec. and Package
[32]	Pre	Single	MF	OB	NPV		Package
[33]	Pre	Single	MF	IC	INV	PE	Single spec. and Package
[34]	Pre	Single L. stock	MF	IC, ARE	LCC	CO_2	Single and Package
[35]	Pre	Single	SF		LCC		Package
[36]	Pre	Single	Office			PE	Single and Package
[37]	Pre	Single	MF		LCC		Single and Package
[38]	Pre	Single L. stock	MF		CO	PE	Single and Package
[39]	Pre		SF		LCC		Single and Package
[40]	Pre	Multiple	MF		PB, NPV	PE	Single spec. and Package
[41]	Pre	L. stock	MF		CO	PE	Single spec. and Package
[42]	Pre	Multiple	MF, Public	IC, ARE	CO	PE	Package

Building type: Single-Family (SF); Multi-Family (MF).

Criteria: Social (SOC)—Indoor climate (IC); Occupant behavior (OB); Additional renovation effects (ARE); Economic (ECO)—Cost-optimal following EU method (CO); LCC not strictly following EU cost-optimal method (LCC); Simple payback (SP); Investment cost (INV); Environmental (ENV)—Life Cycle Analysis (LCA); Reduction of CO_2 (CO_2); Primary Energy(PE).

The last column of Table 1 classifies the renovation level of the reviewed methodologies. None of the presented methodologies deals with evaluation and selection of single renovation actions exclusively. Most of the methods evaluate both single and package solutions, by initially segmenting single actions and combining those one after another in the respective analysis. Even though those methods deal with the individual contributions of separate elements, they do not seem to adopt and use the results directly to create renovation packages. Methodologies accounting and analyzing contribution of single actions specifically are identified and presented as “Single spec. and Package” in Table 1. The most common assessment method is the global cost method, following the EU framework [8,9,19,31,41]. The NPV measure and simple payback are also widely used for evaluation of individual renovation improvements (NPV [8,18,40,41] and payback [18,20,40,41]). The least common parameters for evaluation of single actions are the investment cost [17,33] and CO_2 reduction [17,20].

As evident in Table 1, there are many different methodologies for assessing renovation, most of which integrate a multi-criteria approach for finding an optimal solution. A majority of the presented methodologies are generalized for large building stock, even when demonstrated on single buildings. This generalization results in an investigation of generic renovation solutions, without considering the specifics of the building. This creates a risk that the investigated renovation solution might not be applicable or would cost much more than anticipated when it comes to a specific building.

As stated above, the majority of methodologies are based on finding optimal solution, using LCC calculations. Life cycle cost calculations are necessary to obtain a solution, which leads to energy performance level with the lowest cost during the lifecycle of the building. However, in practice, renovation solutions are selected through an iterative process between designer and client, more often considering short- rather than long-term perspectives. For example, decisions are based on parameters as the available renovation budget, project target, timeline, national and local regulations, distinct building characteristics, etc. Therefore, the proposed methodology aims to support the evaluation and selection process of renovation alternatives for building parts by providing a structured overview of the necessary steps for specific building cases and criteria. Moreover, it attempts to fill in the gap in current methods for selection of renovation measures to comprise a renovation package. In order for transparent and clear cost calculations, the methodology proposes an action ranking based on implementation cost for the owner and resulting energy savings.

2.2. Methodology Development

The methodology proposed in this paper consists of a seven-step approach, as shown in Figure 1.

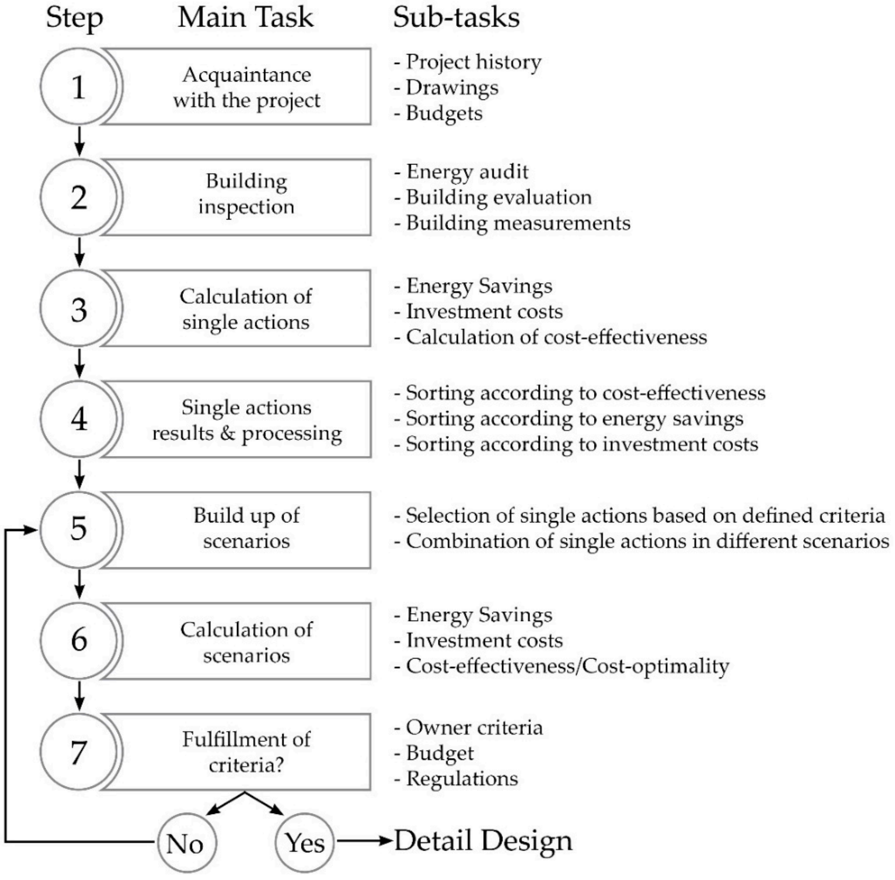


Figure 1. Methodology steps and main activities associated with each step.

Each step represents a stage within the early design processes from the start of the project (introduction of the designer) until determination of viable renovation packages for the building and initiation of the detail design. The main task and subtasks in each step are outlined in Figure 1 and further explained below.

- Step 1. The first step is for the designer to familiarize him- or herself with the project. In some cases, actions/decisions have been made prior to the designers' involvement. Then, one should become well informed of the project' history. In addition, this is the time to study and review existing drawings, time plans, budgets, regulations, architectural or technical restrictions, etc.
- Step 2. This step is attributed to the building inspection, where a physical evaluation of the building and its parts (elements and systems) is performed. At the same time of the physical inspection, an energy audit can be performed (or at least initiated). Available energy data can be acquired from meters or access to such can be granted from the property manager. The building visit should also be used to determine the adequacy of available drawings. In the case of large inadequacies between reality and drawings, it is possible to perform on-site measurements for more accurate representation of the buildings element and/or system. This is also the step to initiate monitoring of indoor climate prior to renovation (if necessary).
- Step 3. Given the information obtained in the previous two steps, a reference building energy model is created. In many cases, the reference model is calibrated with actual (meter) data, if they are available and there are time/resources for it. Theoretical models can also be calibrated via reviewing energy bills for the building. Further, the designer determines possible renovation alternatives for each element and system, and acquires their implementation cost. To be able to compare separate renovation alternatives for the same element/system and different elements/systems between each other, it is proposed to perform energy calculation for each separate improvement with a one at a time approach. The outcome of Step 3 is a list with all applicable renovation actions for all building parts of interest, their implementation cost and the energy saved by each individual action.
- Step 4. In this step, obtained data for the different renovation actions can be sorted with respect to implementation cost or the theoretical energy saving potential. Both approaches can be beneficial depending on the target of the project. Actions can also be sorted according to a calculated value linking both cost and energy, termed "cost-effectiveness" in this methodology and explained below.
- Step 5. Single actions are selected and combined into renovation packages. The sequence and number of single actions within a package are determined by project criteria. These criteria could be: (a) obtain maximum energy savings for a given maximum implementation cost; (b) update all building envelope elements to current regulations with minimal cost; and (c) reduce energy demand of the building to a certain threshold for minimal investment, etc.
- Step 6. As theoretical energy savings of single actions cannot be simply added to obtain total energy saving of a renovation package, the combined packages in Step 5 have to be recalculated to obtain better theoretical estimate of saved energy for each package. In terms of implementation cost, the designer should investigate if the proposed actions are synergetic. If so, some costs may be partially reduced or eliminated.
- Step 7. The last step in the proposed methodology consists of a check of fulfillment to see whether the project criteria are fulfilled. These can be regulatory, financial, or other specific owner targets as improved indoor climate, reduction in energy demand, reaching NZEB standard, etc. In the case the criteria are fulfilled, the process continues with detailed design of the renovation solution. If not, new packages can be constructed and re-calculated. In cases where none of the initially investigated single actions fulfills the criteria, other single actions need to be considered and calculated, taking into account the targets of the project.

In practice, the investment and resulting energy costs for operation of the building are often considered. Investment and construction cost for different actions or complete renovation can be obtained by tender/product offers, company specific method/tool [43], or national databases [44].

Energy savings have to be calculated in accordance to national standards; thereby a designer consultant would have a building energy model to document expected savings.

As explained above and shown in Figure 1, the proposed methodology is based on sorting and selecting different renovation actions. The sorting can be done based on purely energy savings or cost. To link cost and achieved energy savings, a simple value termed “cost-effectiveness” is proposed as the main sorting parameter. The cost-effectiveness represents the implementation cost per saved primary kWh for each investigated action and is calculated using Equation (1).

$$Cost - effectiveness\ [\frac{€}{saved\ kWh}] = \frac{Annual\ investment\ [€/y]}{Saved\ energy\ [kWh/y]} \tag{1}$$

This allows for direct comparison between renovation options for different elements and renovation alternatives for the same element. The annual investment is calculated by dividing the implementation cost by the expected lifetime of the considered element or system. Implementation cost includes costs for materials, labor, rent or use of equipment, disposition of existing parts, and preparation of the workplace (all necessary costs to replace the existing and integrate the new part). This approach is based on a method developed for single-family houses [45] and adapted to multi-family buildings.

To account for the fact that some elements have a longer lifespan than others, the implementation cost of each action is divided by the lifetime of the improved parts(s). The expected lifetime can be taken from product specifications, standard values in building regulations, product declarations or the like.

Cost-effectiveness can also be used to evaluate the renovation packages once they have been compiled by using global energy savings and total implementation cost. Excluding maintenance and running cost is a shortcoming; however, cost-effectiveness may still serve as guiding value for investors or property owners for the overall efficiency of the investment into the building.

3. Results

To demonstrate and test the proposed methodology, it is applied to two residential buildings in Denmark and Switzerland. The results obtained by applying the method are presented in Section 3.1 for the Danish case study and Section 3.2 for the Swiss case study. The general characteristics of the selected buildings, gathered in the first two steps, are summarized in Table 2.

Table 2. Summary of key dimensional coefficients, existing systems, and U-values of building elements for the case study buildings.

Parameter/element	Denmark	Switzerland
Build area [m^2]	5630	1432
HFA [m^2]	5250	1222
Wall to HFA ratio	0.51	0.81
Heating	District heating	Gas boiler
Domestic Hot Water	District heating	Gas boiler
Ventilation	Natural with kitchen exhaust	Natural with kitchen exhaust
Floor [W/m^2 K]	1.48	1.6
External wall [W/m^2 K]	0.58	0.9
Windows [W/m^2 K]	2.9	2.8
Attic slab [W/m^2 K]	0.35	1.6

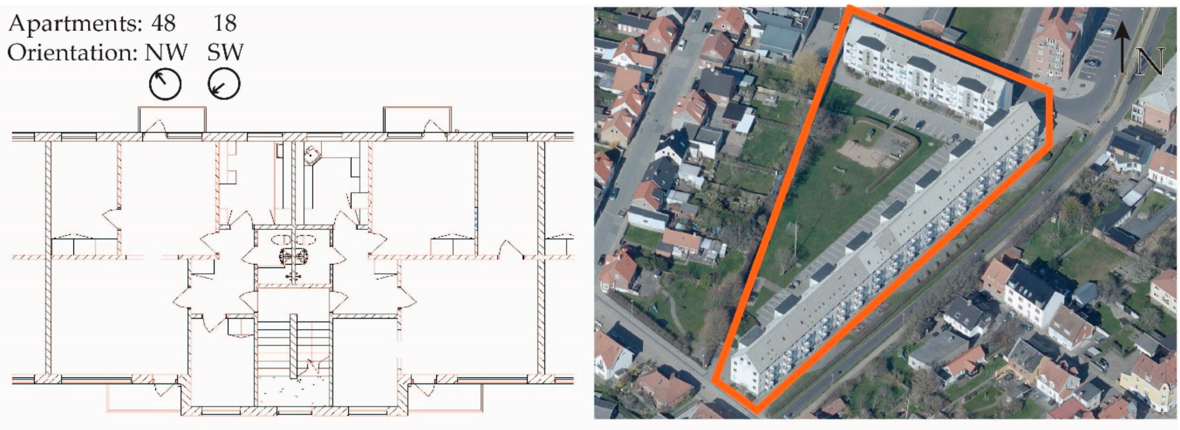
3.1. Denmark

3.1.1. Steps 1–3

The Danish case study is a building complex constructed in 1949 using massive brick walls, concrete slabs, and wooden roof construction. Since the construction of the complex, external walls were insulated with 50 mm mineral wool in 1991, and a new pump for the heating system with outdoor temperature compensation has been installed. Detailed description composition of each element and the existing building state can be found in [46]. The main goals for renovation are increased occupant comfort and compliance with Danish Building Regulations 2018 (BR18). Currently, the main demands in regards to renovation are as follows:

- Fulfilling minimum U-values for building elements.
- Fulfilling one of two voluntary renovation classes, where a minimum reduction of 30 kWh/m^2 per year must be achieved in order to obtain either class.
- Fulfilling energy frames for new buildings.

Figure 2a shows a plan of two neighboring apartments and Figure 2b a picture of the facade of the Danish case study building.



(a) (b)

Figure 2. (**a**) Plan and orientation of the Danish case study building complex; and (**b**) overview of the building complex and its surroundings.

The building complex consists of two neighboring buildings sharing common heating and electricity supply systems. Moreover, the buildings have the same envelope constructions, apartment size, and room disposition, as shown in Figure 2. The difference between the two buildings is the size and orientation. One of the buildings houses 48 apartments (oriented northwest), while the other 18 apartments (oriented southwest).

The building complex is owned by a social housing company and located in the city of Frederikshavn. The main occupants in the complex are elderly people on pension, a few families, and young individuals.

During the energy audit in Step 2, drawings and project information obtained in Step 1 are checked and verified. For this case study, all project information was accurate and readily available. The only discrepancies between original drawings and execution were related to the pipe distribution for heating and domestic hot water (DHW) systems. This required additional measurements of distances and dimensions of pipes and components for a better estimate of the theoretical heat balance. The energy audit also allowed for gathering actual heating and electricity data. It is used to compare and validate values obtained by the theoretical heat balance. All results of the first two steps are summarized in Table 2 and Figure 3.

In Step 3, calculations of energy demand of the building are calculated using the Danish compliance tool Be18. The tool uses a monthly calculation period and is required by the authorities as official documentation for construction permits. For residential buildings, the calculated energy demand includes energy for heating, cooling, ventilation, DHW, and electricity for operation of the building.

Figure 3a compares the measured and calculated total energy for heating and DHW. The calculated total energy was obtained from the theoretical energy model, using Danish primary energy factor of 0.85 for district heating and 1.9 for electricity. The measured consumption for heating and DHW is available for the period 2009–2016. Measured electricity consumption is shown only for 2011, as this is the period when the building complex was fully occupied.

As evident in Figure 3, there is variation of the measured demand for heating and DHW from year to year. The highest value in the available data is during 2013, where the consumption reached 226 kWh/m². Consumption during the remaining years ranges from 119 in 2012 to 174 kWh/m² in 2010. The average consumption (cf. Figure 3a, dashed line) was calculated to be 150 kWh/m² across all years and fits very well with the theoretical calculated heating demand (difference of 1.7 kWh/m²). Excluding the 2013 demand, there is a general decrease in heating demand, which could be explained by the decreasing number of occupied apartments. The peak demand during 2013 could not be explained by occupation, the building owner and manager, or the degree-days for the year [46].

Figure 3b compares the measured electricity consumption for common and private use to calculated values. Values obtained by the compliance software Be18 cover electricity for operation of the building in this circulation pump for heating and DHW. These values are comparable to the common measured consumption, even though it includes electricity for common lighting and laundry appliances. The electricity profile for total consumption of the building, based on occupant type, was also calculated using statistical data from the Danish energy agency-https://sparenergi.dk/forbruger/el/dit-elforbrug. The calculations were made assuming that 60% of the apartments is occupied by a single person, 20% by two people, and 10% by two adults and one teenager. The assumptions are believed to be satisfactory as results are comparable to the measured values for full occupation in 2011. Furthermore, the assumptions are based on information from the property manager and the building owner.

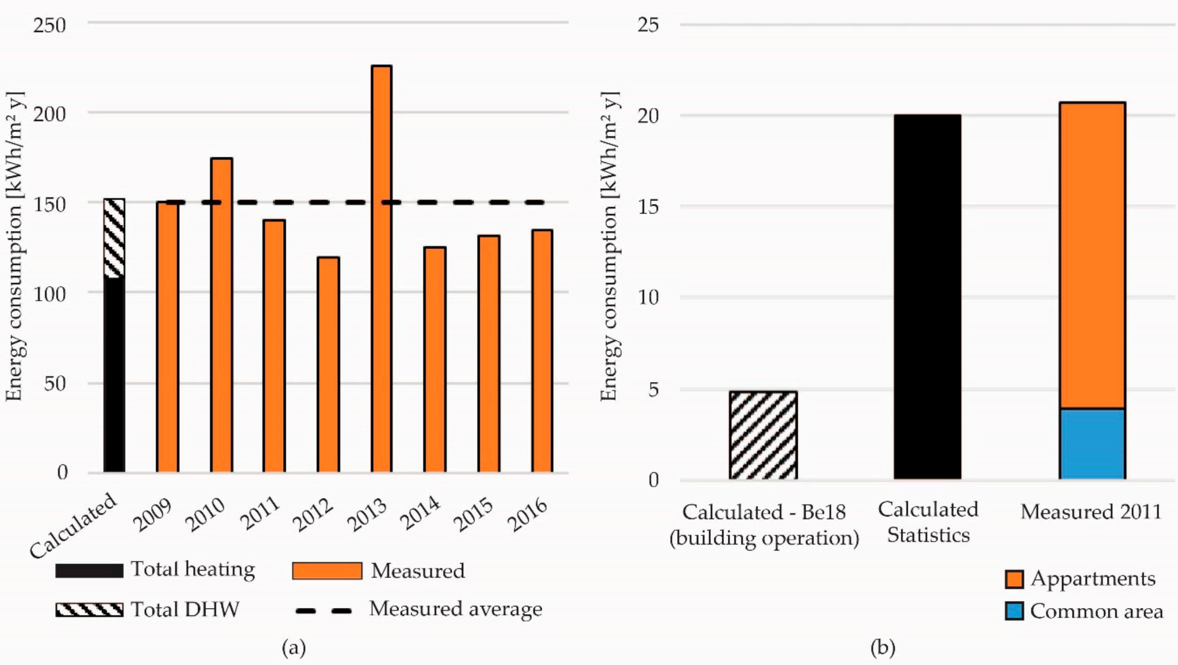


Figure 3. Energy demand of the Danish case study. Comparison of total calculated and measured: heating (**a**); and electricity (**b**).

The work related to the Danish building was done with the purpose of testing the methodology in terms of comparison of different solutions, rather than deciding on specific renovation actions to be implemented. This is also why there is no specific target associated with the outcome of this case study, other than fulfilling BR18 requirements.

The number and variations of investigated solutions for each thermal envelope element are as follows:

- External wall. Three main solutions (wood, brick, and REDArt) with variations in insulation class and thickness. Total of 47 cases, all consisting of preservation of the exiting brick wall, insulation, and new finish.
- Attic slab. Three main solutions distinguished by the usability of attic space after renovation. A solution with usable attic floor accounting for complete floor reconstruction, a solution including

1.2 m wide walking wooden path for access, and a solution with inaccessible attic. All main solutions are variated with different thicknesses and types of insulation, resulting in 114 cases.

- Ground floor slab. Four different thicknesses for insulation Classes 34 and 37.
- Windows. Three frame materials (wood, plastic, and aluminum/wood) and two energy classes for each of the three frames. Special consideration is made for the different possibilities of opening mechanisms, and as such influences the price considerably. The calculations consider six opening mechanisms for wood, four for plastic, and two for aluminum/wood frames. Total of 19 cases.
- Terrace doors. One energy Class A for each of the three frame types and additional energy Class B for plastic frames.
- Heating system. Due to the good technical state of the district heating heat exchangers for heating and DHW systems, the investigated renovation actions are primarily related to insulation of the distribution pipe network. The interventions consist of insulating the pipes with different insulation type, class, and thickness for each of the distribution systems. The considered interventions for the two systems were calculated both separately and combined, adding up to 74 cases. The audits in Step 2 showed that the circulation pump for the heating system has been upgraded in recent years, while the pump of the DHW system is outdated. Therefore, replacement of the DHW pump is also considered.
- Ventilation. The addition of mechanical ventilation with heat recovery (MVHR) is investigated, assuming that decentralized ventilation system for each apparent is in place. For those calculations, the infiltration through the envelope varies from 0.3 to 0.1 L/s/m^2, with the aim to represent how cost-effectiveness varies with different airtightness levels.

Cost data for the investigated renovation alternatives were taken from MOLIO price database - https://www.molio.dk/emner/oekonomi-og-kalkulation/prisdata, using prices specifically for renovation works. The considered cost include materials, working salaries, taxes, renting of equipment, and dismounting, as well as removal and disposition of materials. The lifespan of the different parts was taken from BR18 and constitutes 40 years for insulation works and 30 years for windows, ventilation system, and DHW circulation pump.

3.1.2. Steps 4 and 5

Figure 4 presents the results for cost-effectiveness of all investigated single renovation alternatives, plotted as a function of the resulting primary energy savings.

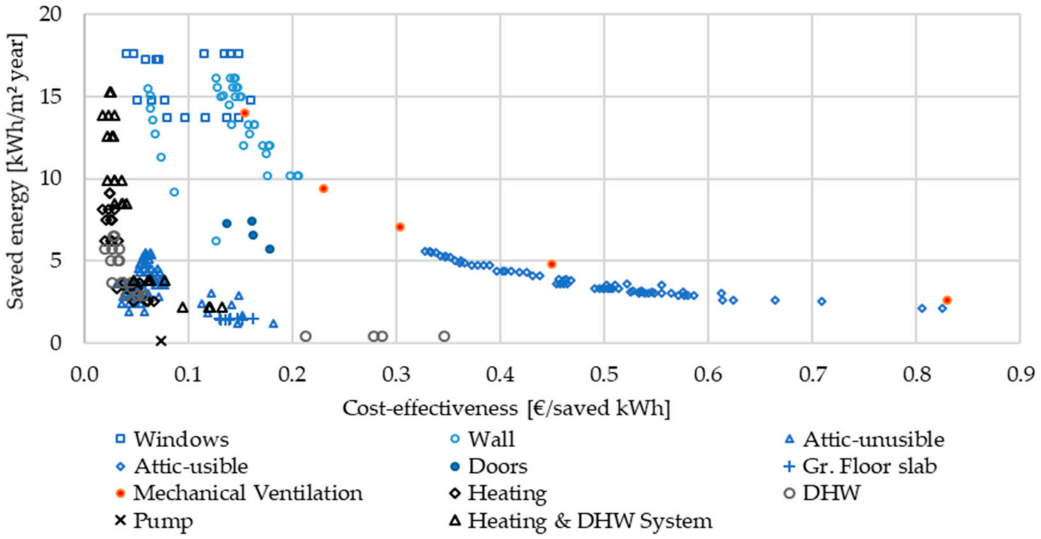


Figure 4. Cost-effectiveness of single renovation actions investigated for the Danish case study building.

This representation allows for visualization and selection of actions with low implementation cost and high energy saving potential (low x-axis and high y-axis value). The most cost-effective actions are those related to insulating the pipe distribution system, followed by windows and external wall renovations.

When considering the envelope renovation actions, the most cost-effective actions prove to be new plastic windows Class A and external wall renovation with standard wooden cladding. In the case of attic slab improvement, the magnitude of efficiency depends on its application after renovation. Large differences can be noticed between the unusable and usable attic spaces. This is due to the extra cost of materials (and work), when the space is to be accessible and a floor surface is required. In cases where the attic slab can be inaccessible, cost-effectiveness of the alterations is comparable to external wall solutions, although resulting in less saved energy. Cases with terrace doors seem to be the intermediate envelope solution in terms of cost-effectiveness and energy savings. Regardless of the obtained results, terrace doors must be prioritized in each case where windows have also changed. This is because of possible synergies achieved due to the type and location of renovation works. Furthermore, in most cases, the terrace door and window are complete wall partitions, making it nearly impossible to change one without the other. Alterations for the ground floor slab are the least cost-effective due to their low amount of saved energy and high cost. The cases presented in Figure 4 consider only actions, which do not require destruction of the apartment floor above; therefore, there are limited possibilities for insulation with a relatively thin insulation layer (due to height restrictions).

Figure 4 also shows that renovation to the heating and DHW system provides the cheapest energy savings in nearly all investigated cases. The cost-effectiveness is relatively constant with an increase in energy savings (insulation thickness). This suggests that insulation thickness has negligible influence on the implementation cost for such actions. In this case, the solution with the highest energy saving should be prioritized over cost-effectiveness.

3.1.3. Steps 6 and 7

To illustrate the potential of envelope and system solutions to reduce the energy demand, three renovation scenarios are studied further in Steps 6 and 7. One scenario where the most cost-effective envelope actions are applied, one with the most cost-effective systems, and a combined scenario where all the most cost-effective actions are applied. The investigated scenarios and the specific U-values for improved building elements are as follows:

- Scenario 1. Envelope elements only: external wall—0.14 W/m^2 K; new windows—0.78 W/m^2 K; attic floor—0.21 W/m^2 K; basement ceiling—0.56 W/m^2 K.
- Scenario 2. Building system improvements: mechanical ventilation, insulation of heating and DHW pipes, and new circulation pump for DHW.
- Scenario 3. Scenarios 1 + 2.

Figure 5 shows results of primary energy demand for the three investigated scenarios, specified above. The resulting total cost-effectiveness is shown for each scenario on the right vertical axis.

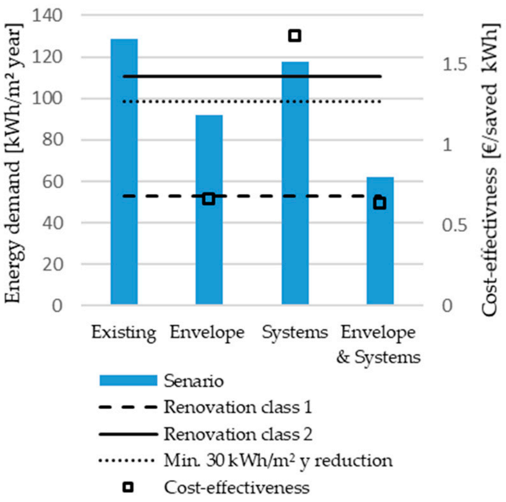


Figure 5. Results of primary energy demand for existing state and applied global renovation packages. Global cost-effectiveness values (right y-axis) and limits for renovation classes according to Danish building regulations 2018 (horizontal lines).

The horizontal solid and dashed lines depict the maximum energy demand for renovation Class 2 and Class 1, respectively. The dotted line represents the minimum reduction of 30 kWh/m^2 year. As seen, the limit for renovation Class 2 is 110 kWh/m^2 year, while the requirement for at least 30 kWh/m^2 year reduction compared to the existing state is 98.6 kWh/m^2 year. This means that in order to reach renovation Class 2 the building complex must have maximum 98.6 kWh/m^2 year primary energy demand.

The first scenario provides 29% reduction in energy demand compared to the existing state, fulfilling requirements for renovation Class 2. This scenario assumes that the attic of the building is not accessible. If this assumption is true, the attic floor is the most cost-effective envelope action, when insulated with 70 mm mineral wool insulation. Following, the attic is wooden frame windows energy Class A. The most cost-effective type of windows is fixed as they are cheapest; however, the calculation model assumes natural ventilation during summer; therefore, the second most cost-effective window type is selected (top hinged). The external wall with regular timber cladding is the second most cost-effective envelope action after the windows. For that action, the main cost is attributed towards the cladding and other activities, while the insulation is only a minor part of the total implementation cost. Therefore, the thickest investigated mineral wool insulation of 245 mm is also the most cost-effective one. The last two actions are insulation of the ground floor slab and replacement of terrace doors. The most cost-effective ground floor solution is with 120 mm mineral wool insulation, while the best performing door type is energy Class A with timber frames.

In the second scenario, where only the systems are improved with the most cost-effective actions, the primary energy savings are approximately 9%. In this scenario, the distribution network for heating and DHW is insulated with 40mm flexible pipe sections, covered with aluminum foil. As shown in Figure 4, all investigated cases are with similar cost-effectiveness; therefore, the most cost-effective is also the one providing the most energy savings. For this scenario, it is assumed that no improvements are done to the thermal envelope. Therefore, the MVHR is modeled with an infiltration rate for the envelope of 0.3 L/s/m^2. Because of that, the 9% saved energy is mainly due to insulating the distribution pipe network. A small contribution is achieved by installing the new energy efficient circulation pump for DHW.

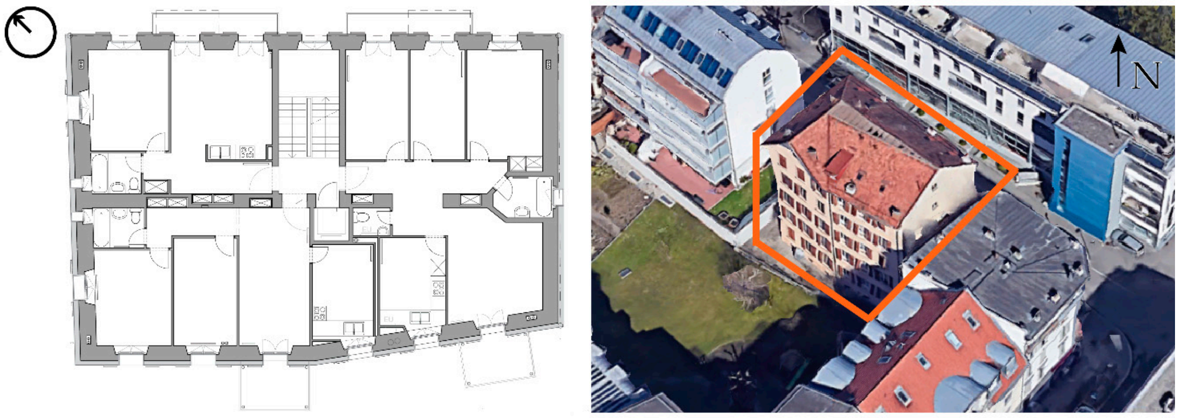
The third investigated scenario combines single actions for envelope and system. It results in a 52% reduction in primary energy consumption, which is by 14% point more than the sum of the first two scenarios. Here, it is evident that synergies between envelope and systems help to reach considerable energy savings. The resulting primary energy demand satisfies the requirements for renovation Class 2 and is 10 kWh/m^2 per year over the maximum value for renovation Class 1. It must be noted that the described single actions are, in all cases, not the one providing the most energy savings. Further optimization beyond cost-effectiveness would allow even greater energy savings and could allow for obtaining renovation Class 1, without addition of renewable energy.

The smallest cost-effectiveness is observed for the third scenario with a cost of 0.63 €/saved kWh. Scenario 1 results in slightly higher cost-effectiveness of 0.66 €/saved kWh, while Scenario 2 is more than two times higher. This is due to the high infiltration rate when implementing Scenario 2, as there are no envelope actions, which improve the airtightness of the buildings and the high implementation cost of the MVHR.

3.2. Switzerland

3.2.1. Steps 1–3

The building in Switzerland was built in 1912 and is located in the town of Vevey. It consists of 15 apartments distributed over five floors with a total heated floor area of 1222 m^2. Figure 6 shows a representative floor plan (Figure 6a) and an aerial view of the building and its surroundings (Figure 6b). The building is equipped with an unheated basement and attic areas, used for common areas and technical installations. The floor plan in Figure 6a shows that there is one apartment with southwest orientation, one with northwest orientation, and one with both south- and north-oriented windows.



(a) (b)

Figure 6. (**a**) Plan and orientation of the Swiss case study building; and (**b**) overview of the building and its surroundings.

The external walls of the building consist of 60 cm rubble layer, covered with external and internal plaster. Walls to the unheated premises are constructed from hollow cement bricks with thickness of 15 cm. The floors to the unheated basement are made of 20 cm concrete slab and 10 cm screed. The floor slab between the attic and the apartments is constructed of wooden flooring and concrete slab.

The heating supply is provided by a 129 kW gas boiler installed in 2014. During the review of the drawings and the energy audit, the heating supply efficiency was estimated to be 87%. The energy demand of the building is calculated using the CECB tool, which is one of the official tools in Switzerland. The calculation results in a primary energy demand of 158 kWh/m^2 per year for heating and DHW, which compares well with the average value of 150 kWh/m^2 per year for the Swiss real estate [47]. The calculated electricity consumption according to the national labeling method is 18.5 kWh/m^2 per year. This includes electricity for operation of the building and private consumption of the building occupants.

The owner of the building has a target of reducing the primary energy demand by 60%, which in this case corresponds to a reduction of approximately 100 kWh/m^2 per year primary energy. An additional criterion in this case study was to provide a solution which is within budget, getting as close to NZEB as possible. The methodology presented in Figure 1 was adapted for this case study in a way that the cost-effectiveness of single actions is investigated in order to get an idea how much energy each envelope element saves and how substantial an investment it is. Based on that, three global renovation scenarios were selected for further evaluation.

To calculate the energy savings, two tools were used: the compliance tool CECB for calculation of heat balance and a specialized tool for technical installations (ECOSOLUTION). The implementation cost associated with each renovation action are acquired using the software EPIQR, and supplier offers for technical installations.

3.2.2. Steps 4 and 5

Figure 7 presents results for cost-effectiveness as a function of saved energy for each of the investigated actions in the Swiss demonstration building.

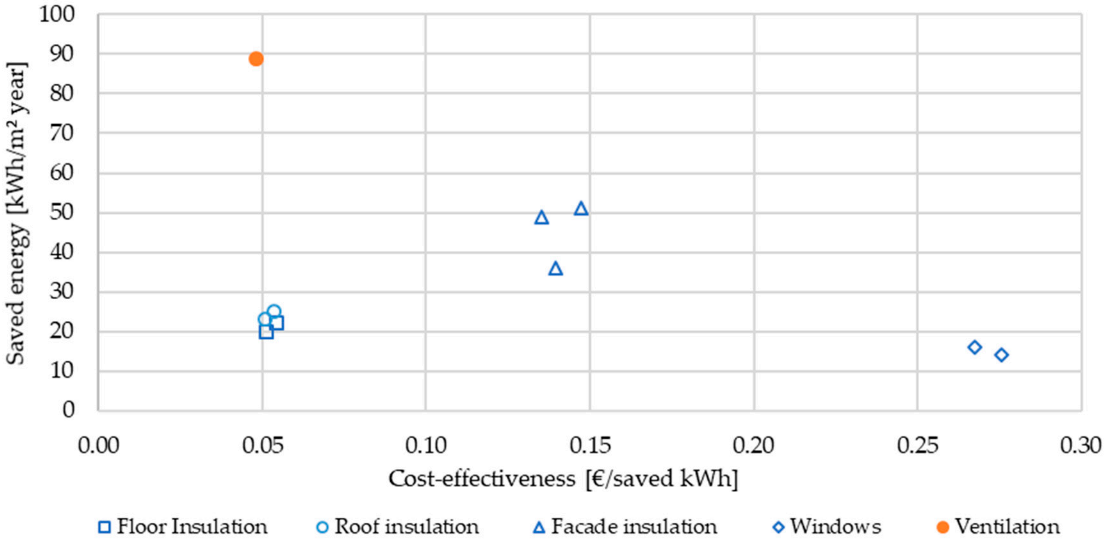


Figure 7. Cost-effectiveness of single renovation actions investigated for the Swiss case study building.

All of the investigated envelope actions incorporate two variants in respect to the level of renovation: one complying with the minimal U-value requirements and one incorporating better U-values than the suggested values by the regulation. For the case of the facade, a third option with superinsulation is also investigated. This is done as the north facade of the building is architecturally protected and may not be changed. Furthermore, the east facade has very limited space to the neighboring building, which makes it hard to place insulation. The additional case with superinsulation is done to investigate if the better insulation would be able to compensate for not insulating one of the external walls.

As seen in the figure, the floor and attic insulation provide energy savings of around 20 kWh/m^2 year. The windows provide approximately 15 kWh/m^2 year, and the facade solutions vary from 36 to 51 kWh/m^2 year.

One action is related to the MVHR. As discussed above, this action is more complex as it depends on the state of the building envelope, heat recovery efficiency, type of ventilation (e.g., variable or constant), airflow requirements, etc. In this case, the investigated action consists of demand controlled mechanical ventilation with 70% heat recovery. The envelope is assumed to be improved to the minimum requirements for the renovated elements, while airflow due to infiltration and window opening is reduced from the standard value of 0.7 to 0.4 m^3/h/m^2. As mechanical ventilation observes relatively high savings and almost reaches the target savings for the global renovation (60% reduction compared to reference ~100 kWh/m^2 year), the conclusion is that it is not necessary to perform all renovation actions in order to reach the project goal. However, given the above-mentioned assumptions, some improvements in the envelope must be implemented to obtain the calculated savings.

In terms of cost-effectiveness, Figure 7 suggests that the most cost-effective action is the ventilation, followed by roof, floor, and façade insulation, where replacement of the windows seems to be least cost-effective. If cost-effectiveness and saved energy were the only considered evaluation parameters, the first action to be dismissed would be the windows. However, as mentioned above, the purpose of the single actions investigation in this case is only for guidance. Expensive actions such as the windows and facades are actions with high global potential, which makes them necessary to reach deep energy savings.

3.2.3. Steps 6 and 7

The results presented in Figure 7 were the basis for discussions with involved stakeholders regarding multi-criteria solutions, leading to the following three scenarios:

- Scenario 1: Covering the minimum requirements for energy and safety.
- Scenario 2: Reaching requirements set by the "Minergie" Geneva canton standard—deep refurbishment with lower U-values for building envelope elements (total weighted energy demand of 55 kWh/m^2 for heating, cooling, ventilation, and DHW).
- Scenario 3: Best compromise between Scenarios 1 and 2. Reaching reasonably better U-values, installation of photovoltaic panels on the roof, and connection to renewable district heating.

Figure 8 presents energy demand results for heating and DHW for the existing case as well as the three investigated scenarios. The renovation goal of 60% reduction in energy demand is marked with a horizontal black line. It is clear that the basic and Minergie scenarios are below the target energy demand of 64 kWh/m^2 per year. The investigated NZEB scenario is slightly above the target with 5 kWh/m^2 per year.

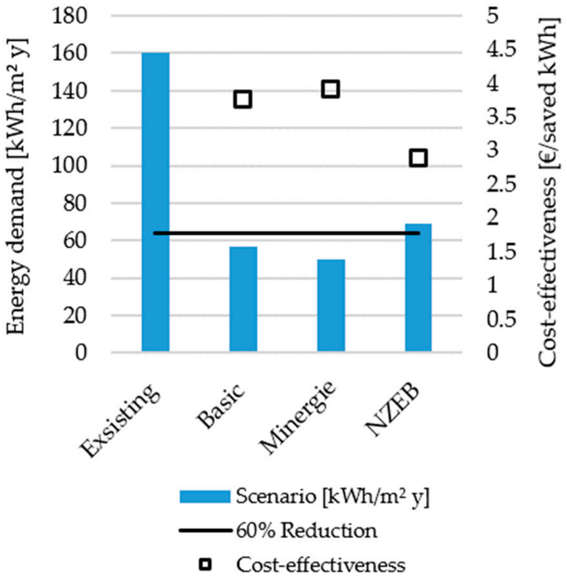


Figure 8. Results of primary energy demand for existing state and applied global renovation packages. Global cost-effectiveness values (right y-axis) and target limit for the renovation (horizontal line).

Figure 8 also presents the global cost-effectiveness of each scenario (right-hand side axis). The cost-effectiveness is calculated using Equation (1), considering the achieved savings and the energy related costs for each case. As evident in Figure 8, the NZEB case is the most cost-effective, despite it having higher energy demand. The global energy demand is higher due to the compromises on the envelope improvements, compared to the other two cases. The lowest cost effectiveness is achieved due to the relatively cheaper solution to connect the building to district heating, contrary to expensive renovation of some elements. Furthermore, changing the heating source of the building from gas to wood fired district heating plant also imposes a change on the primary energy factor from 1.06 to 0.1.

Despite the high heating and DHW demand, scenario NZEB was selected for implementation by the stakeholders involved in the renovation. The main argumentation for that was that it is more financially viable, when compared to the basic and Minergie scenarios. The cost-effectiveness of NZEB scenario was calculated to be 2.9 euro for each saved kWh, while the other two scenarios would have cost 3.8 and 3.9 euro per saved kWh for basic and Minergie scenarios, respectively. This difference in cost was enough to outweigh the larger energy demand, in relation to both the other two cases and the 60% target.

3.3. Comparison with Similar Methods Found in the Literature

This section provides a comparison of the proposed method with methods found in the literature, applying similar approach although in countries with different climates. In [17], using investment, payback and achieved savings for different building types in Spain, the authors found that the savings from facades are the most cost-effective: about two times more than those achieved by replacing of windows and almost three times more than savings from changing the roofs. This trend is noticed for all investigated building types in [17], where the energy saving measures are focused only on envelope renovations. Similar conclusions are made for the northern Spain region in [18]: façade improvements are found to be the most cost-effective, followed by roof renovations. Windows in this case are specified to be least-cost effective; however, it is done without economic evaluation of the windows. For the region of Bologna Italy, the authors of [40] applied payback time to evaluate energy retrofitting options (insulation of wall, window change, and two variants for addition of sunspace) and few combinations of 2–3 single actions. When considering the proposed actions individually, the calculated payback time is 9, 19, and 29 years, for wall, windows, and the two investigated sun spaces, respectively. Despite that, each of the referenced studies has applied a different approach in obtaining an optimal solution. The results from all three studies find that insulation of external wall is most cost-effective. Moreover, the observed difference in achieved energy savings between the external wall and the other investigated building parts is considerably large.

Those observations are rather different from the results for the two case studies investigated in this paper. In the Danish case study, the most cost-effective actions (insulation works of heating and DHW distribution system, window replacement, and external wall insulation) lay relatively close to each other. On the other hand, results from the Swiss case study building show that windows and wall are the least cost-effective actions. In this case, insulation of the floor and roof are superior in to the wall elements.

The differences between the results from the proposed method and those discussed in the previous paragraph can be explained by many different parameters—scope of considered costs, applied evaluation criteria, focus of the methods, scope and approach of calculated energy savings, etc. However, the main discrepancy is believed to be due to the different climatic conditions and costs of material and labor. In a cold climate, heat loss reduction is the main objective in renovation projects. Moreover, materials and implementation cost are generally higher. In accordance to price level indices from EUROSTAT for EU27-2020 = 100; Switzerland = 164.3; Denmark = 142.6; Italy = 104.4; Spain = 96.7 [48] In a hot climate, the main energy savings are obtained from reduction of cooling needs. That is why just a thin layer of insulation provides considerable savings, and, in all reviewed cases, this action is the most cost-effective one. The observed difference in cost-effectiveness of window change between countries with hot and cold climates comes from the fact that, the obtained savings in cooling dominated climates is relatively lower than those in heating dominating climates, while the cost of windows is proportional. Overall, the observed differences are considered to be mainly due to the different boundary conditions and project specific. Therefore, the proposed methodology can be applied in hot climates as well; however, the calculation tools for energy saving have to be more advanced in order to take short-terms dynamic effects into account.

4. Discussion

The proposed methodology was applied to two residential buildings, with different goals and motivation for the renovation. The proposed structure, workflow, and evaluation criteria allowed the methodology to be adapted and used according to project specific needs. Findings from the first three steps provided a solid background information regarding the state and performance of the studied buildings, as well as the regulatory and owner requirements. Furthermore, gathered information during the audits and familiarization with the documentation was applied in the developed models for estimation of energy demand of the buildings. In the Danish case, the focus was to evaluate how different renovation options for the same element compare in terms of cost-effectiveness and how much energy savings could be achieved by a combination of the most cost-effective actions. In the Swiss case, the cost-effectiveness method was used to select a renovation package that brings the building closest to NZEB. This was done by ranking and combining envelope and system renovation actions into global packages, based on energy saving and cost-effectiveness. While generalization of the findings for the larger building stock is out of the scope of the proposed method and this paper, it can be done by applying approaches previously applied by the authors of [19,34,38].

Energy savings and implementation cost are selected as key evaluation criteria of the method, because they are already part of the working culture of designers. Energy calculations are required by national regulation to document energy savings, while implementation costs are essential for the client. The proposed combination of energy savings and implementation cost into cost-effectiveness value for each renovation allows for comparing single actions, regardless of their applicability. It can be argued that the cost-effectiveness approach is too simplified for the complex renovation project and a more holistic approach is required. However, the cost-effectiveness value is meant to be used as a pre-selection of which elements to be considered for renovation and to what extent. Moreover, the method allows a building owner to obtain a clear overview of how different renovation options could be compared in terms of required investments and resulting savings.

Some of the investigated measures (mainly envelope elements) impact aspects beyond energy savings, such as improved comfort, increased property value, other co-benefits, etc. Others actions have big impact on energy savings but no impact on the indoor environment and/or other benefits listed above, e.g., insulation of heating and DHW network or change of circulation pumps. That is why the authors find it worthwhile to propose a simple methodology that establishes a common evaluation ground for all actions, which can be further combined with additional evaluation criteria based on the project needs. Moreover, the evaluation of changes in indoor environmental and other non-energy related parameters is challenging, especially when comparing different solutions for the same element (e.g., varying insulation thickness or type). If required by the project needs, such evaluation of single actions can be done with dynamic calculation models or other specialized tools (e.g., [49]).

Both case studies make use of compliance tools in order to create a reference energy model of the existing building and investigate energy saving potential of single actions and global scenarios. There are several other ways of how potential energy modeling could be made. More detailed calculation (e.g., dynamic hourly based [8,19], multi-zone models [31,33], and grey box [22]) can represent the existing conditions in a building to a higher degree. However, those calculations also require more modeling and computation time. Nevertheless, the structure of the methodology allows the designer to apply their preferred method, or such that it satisfies a specific case requirement. It is important to note that the performance gap resulting from the difference between the predicted and achieved savings can be considerably different. Among others, the performance gap will highly depend on the selected calculation method, quality of the renovation work, occupant behavior, etc.

Few methodologies in the reviewed literature apply investment cost [13,15,33]. The majority of the methods apply LCC calculations, either following the EU cost-optimal method [8,9,19,23,24,30,41,42] or integrating LCC in another context [13,16,18,32]. Cost calculations integrated in the proposed method are limited to implementation cost, and disregard operation and maintenance. While this is a simplified approach compared to LCC calculations, it is done as the main purpose of the method is to compare and select single renovation actions for global renovation scenarios. This can serve as a pre-step to LCC calculations by supporting the selection of single actions to form packages. Furthermore, implementation of cost data for renovated building parts is necessary for LCC calculations. An advantage of investigating each renovation action separately is that it allows for easier planning of step-by-step renovation. That is because the designer can select actions that fit within the available budget or goal for each of the planned steps. It is important to plan and execute the steps in a way that lock-ins are avoided and that the overall goal(s) is met after the last step is implemented.

The method lacks a thorough comparison of different energy supply types and renewable energy production technologies. In the Danish case study, system renovation actions were mainly related to re-insulation of the distribution pipes, whereas in Switzerland different supply systems are investigated on a package level only. Further studies are necessary for validating the proposed cost-effectiveness parameter and discovering if it can provide reasonable comparison for different supply systems. The methodology needs further development to include evaluation and comparison of renewable energy production systems. A similar, simplified approach for evaluation and selection of renewable systems is desired. The goal is to rank renewable energy producing technologies and assist in decision making so balanced investment between renewable technologies and building parts can be established. Although simplified, the approach must include costs related to implementation and operation of the system in question, their efficiency, system demands, the amount of direct energy consumption, and grid interaction.

5. Conclusions

This paper presents a new assessment methodology, targeted to the early design phases of the renovation process from start of the project up until the selection of renovation packages for detail design. It is developed for multi-family buildings and structured in seven steps, providing a structured overview of the entire process. The method supports the selection of which building parts to renovate and to what extent for specific building cases, accounting for energy savings, implementation cost and expected lifetime.

The proposed method was applied to two apartment buildings in Denmark and Switzerland. In the Danish case study, the target of the method was to compare different renovation options per element and across different elements. The results show that applying the most cost-effective envelope actions satisfies renovation Class 2, as defined by the Danish Building Regulations 2018. By integrating all renovation actions related to system improvement, no renovation class could be reached, while a global renovation package consisting of the most cost-effective actions results in a 51% primary energy reduction. In the Swiss case study, the proposed methodology was used to select a renovation package for the building, based on the proposed cost-effectiveness parameter. Comparison of single actions is used to obtain an overview of the magnitude of saved energy by each element, whereas three defined renovation scenarios were evaluated in respect to saved energy and cost-effectiveness. The method resulted in selecting a renovation scenario, which was slightly above the renovation target but considerably cheaper than the more energy ambitious alternatives.

The simplicity of the proposed method makes it robust and provides flexibility, which is necessary when working with a specific project. The ability of tailoring the method to specific goals and needs is one of its core strengths. In principle, the user can apply energy and cost calculation models of their preference, and still obtain a comparison of renovation actions. The fact that it follows structured workflow, incorporating well-known calculations and parameters allows for a higher uptake from practitioners and designers. The methodology can also serve to communicate information and findings between designers and building owners. Comparing all relevant renovation actions on the basis of implementation cost and energy savings provides a clear overview of all necessary costs, tasks, and activities for each relevant building part. This information is vital for avoidance of lock-in situations and planning of step-wise renovation. Moreover, it supports the renovation process by keeping a project within budget and energy improvement targets.

The simplicity is also a major weakness of the methodology. Currently, the method focuses mainly on envelope solutions and few system improvements. Extending the method so it can account for and evaluate energy-producing technologies and contribution from renewable sources would allow for a wider range of optimal solutions. Moreover, the renovation alternatives are evaluated only with respect to energy savings and cost. Even though designers can integrate indoor environment criteria as a project target and check if it is fulfilled at a package level, there is need for more definitive evaluation criteria of indoor comfort. Linking renovation actions with their contribution to improved indoor quality would provide for additional dimension of evaluation and selection of which building parts to renovate and to what extent.

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