Residential renovation assessment of nearly zero energy

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ENGLISH SUMMARY

The majority of the existing building stock is aged and energy-inefficient. Considering that buildings are the single largest contributor to greenhouse gasses and energy use, renovation of the existing building mass is crucial for meeting future energy efficiency and environmental targets.

With the implementation of the Energy Performance of Buildings Directive recast (EPBD) in 2010, there has been a solid legislative drive towards transforming existing buildings into nearly Zero Energy Buildings (nZEB). The EPBD required the Member States of the European Union (EU) to specify and implement definitions and metrics for national nZEB standards. While recent reports on the status of nZEB implementation show considerable progress across the EU, a drawback of the initiatives set by the EPBD regarding nZEB demands is the primary focus on public buildings. Moreover, the most significant ambitions in the EPBD are related to new buildings.

A more recent Directive 844/2018 required the Member States to develop national long-term renovation strategies for a cost-effective transformation of all buildings into nZEB. Moreover, a new version of the EPBD expected in 2021 will likely strengthen the focus on renovation even more. Legislations, regulations and demands stipulate renovation from the “top-down”. The EU has also committed to supporting the uptake of deeper renovations from the “bottom-up” by several initiatives from Renovation Wave communication, published in 2020.

Because of the strong drive towards nZEB uptake, a number of techniques have been developed to assess renovation projects and find a favourable strategy respecting pre-defined objectives. A literature review on existing methods for assessing renovation identified that in most cases, an “optimal” renovation is quantified by multiple evaluation criteria integrating cost and energy savings as a minimum. Despite the wide range of available methods, a central focus in the reviewed literature is evaluating package solutions. Overall, the review found a shortage in the optimisation procedure for selecting the contents of renovation packages. In addition, the need for decision support in the distribution and balance between investments in energy-saving and energy-producing measures was identified.

Based on literature review findings, the motivation for the PhD project is to develop and exemplify a flexible assessment method that respects regulatory frameworks, building specifics and local conditions. The target users of the method are stakeholders in the early stages of the renovation process, dealing with the selection of "what to renovate and to what extend." For instance, professional building owners, practitioners and renovation experts. The method has been developed and applied to residential buildings as those attain the most significant share of the total building stock (>75%).

Contributions:

- A targeted literature review determined the need for a structured approach that evaluates contributions from individual renovation actions and a systematic selection of the contents of the renovation package.
- A proposed generic assessment method for arriving at a final renovation solution with a nZEB goal. The main contributions of the method are the least-cost approach for the selection of the contents of a renovation package. The approach involves a preliminary step to LCC calculations based on a proposed cost-effectiveness parameter (CEP). The CEP accommodates an individual assessment of measures before assessing renovation packages.
- A flexible method that does not need to involve specific tools for deriving assessment criteria or specific nZEB requirements. This allows the method to be suited to specific buildings and MSs targets for nZEB, which is then analysed by tools of choice by the user.
- Integration of the method in an online assessment platform that combines and handles results from different renovation assessment tools. The platform allows the selection of preferred ranking criteria for single actions such as total cost, total energy savings, cost-effectiveness, CO_2-effectiveness or LCA-effectiveness. The creation and comparison of renovation packages are made quickly and interactively.
- A test of the robustness of the method's results and investigation of the relationship between output and input in the LCC calculation model. A definition of the sensitivity of the output for every input parameter and the combined effects of the most sensitive parameters.

DANSK RESUME

Størstedelen af den eksisterende bygningsmasse er forældet med store energiomkostninger. Taget i betragtning at bygninger er den største bidragyder til drivhusgasser og energiforbrug, er renovering af den eksisterende bygningsmasse afgørende for at nå fremtidige energieffektivitets- og miljømål.

Med implementeringen af direktivet om bygningers energimæssige ydeevne (EPBD) fra 2010 har der været en solid lovgivningsmæssig drivkraft mod at omdanne eksisterende bygninger til næsten nul-energibygninger (nZEB). EPBD krævede, at medlemsstaterne i Den Europæiske Union (EU) specificerer og implementerer definitioner og mål for nationale nZEB-standarder. Selvom nylige statusrapporter for nZEB-implementering viser betydelige fremskridt i hele EU, er det primære fokus på offentlige bygninger en ulempe i de initiativer, som EPBD har sat vedrørende nZEB-krav. Endvidere er de mest betydningsfulde ambitioner i EPBD relateret til nye bygninger.

Et nyere direktiv 844/2018 krævede, at medlemsstaterne udviklede nationale langsigtede renoveringsstrategier for en omkostningseffektiv transformering af alle bygninger til nZEB. Endvidere vil en ny version af EPBD, der forventes i 2021, sandsynligvis styrke fokus på renovering yderligere. Lovgivninger, forskrifter og krav kræver renovering fra "top-down". EU har også forpligtet sig til at støtte optagelsen af større renoveringer fra "bottom-up" ved flere initiativer fra Renovation Wave-kommunikation, der blev offentliggjort i 2020.

På grund af den stærke drivkraft mod nZEB-optagelse er der blevet udviklet en række teknikker til at vurdere renoveringsprojekter og finde en gunstig strategi, der respekterer foruddefinerede mål. En litteraturgennemgang af eksisterende metoder til vurdering af renoveringer identificerede, at en "optimal" renovering i de fleste tilfælde kvantificeres ved flere evalueringskriterier, der som minimum integrerer omkostnings- og energibesparelser. På trods af den brede vifte af tilgængelige metoder er et centralt fokus i den gennemgåede litteratur at evaluere pakkeløsninger. Samlet set fandt gennemgangen en mangel i optimeringsproceduren for valg af indholdet i renoveringspakker. Desuden blev behovet for beslutningsstøtte i fordelingen og balancen mellem investeringer i energibesparende og energiproducerende foranstaltninger identificeret.

Baseret på fund fra litteraturgennemgang er motivationen for dette ph.d.-projekt at udvikle og eksemplificere en fleksibel vurderingsmetode, der respekterer lovgivningsmæssige rammer, bygningsdetaljer og lokale forhold. Målgruppen for brugere af metoden er interessenter i de tidlige faser af renoveringsprocessen, der beskæftiger sig med udvælgelsen af "hvad der skal renoveres og i hvilket omfang." Dette er eksempelvis bygningsejere, praktikere og renoveringseksperter. Metoden er udviklet og anvendt på beboelsesejendomme, da de optager den største del af den samlede bygningsmasse (> 75%).

Bidrag:

- En målrettet litteraturgennemgang som fastslog behovet for en struktureret tilgang, der evaluerer bidrag fra individuelle renoveringshandlinger og et systematisk valg af indholdet i renoveringspakken.
- En foreslået generisk vurderingsmetode til at opnå en endelig renoveringsløsning med et nZEB-mål. Metodens vigtigste bidrag er den "færrest omkostninger"-tilgang til valg af indholdet i en renoveringspakke. Fremgangsmåden indebærer et indledende trin til LCC-beregninger baseret på en foreslået omkostningseffektivitetsparameter (CEP). CEP'en rummer en individuel vurdering af foranstaltninger, før renoveringspakker vurderes.
- En fleksibel metode, der ikke forudsætter at specifikke værktøjer benyttes til at udlede vurderingskriterier eller specifikke nZEB-krav. Dette muliggør, at metoden passer til specifikke bygninger og MS-mål for nZEB, som derefter analyseres ved hjælp af valgfrie værktøjer af brugeren.
- Integration af metoden i en online vurderingsplatform, der kombinerer og håndterer resultater fra forskellige værktøjer til vurdering af renoveringer. Platformen tillader valg af foretrukne rangeringskriterier for enkeltaktioner såsom samlede omkostninger, samlede energibesparelser, omkostningseffektivitet, CO2-effektivitet eller LCA-effektivitet. Oprettelse og sammenligning af renoveringspakker foretages hurtigt og interaktivt.
- En test af robustheden af metodens resultater og undersøgelse af forholdet mellem output og input i LCC -beregningsmodellen. En definition af outputtets følsomhed for hver inputparameter og de kombinerede effekter af de mest følsomme parametre.

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Lastly I would like to thank my family and fiancé for the unconditional love and support troughout the PhD period. I could not have done it without you.

Thank you.

Aalborg, August 2021
Yovko Ivanov Antonov

PREFACE

The work presented in this thesis is part of a PhD project funded by the Department of the Built Environment, Aalborg University, Aalborg and the European Union's Horizon 2020 Research and Innovation programme, with grant agreement number 768576 (RECO2ST). The work presented in Paper 1 is funded by the same European Union's Horizon 2020 programme under the project grant number 649865 (REFURB). Yovko Ivanov Antonov has carried out the work from March 2018, to September 2021.

This thesis is paper-based and consists of an extended summary and appended papers [1] to [5]. This format is selected to present the research, contributions, and findings without having to read the papers first.

OVERVIEW OF PAPERS

This paper-based thesis consists of the following collection of papers:

Paper [1] ***"Development of energy renovation packages for the Danish residential sector"***
Pomianowski, M. Z., Antonov, Y.I, Heiselberg, P.K
10th International Conference on Applied Energy – Hong Kong, China; Energy Procedia 2019

Paper [2] *"**Methodology for Evaluation and Development of Refurbishment Scenarios for Multi-Story Apartment Buildings, Applied to Two Buildings in Denmark and Switzerland**"*
Antonov, Y.I., Heiselberg, P., Flourentzou, F., Pomianowski, M.Z.
Buildings, 2020

Paper [3] *"**Novel Methodology toward Nearly Zero Energy Building (NZEB) Renovation: Cost-Effective Balance Approach as a Pre-Step to Cost-Optimal Life Cycle Cost Assessment.**"*
Antonov, Y. I., Heiselberg, P. K, Pomianowski, M. Z
Feature paper in Special issue Retrofitting Buildings and Energy Efficiency

Paper [4] "Investigations of building-related LCC sensitivity of a cost-effective renovation package by one-at-a-time and Monte Carlo variation methods."
Y.I. Antonov, K.T. Jønsson, P.K. Heiselberg, M.Z. Pomianowski
Original manuscript to be submitted to an international peer-reviewed international journal in September 2021

Paper [5] *"Methodology and platform for NZEB renovation of residential buildings"*
Antonov, Y.I., Heiselberg, P., Egger, J., Flourentzos, F., Pomianowski, M.Z.
Proceedings of the 15th Conference on Advanced Building Skinks, 2020

Aside from Papers 1 - 5, the author has taken part in research activities outside the scope of the PhD project. Some of those activities resulted in the publications listed below. Papers 6-12 are not part of the thesis work and should not be evaluated. However, they are listed to show the additional research topics that the author has taken part in. A full list of the authors' publications is available at: www.vbn.aau.dk/da/persons/138371/publications/

Paper 6 **Margheritini, L., Møldrup, P., Jensen, R. L., Frandsen, K. M., Antonov, Y. I., Kawamoto, K., de Jonge, L. W., Vaccarella, R., Bjørgård, T. L., & Simonsen, M. E. (2021)**
"Innovative Material Can Mimic Coral and Boulder Reefs Properties." **Frontiers in Marine Science, 8, [652986].**
https://doi.org/10.3389/fmars.2021.652986

Paper 7 Johra, H., Margheritini, L., Ivanov Antonov, Y., Meyer Frandsen, K., Enggrob Simonsen, M., Møldrup, P., & Lund Jensen, R. (2021). "***Thermal, moisture and mechanical properties of Seacrete: A sustainable sea-grown building material."*** *Construction and Building Materials*, 266(Part A), [121025].
https://doi.org/10.1016/j.conbuildmat.2020.121025

Paper 8 Frandsen, K. M., Antonov, Y. I., Johra, H., Møldrup, P., & Jensen, R. L. (Accepteret/In press). "***Experimental investigation of water vapor diffusivity in bio-based building materials by a novel measurement method***." I RM4L 2020 International Conference

Paper 9 Christiansen, L., Antonov, Y. I., Jensen, R. L., Arthur, E., de Jonge, L. W., Møldrup, P., Johra, H., & Fojan, P. (Accepteret/In press). "***Heat and air transport in differently compacted fibre materials*"**.** Journal of Industrial Textiles. https://doi.org/10.1177/1528083719900386

Paper 10 Antonov, Y. I., Frandsen, K. M., Jensen, R. L., & Møldrup, P. (Accepteret/In press). "***Simulation of moisture transfer through bio-inspired materials using independent measurements of water vapor sorption and diffusivity*.**" I RM4L 2020 International Conference

Paper 11 Frandsen, K. M., Antonov, Y. I., Møldrup, P., & Jensen, R. L. (2020). "***Water vapor sorption dynamics in different compressions of eelgrass insulation.***" I J. Kurnitski, & T. Kalamees (red.), 12th Nordic Symposium on Building Physics (NSB 2020) (s. 1-7). [17005] EDP Sciences. E3S Web of Conferences Bind 172 https://doi.org/10.1051/e3sconf/202017217005

Paper 12 Liu, M., Heiselberg, P. K., Antonov, Y. I., & Mikkelsen, F. S. (2019). "***Parametric analysis on the heat transfer, daylight and thermal comfort for a sustainable roof window with triple glazing and external shutter.***" Energy and Buildings, 183, 209-221. https://doi.org/10.1016/j.enbuild.2018.11.001

Paper 13 Flourentzou, F., Antonov, Y. I., & Pantet, S. (2019). "***Understand, simulate, anticipate and correct performance gap in NZEB refurbishment of residential buildings.***" Journal of Physics: Conference Series (Online), 1343, [012177]. https://doi.org/10.1088/1742-6596/1343/1/012177

TABLE OF CONTENT

ABBREVIATIONS

EU	European Union
EPBD	Energy Performance of Buildings Directive
MS	Member States (of the EU)
nZEB	nearly Zero Energy Building
SF	Single-family
MF	Multi-family
LCA	Life Cycle Analysis
NPV	Net Present Value
LCC	Life Cycle Cost
RAM	Renovation Assessment Method
LCM	Least-Cost Method
DHW	Domestic Hot Water
CEP	Cost-Effectiveness Parameter
DH	District Heating
HP	Heat Pump
SRC	Standardised Regression Coefficient
GWP	Global Warming Potential
ADP	Abiotic Depletion Potential

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INTRODUCTION

The building industry is the single largest contributor to global emissions. On a global scale, 38% of the emissions and 35% of the final energy are building-related. Residential buildings alone contribute with 22% of the total energy and 17% of all emissions. [6]. On a European level, the Union targets reducing greenhouse gas emissions by 55% by 2030, compared to 1990 levels and becoming climate neutral by 2050 [7]. As a significant contributor to emission and energy use, buildings are essential in achieving future environmental targets.

This is reflected in the strong legislative drive in the European Union (EU) towards more efficient and socially responsible buildings. Perhaps one of the key EU directives, well-known within the industry, is the recast of Energy Performance of Buildings Directive (EPBD) [8]. This required Member States (MS) to develop and adopt national regulations for minimum energy requirements for buildings and national definitions for nearly Zero Energy Buildings (nZEB). Furthermore, the EPBD stipulates that all new buildings after 2020 and publicly owned and occupied buildings after 2018 must be nZEBs. Even though the EPBD has been amended since its publication in 2018 [9] and another revision is due by the end of 2021[10], the general definition of nZEB remains unchanged:

> *"…a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby;"*
>
> *Article 2(2)* [8].

Every Member State was further obligated to provide national definitions, limit values for nZEB classification and specifications of renewable energy integration.

Although the ambitions for new buildings in the EPBD are high, the renovation of buildings is considered to a much smaller extent. The only provisions regarding existing buildings as stated in the EPBD are to ensure minimum energy demands for the building or its renovated part in the case of major renovations.

A recent status report on the implementation of national nZEB definitions, legislation, numerical indicators and the demands for new buildings [11] reveal considerable progress in meeting the different deadlines with the objectives above as set by the EPBD. With that said, it should be noted that there are still MS that lack nZEB legislation (3), primary energy indicators (6) or clearly defined renewable energy requirements (12) [11]. Nevertheless, a comparison of the selected limit values for primary energy for single-family buildings in the different MS (shown in Figure 1) reveals a wide variation in the selected limit values. The observed variation can be partially attributed to varying climates and thereby, distinct heating and cooling needs. In practice, the limit value IS based on additional socio-economic and political factors, along with the ambition level of the country.

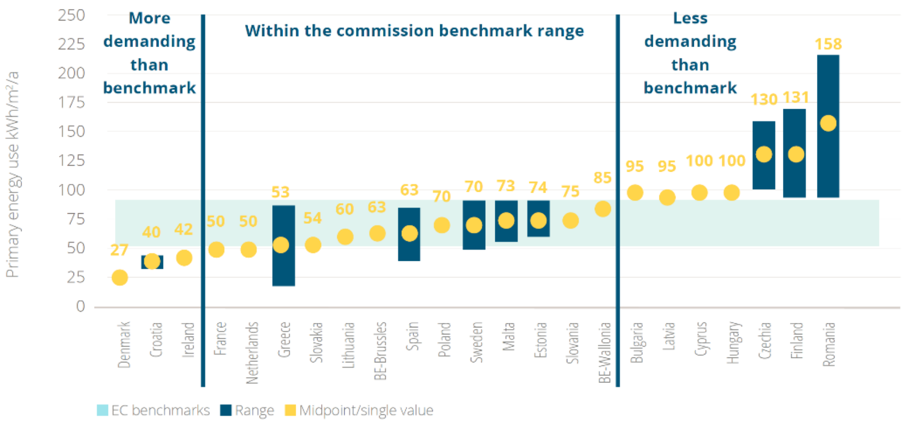


Figure 1 “nZEB kWh/m² per year values for single-family homes in the EU” Source: [11]

While there has been significant progress in developing standards for new buildings, requirements related to the renovation of exciting buildings are still lacking. Compared to existing buildings, new buildings require considerably less energy for operation [12]. Furthermore, considering that most of EU buildings’ stock has aged [13] and is far from meeting current energy requirements [12], it is evident that the renovation of residential buildings is crucial for reaching EU climate and energy targets. Directive [9] and the recently published Renovation Wave initiative [13] increase the focus on renovation with specific implications. This is discussed further in the next section.

1.1. BUILDING STOCK CHARACTERISTICS

Providing common characteristics of the relatively broad and diverse research area of building renovation requires a differentiation between the different types of buildings. When the buildings' function is considered, reports show that 75% of the total building stock has a residential function. The remaining 25% constitutes offices, public buildings and other buildings types [13].

In addition to their large share, the age of residential buildings amplifies the need for additional efforts in the area. Figure 2 shows an estimated breakdown of the construction period of residential buildings in the EU and United Kingdom [13]. In at least half of the EU countries, Figure 2 shows that around 80% of residential buildings were constructed before 1990. This is before implementing ambitious energy efficiency standards, which can be used as a good indicator of the overall efficiency of the building stock in each country [13].

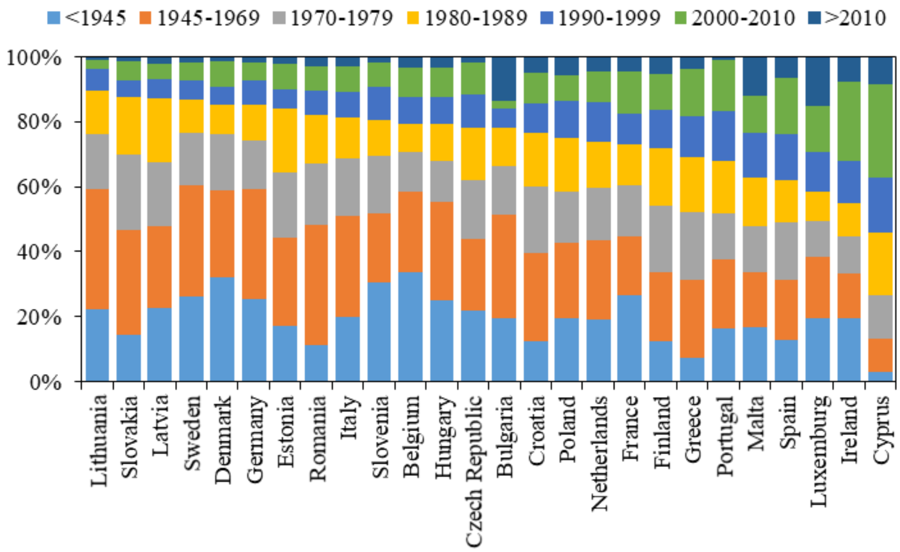


Figure 2 Breakdown of residential building stock by construction year. Adapted from [13].

Considering the facts above, transforming existing residential buildings into healthy, energy-efficient entities is essential for reaching upcoming EU targets. This is also evident from Directive 2018/844 [9], which strongly focuses on renovation. The Directive calls upon MS to prepare and submit cost-effective, long-term strategies for converting the inefficient, existing building stock into nZEBs. Directive [9] elucidates that reaching the future efficiency and environmental targets requires 3% of existing buildings to be renovated each year. However, a report published in November 2019 by the European Commission on the activities and uptake of nZEBs regarding energy renovation exposes alarmingly low renovation rates [14]. The report considers the following four qualitative parameters for evaluating the progress and uptake: renovation rate, primary energy savings, investment costs and the number of constructed nZEBs for 2016-18. The report findings are alarming as the average weighted renovation rate for residential buildings spans 0.4-1.2%, depending on the MS. Furthermore, renovation rates for deep renovations (>60% primary energy savings) are in the range of 0.1-0.3% [14].

The EU's Renovation Wave strategy also underlines the need to accelerate deep renovations of existing residential buildings, with a strong focus on tackling the worst performing buildings, energy poverty, social housing and decarbonising heating and cooling [15]. The main objective of the Renovation Wave is to (at least) double the current renovation rate in residential and non-residential buildings by several financial, legislative and non-legislative instruments [15]. This clearly shows the intention of the EU to stimulate renovation from "all sides" (from the "top-down" by legislations and regulations; from the "bottom-up" by financing support for owners and actors in the renovation process). This calls for a need for combined efforts from all actors involved in the renovation process.

1.1.1. SINGLE- VERSUS MULTI-FAMILY BUILDING RENOVATION

Residential renovation is a complex process, with many aspects and actors in play. Firstly, the complexity stems from the wide variation of residential building types - detached, townhouses, large apartment buildings, student accommodation, social housing, etc. Secondly, there is a significant variance of motivation and barriers in a residential renovation. Finally, the increasing and changing regulations do not help the process from a practical point of view. Differentiation between residential building types is necessary to evaluate the differences in motivation and barriers in the wide variety of residential configurations.

The motivation, barriers and contextual parameters are project-specific and dependant on a number of behavioural characteristics that influence the homeowner's decision to renovate [16]. Some of these parameters are the building type, location, owner-occupant configuration, owner ambition etc. In general, regardless of the building type, an occupant that owns the property and has decided to renovate would consider the associated costs and desired benefits/improvements. However, studies have shown that energy savings are often not a priority for single-family building owners, but some of the priorities may lead to energy savings [17]. This is also confirmed by a study investigating Dutch homeowners' behaviour towards energy renovations [18]. The study found that actions improving the quality of life are often the primary motivators.

At the same time, the cost of the different energy-saving measures is a common implementation barrier.

The situation with multi-family buildings is quite contrasting. An essential prerequisite for discussing renovation for this segment of building stock is the type of owner-tenant configuration, e.g. owner-occupied or tenant-occupied dwelling unit in the multi-family building in question. Indeed, any homeowner directly influences any undertaken renovation at their property, compared to a tenant. However, this is more suited for detached houses rather than dwellings in a multi-family building configuration.

In multi-story dwellings with owner-based occupants, renovations to the individual dwelling units are very often limited to internal works. Even if the primary motivation in such improvements (applied to a single dwelling unit in a multi-story, multi-family building) is energy savings, the overall impact on the total energy demand of the building is somewhat limited. Thereby, the renovation of single dwelling units within multi-family buildings is not considered in this thesis.

Multi-family buildings that are owned by a real estate company, public housing associations, or any other constellation capable of initiating and setting global renovation targets for the whole building, have a much greater energy-saving potential. Firstly, the efficiency is higher because the renovated floor area is much greater when the project contains the whole building rather than an individual dwelling unit. Also, costs per renovated floor area can be reduced due to the scale of the project such as through the repetition of specific tasks or purchasing and handling large quantities of building products.

While the renovation of existing buildings is not a new topic, recent developments in legislation and stricter requirements pose challenges in selecting the optimal building parts to renovate to satisfy the legislative requirements and fulfil the building owner's goals. The process and number of actors are highly dependent on the type of residential building in question. An optimal solution can be determined based on either a single- or multi-parameter assessment. Various methods for assessing and selecting “optimal” renovation solutions are readily available. Considering that there are many different reasons to renovate and many ways to achieve renovation targets, such methods vary greatly in approach, evaluation parameter(s), target audience, required skill set and time.

1.2. RENOVATION ASSESSMENT METHODS

In order to position the work of the thesis, literature streams and legislation on the topic of residential renovation assessment have been checked periodically. This section presents an overview of relevant references used for defining the PhD project.

Since residential renovation is a broad research area with diverse topics and considerable developments in regulatory requirements, review articles have shown that the available literature concerning the topic is extensive [19,20]. The more recent study [20] reviews 234 references on multi-family building renovations and identified the need for an in-depth analysis of contributions from different renovation measures. The study also pointed out a gap between in-depth and broader RAMs.

In that regard, the literature review presented in Paper [2] focused on characterising RAMs found in the literature concerning the renovation phase, building scale and type, evaluation criteria and renovation level. Table 1 presents the study results where the following paragraphs include a short recap of the scope and findings for each studied topic. A list with the complete method characterisation areas is available at the bottom in Table 1.

The reference number (Ref.) depicted in the first column of Table 1 corresponds to the reference list in Paper [2]. To make things easier for the reader, citations concerning Table 1 respect the original numbering in the study. To distinguish these from citations of this document, they are placed in parentheses and marked in grey in the following way: (i).

The renovation phase that methodologies support is differentiated by a preliminary stage that includes activities up until the physical implementation of renovation on the building. In contrast, the post-renovation stage includes activities after the execution of renovation. All reviewed methods in Table 1 support the pre-renovation stage, while only three (14,21,22) address works post-renovation.

The building scale in Table 1 refers to whether the respective method is applied to a single building, a collection of (a few) buildings or a large building stock on a regional or national level. Findings in this regard show that the majority of methods assess a single building selected as a reference for a large share of the building stock. Concerning building type, Table 1 depicts public, office and residential buildings where single- and multi-family buildings (SF and MF) are indicated separately. The results in Table 1 clearly show that the multi-family building type is the most common in the studied sample; however, all building types are represented in the referenced methods.

Table 1 Literature study on renovation assessment methodologies. Ref. number corresponds to the reference list in the Source [2]

Ref.	Phase	Building Scale	Building Type	Evaluation Criteria SOC	ECO	ENV	Renovation Level
[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).

Even though most of the reviewed methods are applied to a single building, a generalisation for the total building stock is often applied. While such generalisations are powerful for estimating the global potential for renovation (in terms of energy savings, cost, CO_2 reduction etc.), those result in generic renovation solutions incapable of addressing case-specifics challenges.

Paper [2] categorised evaluation criteria applied in the reviewed RAMs with respect to the domain of the considered indicator(s), i.e., social, economic and environmental (see bottom of Table 1). The analysis shows that many reviewed methods integrate multi-criteria to determine an "optimal" renovation solution. The EU's cost-optimal comparative methodology has been widely applied to various building types (8,23-25), both strictly following the framework from [21] (indicated as "CO" in Table 1) and in combination with additional indicators such as CO_2 reduction (28-30), Life Cycle Analysis (LCA) (26,27), thermal comfort (31) and qualitative co-benefits (30) [2].

Authors have also applied multi-criteria methods as an alternative to the EU cost-optimal method. Methods considering evaluation criteria in all three sustainability domains are (13,15,16,32-34). As noted in Table 1, such methods integrate indoor comfort, architectural or occupant-related criteria in the social domain. These are often combined with economy-related criteria such as the payback time, net present value(NPV), investment cost, or Life Cycle Cost (LCC), although not strictly following the cost-optimal framework in [21]. In addition, the reviewed methods integrate environmental-related indicators such as primary energy demand, CO_2 reduction or LCA [2].

Another review goal in [2] was to gain an insight into available approaches for compiling energy renovation packages/scenarios. In other words, to find the selection process for which building parts to include in a renovation package. To gain insight into this area, the last column in Table 1 divides the methods into a "Single specific and package", "Single and package" and "Package". Here, references denoted with "Package" include an analysis and evaluation of renovation packages only, whereas "Single Spec. and Package" denotes methods analysing and presenting contributions from individual (single) energy-related renovation actions and packages [2].

Nearly all referenced methods deal with the contribution from individual actions to some extent; however, none of the methods applies those results for "compiling" the studied renovation packages. While individual contributions from different building parts regarding energy and cost are often determined, they are <u>not</u> actively used to decide on the composition of the renovation packages [2].

In theory, the well-known cost-optimal method [21] can evaluate individual contributions from different building envelope elements and systems. However, in practice, there is a shortage of methods of doing so. Paper [2] points out that in practice, the decision of "what to renovate and to what extent" is the result of an iterative process between the building owner and designers; more often based on a short-term investment cost (payable at the end of the renovation process) than a long-term LCC. In addition, a LCC is yet to become common practice in the construction industry.

Paper [2] merely reviewed 32 methods; however, the findings align with those identified in [20]. In respect of the evaluation criteria, most RAMs consider economic and energy efficiency indicators to find a cost-optimal solution. A great deal of these methodologies stem from requirements in the EPBD for a cost-optimal definition of national energy efficiency requirements and the resulting comparative methodology [21].

Taken together, the results from the literature review of RAMs in Paper [2] revealed a lack of:

- Structured methods for evaluation of the cost-benefits of separate building elements and systems.
- Common approaches for deciding which building parts and systems to include in a renovation package. Moreover, the distribution of investments between energy efficiency and energy production.
- Practical methods that target specific buildings.

From the time of the literature review in Paper [2], additional, periodic literature searches allowed the discovery of newer research papers and unintentionally overlooked publications. These studies are discussed closely in the relevant appended papers, whereas key developments are briefly mentioned in the following two paragraphs.

It is worth mentioning that there is an increased focus on renovation with a nZEB target [22,23]. In their study, Qu et al. [22] proposed an EPC-based RAM, with a stronger emphasis on exploring interconnected and coupled impacts of energy retrofit measures, based on the: "*…difference between primary and renewable energy consumption in the extreme cold winter and hot summer months.*" [22]. Teréz et al.; propose a cost-effective method for building renovation at a district level [23].

A comprehensive study on the uptake of nZEB in EU MS during the period 2012-2016 [14] found a rising trend in nZEB, more so for new buildings than renovations. The study also identifies an energy performance gap between cost-optimal and nZEB solutions. The gap between cost-optimal and nZEB solutions is also recognised in studies looking to quantify or reduce it [24–26]. Moreover, despite the increasing trend in nZEB uptake, [14] identifies annual renovation rates for deep renovations (>60% primary energy savings) to be just 0.2-0.3%

across the EU. Further efforts in the research topic are needed considering that the stipulated renovation rate of 3% (Directive 2018/844 [9]) and goals of the EU Commission are to (at least) double the renovation rate by 2030 and accelerate deep renovations [27].

1.3. RESEARCH OBJECTIVES AND SCOPE

As pointed out in the preceding section, a number of Renovation Assessment Methodologies (RAMs) exist. This research aims to support the uptake of nZEB renovations and increase the renovation rate by:

1. Investigating the essence and scope of existing RAMs. Identify if any of these methods have established frameworks for a cost-balance between energy renovation measures and investments in renewable energy.
2. Proposing a flexible assessment methodology for the least-cost renovation of existing residential buildings to nZEB; targeted to reach practitioners, renovation experts, professional building owners and builders.
3. Testing the robustness of the method and obtaining a better understanding of the relationship between input and output parameters of LCC calculations.

The scope of the PhD project is limited to cost and energy savings as indicators for the assessment of renovation alternatives. Additional indicators that can be applied are discussed and noted through the targeted literature review in **Paper [2]** and Chapter 5.

Key research questions for the PhD project include:

• What is the most cost-effective way to reach nZEB, considering different costs for the renovation of building elements, systems and energy-producing technologies?

• Which renovation actions provide the greatest energy savings? What is their investment, life cycle cost and life expectancy?

• How should single refurbishment actions be prioritised and combined into a cost-optimal scenario while complying with nZEB requirements for multi-family apartment buildings?

• What are the existing options for renewable energy production? What are their investment and running costs? How do those costs compare to envelope and system-related costs?

• What is the magnitude of the uncertainties related to the required energy and cost calculations?

1.4. THESIS OUTLINE

Chapter 1 presents the background and challenges of the research area, including the objectives of the PhD project.

Chapter 2 defines the approach applied to reach the objectives. The chapter *positions* the thesis within the field of residential renovation assessment with respect to the literature review and the identified gap between the evaluation of packages and individual (single) renovation actions. As defined in the objectives, the method is targeted at multi-family building(s). Moreover, the chapter provides an overview of the applied approach for accomplishing the PhD project.

Chapter 3 describes the proposed assessment methodology originating from **Paper [1]** and further developed through **Paper [2]** and **Paper [3]**. In addition, the chapter summarises the key observations and findings from developing and applying the method to the case study buildings.

Chapter 4 discusses the robustness and uncertainties associated with costs when applying the proposed method investigated in **Paper [4]**.

Chapter 5 provides an example of the practical application of the method in a newly developed online platform for the assessment of residential renovations. The chapter describes the integration level of the method in the platform and exemplifies the application with an alternative to cost parameters.

Chapter 6 concludes on the main findings and highlights areas for possible further exploration within the topic.

2

RESEARCH DESIGN

To accomplish the objectives of the PhD project, the research was centred around designing a flexible assessment methodology for the least-cost nearly Zero Energy Building (nZEB) renovation with practical implications.

2.1. POSITIONING

Positioning the method within the framework of residential renovation is accomplished by using work by Janda et al. [28]. They define a framework for societal change with respect to where the change is initiated - Figure 3 [28]. In this schematic framework, a “top-down” influence entails rules, regulations, directives and so on coming from bodies with regulatory power. On the contrary, “bottom-up” relates to individuals (homeowners, tenants, landlords) or tools and activities that assist in complying with the regulations coming from the top.

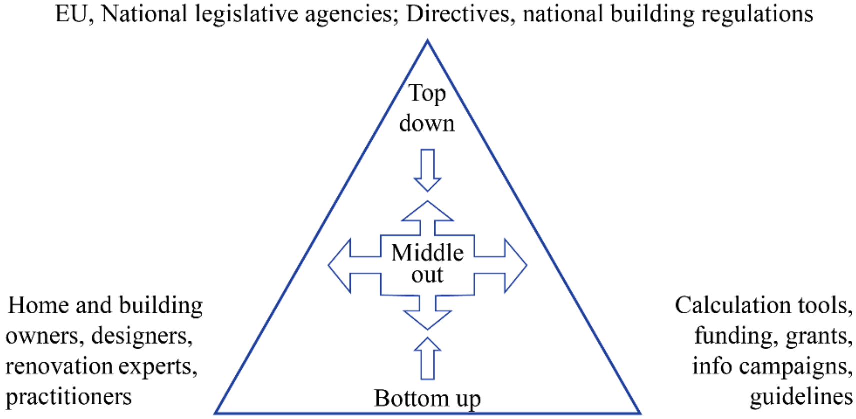


Figure 3 Directions of influence. Adapted from [28]

The developed method falls within the “middle-out” section of the framework shown in Figure 3 as it is aimed to support actors from the “bottom” while respecting national regulations from the “top”.

The flexibility refers to the broad target audience with various national, local, private or commercial tools for evaluating a renovation project's cost and energy savings. The practicality is built around integrating the method into an online refurbishment assessment platform.

Considering that renovation is a broad area with multiple possible solutions for a given building, many methods presented in the introduction are optimisation-based. However, in practice, optimisation is performed on a single (or a maximum of a few) solution(s) rather than the entire solution space. This can be explained by the additional time required for optimising a renovation problem. In practice, it is common to select proven solutions and optimise these to reach the desired targets or requirements to save time and ensure quality.

In light of the considerations made above, the Least-Cost Method (LCM) developed in this project is not optimisation-based. An intention for the method from the start was to allow its user to evaluate and select renovation alternatives tailored to the specific project in hand by using available standard methods and evaluations for renovation.

2.2. APPROACH

The overall approach applied throughout the PhD project is shown in Figure 4. Initially, a structured literature study on existing RAMs was performed to identify gaps in the renovation decision process. As presented in section 1.2 and more detail in section 2.1 in **Paper [2]**, the literature study identified a need for a method that compares alternative renovation options and selects a renovation package with the least cost from the building owners' perspective.

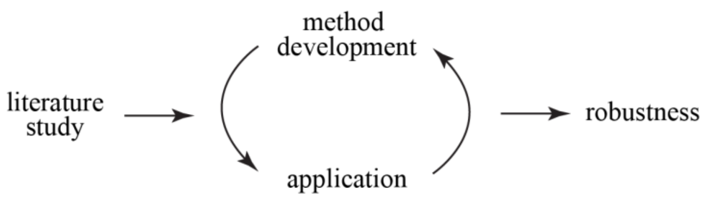


Figure 4 Approach and main aspects in the development of the least-cost method (LCM).

The development of the method was a main activity throughout the PhD period. It consisted of identifying well-known concepts within the practical decision process of what to renovate and to what extend. Following the identification of commonly used criteria (investment cost for renovated parts, energy savings and lifetime of products or parts), a simplified parameter linking those and representing the cost for achieved savings is proposed and applied to a single-family building in **Paper [1]**. Further, the proposed indicator was tested with a higher number of energy-saving renovation actions concerning envelope and system improvements, as well as the integration of mechanical ventilation with heat recovery for a multi-family residential building (**Paper [2]**). In addition, **Paper [3]** tested the parameter on several different energy supply systems and compared it to Net Present Value (NPV). The reliability of the parameter for decision support in selecting which elements to include in a renovation package and the balance between energy savings and renewable energy production was also studied in **Paper [3].**

The application of the method was considered alongside its development in two distinct domains. The first is by applying the method to actual building case studies where iteration back to the development phase is performed after each application. Secondly, the method was integrated into a novel online assessment platform developed alongside the PhD project as part of the RECO2ST project. The integration and practical application of the method within the platform was also the main activity during two external stays abroad in 2019 and 2020, respectively.

Considering that the method targets practitioners and building owners, verifying the robustness of the procedure is deemed essential for the future application of the method. This was performed on two separate occasions and proportions. Firstly, by comparing the proposed economic indicator with NPV and observing any changes in the hierarchy of investigated renovation actions. Secondly, a targeted and structured study investigates uncertainties in renovation-related costs and the resulting variance of the final results. The results from both robustness checks are summarised in Chapter 4, while a complete description of analyses is part of **Paper [4]**.

The LCM aims to identify the least-cost renovation for nZEB. Therefore, it is necessary to specificity the definition and the related costs for different renovation measures. As noted in the introduction, the nZEB definition is country-specific. In Denmark, nZEB is defined by a maximum limit value of primary energy demand. Therefore, it is used as the main evaluation criteria besides cost. For residential buildings, primary energy includes heating, cooling, domestic hot water (DHW) and electricity for the operation of the building. As illustrated in Figure 1, the Danish limit value is the most ambitious of all EU countries.

The costs are also country-specific. The starting point of the method is Danish cost databases. However, the desired flexibility should allow the use of the methods or sources in other countries besides Denmark.

The cost of individual measures is used to test the proposed approach for compiling the least-cost renovation packages. The approach is intended to select renovation measures and renewable producing systems and balance their investment while respecting the nZEB ambition and intended practical application.

3

RESIDENTIAL ASSESSMENT METHOD

This chapter presents the proposed residential assessment method and outlines the main stages in its development. The last section of this chapter presents the case studies used throughout the development of the method.

3.1. DESCRIPTION OF THE LEAST-COST METHOD

The least-cost method (LCM) developed throughout the PhD project is derived from the research presented in **Papers [1–3].** This section summarises the main parts and functions of the LCM and links their development to the respective papers.

A flowchart published in [29] and originating from the comparative EU cost-optimal method [21] inspired the expression of the LCM. The referenced flowchart is shown in Figure 7 and consist of two initial steps before evaluating energy and economic performance separately. The first step defines the reference buildings of the analysis, whereas the second step defines the renovation packages applied to the reference buildings.

The intentions for a flexible and practical application while striving towards nZEB categorisation resulted in the schematic representation shown in Figure 5. This representation guides the user in the activities and analysis necessary to evaluate single renovation actions and combine these in renovation packages.

Figure 5 presents the final version of the LCM as presented in **Paper [3]**. As observed in Figure 5, the method includes three main stages; the first and last stages are compatible with the cost-optimal method in [21]. The project definition stage includes activities related to the definition of the renovation project, including characterisation of the building (energy demand, age, condition, function), energy audit, setting requirements, performance analysis of the existing condition of the building in question. In essence, securing all required data for the energy and economic analysis performed in the next stage of the LCM.

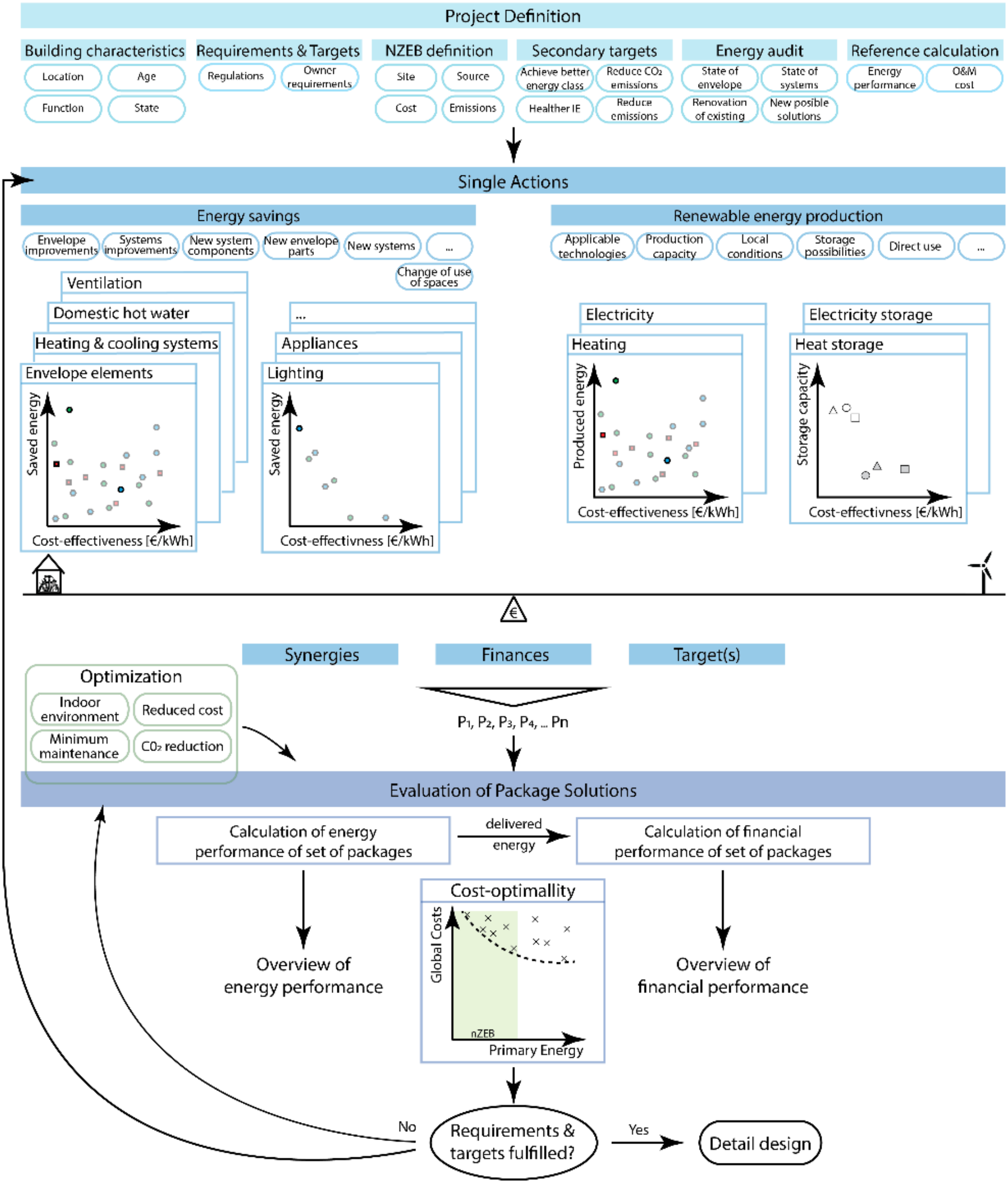


Figure 5 Least-cost renovation assessment method. Source [3].

The second stage of the method accommodates the energy savings and cost analysis for renovation actions deemed relevant to the renovation project. As defined in [2,3], the implementation cost involves all costs required to implement a renovation measure, including the removal and disposal of replaced buildings parts, salaries and equipment rental. Energy savings can be calculated by a context-suited (building type, location, targets) energy analysis tool. For example, Paper [2] illustrated two compliance tools for energy demand calculations, BE18 for the Danish and CECB for the Swiss case study. The cost used in the analysis is obtained from a cost database for the Danish case. In the Swiss case, renovation costs are estimated by a tailored tool for the cost analysis of renovations.

The second stage of the LCM consists of the computation and evaluation of single renovation actions and renewable energy-producing systems. In addition, the second stage of the method combines the single actions into a cost-effective package. The second stage of the LCM has developed through groundwork presented in **Paper [2] and [3].**

Paper [2] focuses on efficiency improvements related to building envelope elements, the distribution system and the addition of mechanical ventilation with heat recovery. The main contribution of **Paper [2]** to the development of the method is the testing of a proposed cost-effectiveness parameter (CEP), essential in the second stage of LCM. The investigation of the applicability of the CEP to renewable energy-producing systems is presented in **Paper [3].** The paper also explores the suitability of CEP as a ranking parameter in selecting the contents of a renovation package.

Moreover, analysis in **Paper [3]** determined the cost-optimality of the investigated individual and package solutions. Balancing investments in energy efficiency and renewable energy production is determined by examining the individual and combined contributions of the systems in the same manner as energy-saving actions – by calculating the CEP with the same units (€/kWh) but for produced instead of saved energy.

The third and last stage of the method is the evaluation of renovation packages, which includes primary energy demand and LCC calculations. Renovation packages are evaluated in a cost-optimality plot as illustrated in Figure 5. The maximum primary energy limit for obtaining nZEB classification is depicted on the plot to identify the packages fitting (or closest to) the limits. At last, if a satisfactory renovation package fulfilling all requirements and targets is found, the detailed design of the renovation can be initiated. Alternatively, in a case where a suitable package is not found, the user can take a step back to optimise the analysed packages (either in terms of cost or project-specific parameters). In addition, if none of the investigated renovation packages come close to the targets, the user can create new packages by revisiting the previous stage of the method.

3.2. PROCESS

To begin with, the method in **Paper [1]** proposed a calculated indicator based on the implementation, cost, lifetime and saved energy of individual renovation actions. The indicator is termed "cost-efficiency" in **Paper [1]** and changed to the cost-effectiveness parameter (CEP) in **Paper [2] and [3]**. Essentially, the CEP represents the relationship between the implementation[1] cost and energy savings during the lifetime of the measure at hand or, in short, the cost of achieved energy savings. Because the focus of **Paper [1]** was an occupant-owned, single-family house, the criteria for selecting a renovation alternative is the total investment cost for the owner. In this early stage of the development process, the methodology consisted of the following three steps:

"1) Select the most cost-efficient option as presented in Table 31 [9]

2) Check the investment cost of the selected technology in Table 32 [9]

3) Compare the cost of the technologies with the available amount of funds in the package."

Paper [1]

Table 31 and Table 32 in reference [9] (c.f. Reference list of **Paper [1]**) contain a list of CEP and total investment cost for all considered solutions in **Paper [1]**, respectively. The CEP is expressed as:

$$\text{“}Annual\ investment\ cost = \frac{Investment\ cost}{Lifetime}\left[\frac{€}{year}\right]$$

$$Cost\ Efficiency = \frac{Investment\ cost\ per\ year}{Saved\ energy}\left[\frac{€}{year}\ per\ saved\ \frac{kWh}{m^2}\ per\ year\right]\text{”}$$

Paper [1]

The concept of applying CEP as a selection criteria for ranking renovation alternatives was expanded in **Paper [2]**, but with few minor adjustments to terminology and representation. As noted above, the term "Cost Efficiency" used in [1] is revised to "Cost-effectiveness". This decision was taken as "effectiveness" represents the parameter better than "efficiency". In addition, the

[1] The cost for all required products, activities and materials to implement a renovation measure, including salaries and machinery.

representation of the unit of the CEP in **Paper [2]** is simplified to show the total energy saving throughout the lifetime of an element or system for the building under consideration by integrating the heated floor area (m^2) and lifetime (years) in the calculation as:

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

Paper [2]

In addition to the adapted terminology and unit of CEP, the method in **Paper [2]** is extended to seven steps for ranking energy renovation actions shown in Figure 6.

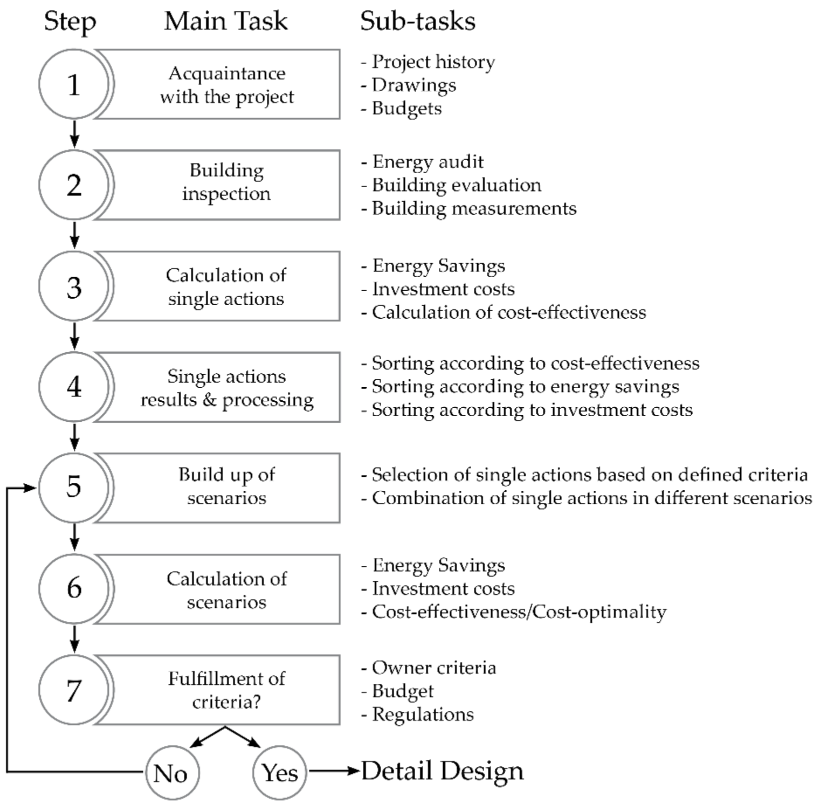


Figure 6: Seven-step methodology and activities associated with each step. Source [2].

The steps and activities depicted in Figure 6 reflect the required practical process for building up renovation scenarios based on CEP. The methodology is applied to two case study buildings in **Paper [2]**, presented in the next section. This is considered a "bottom-up" approach as the project activities and analysis is based on the specific conditions and requirements. As noted at the beginning of Chapter 3, the method was inspired by the comparative framework for calculating cost-optimal minimum energy efficiency demands in the MS of the EU [21]. In particular, the representation of the cost-optimal method is included in [29] and shown in Figure 7.

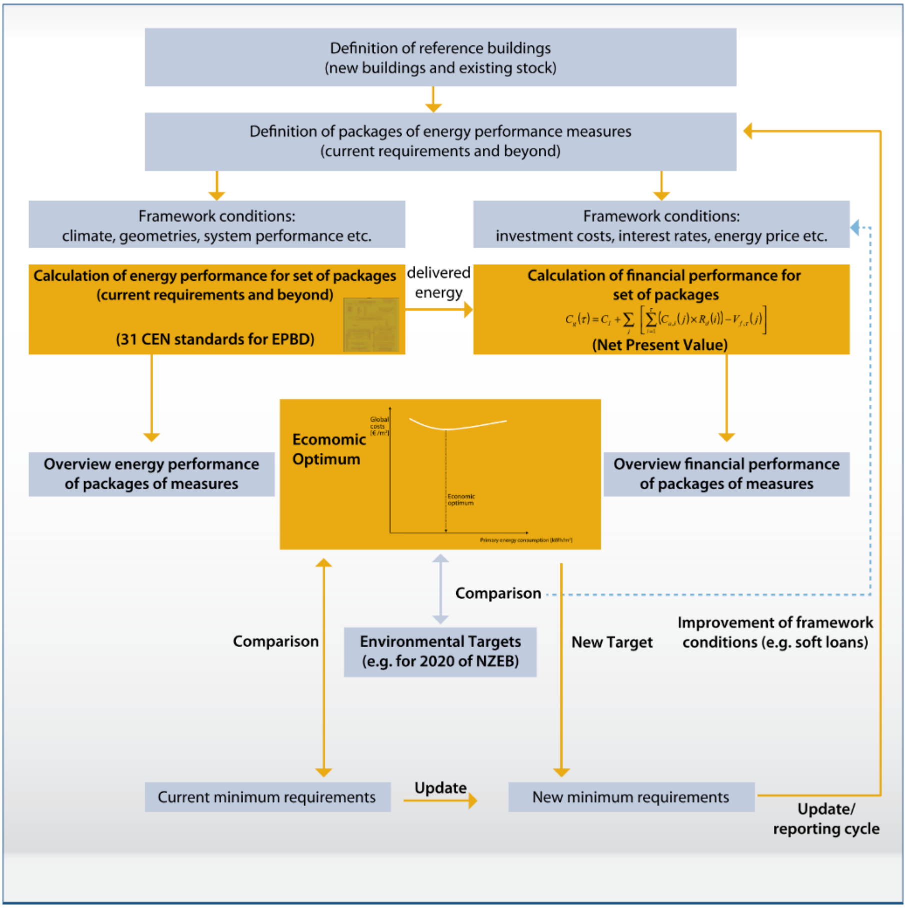


Figure 7 "Comparative methodology – flowchart". Source [29]

The final version of the LCM presented in Figure 5 arose from combining the building-specific approach in Figure 6 and the comparative cost-optimal methodology in Figure 7. The final version of the LCM expanded the flowchart in Figure 7 by including a pre-step for evaluating individual renovation actions, renewable energy systems and the selection of the entities in a renovation package. Furthermore, key aspects and activities in the project definition stage are characterised and structured respecting the target application of the building-specific renovation assessment.

The proposed LCM provides an overview of the renovation process and can serve as a roadmap for communication between the targeted users in the early stages of renovation. Investigations in terms of the method's robustness are described in the next chapter. In addition, Chapter 5 presents the integration of the method in an online assessment platform and lessons learned during application and development.

3.3. CASE STUDIES

Four different case study buildings have been used to exemplify and test the proposed LCM. Each of the case studies is applied at different stages of development and to a different extent. The complete method is applied to one of the four case study buildings; for ease, it is referred to as the "main case study" in this thesis. Sub-section 3.3.1 summarises the results for the main case study obtained after each stage of the LCM. The additional case study buildings and their relation to the LCM are discussed in the individual appended papers.

3.3.1. MAIN CASE STUDY

The main case study is a multi-family apartment complex consisting of two buildings located in Denmark and visualised in Figure 8.

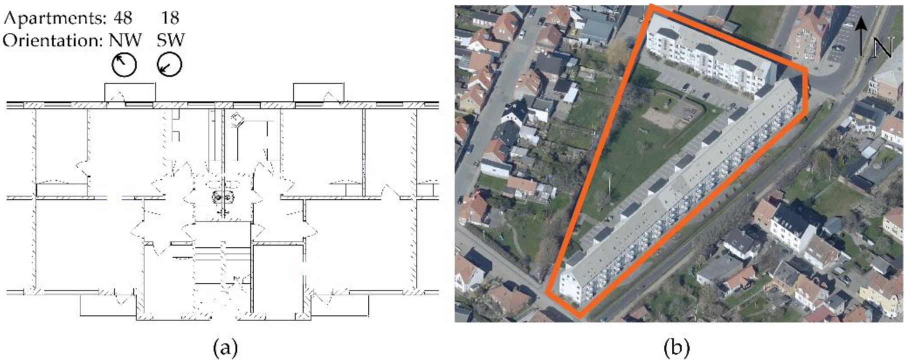


Figure 8: Plan and orientation of the main case study (a); overview of the building complex and its surroundings. Source [2].

The main outcomes and results from the project definition stage are detailed in **Paper [2]**, whereas the results from the energy audit and reference calculations are shown in Figure 9. The figure presents measured energy from metering at the building and the calculated value using the compliance tool BE18. The primary energy demand for the building was found to be 130 kWh/m^2 year and includes energy for heating, cooling, ventilation and electricity for the building's operation. The total electricity (including home appliances) was also investigated to be later compared to the potential energy production by on-site renewable energy systems. Determining the existing energy demand and validating the BE18 reference calculation model concluded the project definition stage of the LCM.

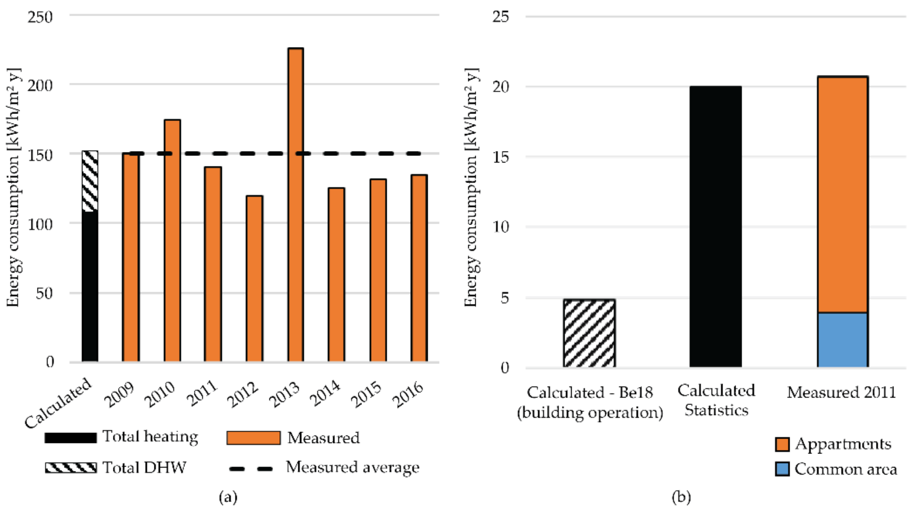


Figure 9 Energy demand for the case study. Comparison of the calculated and measured total energy demand for heating (a) and electricity (b). Source [2].

The main contribution of **Paper [2]** lies in the development of the second stage of the LCM – Evaluation of single actions. The CEP is applied to a broader range of elements and more alternatives for each element are defined. Besides the building envelope, CEP is calculated for mechanical ventilation with heat recovery, re-insulation options of the distribution network for space heating and domestic hot water (DHW), and change of circulation pump for DHW. Results for the CEP of all calculated building parts are shown in Figure 10.

Regarding the third and final stage of the LCM, the analysis in **Paper [2]** considered three exploratory packages (scenarios). The three scenarios consider renovation with the most cost-effective envelope elements, systems and a combination of both. The results for compiling packages on the basis of CEP ranking were promising as the scenario including the most cost-effective element and system reached 51% of primary energy savings where the selected measures were not those providing maximum energy savings.

The evaluation of single renovation actions regarding renewable energy-producing systems was further developed in **Paper [3]** for the same case study building. In order to allow for a direct comparison between actions related to the envelope, system and renewable energy production, the unit of the CEP for all types was kept identical. For energy-saving actions, the unit represents costs per saved energy, whereas for renewable systems, costs per produced energy. While the calculation procedure differs, a comparison between Figure 10 and Figure 11 clearly showed that investments for renewable energy production are much more cost-effective than energy-saving actions [3].

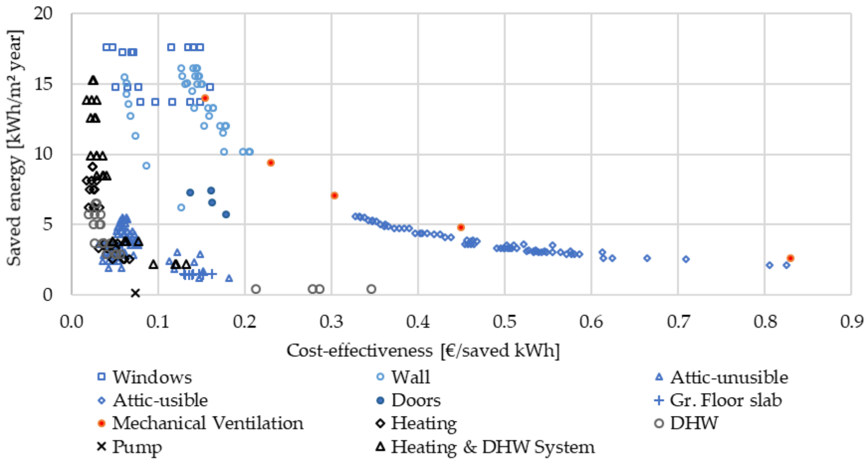


Figure 10 Cost-effectiveness of single renovation actions for the main (Danish) case study. Source [2].

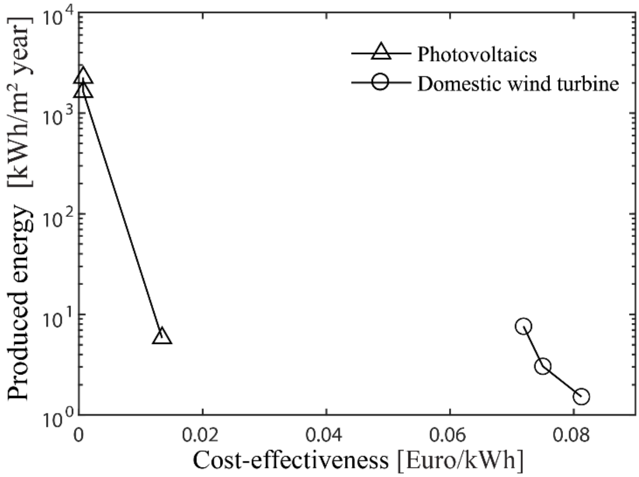


Figure 11 Cost-effectiveness parameter (CEP) of renewable energy-producing systems. Adapted from [3].

This comparison was also checked globally and some of the results are presented in Figure 12. For clarity, Figure 12 depicts only some of the combinations of renovation packages and renewable production. A complete list and explanation of the results is included in **Paper [3]**. Nevertheless, Figure 12 shows six out of the ten compiled packages and their combination with PV and domestic wind turbines of different sizes. The study focused on investigating whether CEP-based package creation (applied for Package 7, marked in black) forms a cost-optimal package. The study concluded that CEP is suitable for determining renovation package contents as Package 7 was identified to obtain the most energy savings for the least cost increase. Because of this, in combination with a 110 kWp PV system, Package 7 was selected for the further analysis conducted in **Paper [4]** and discussed in Chapter 4.

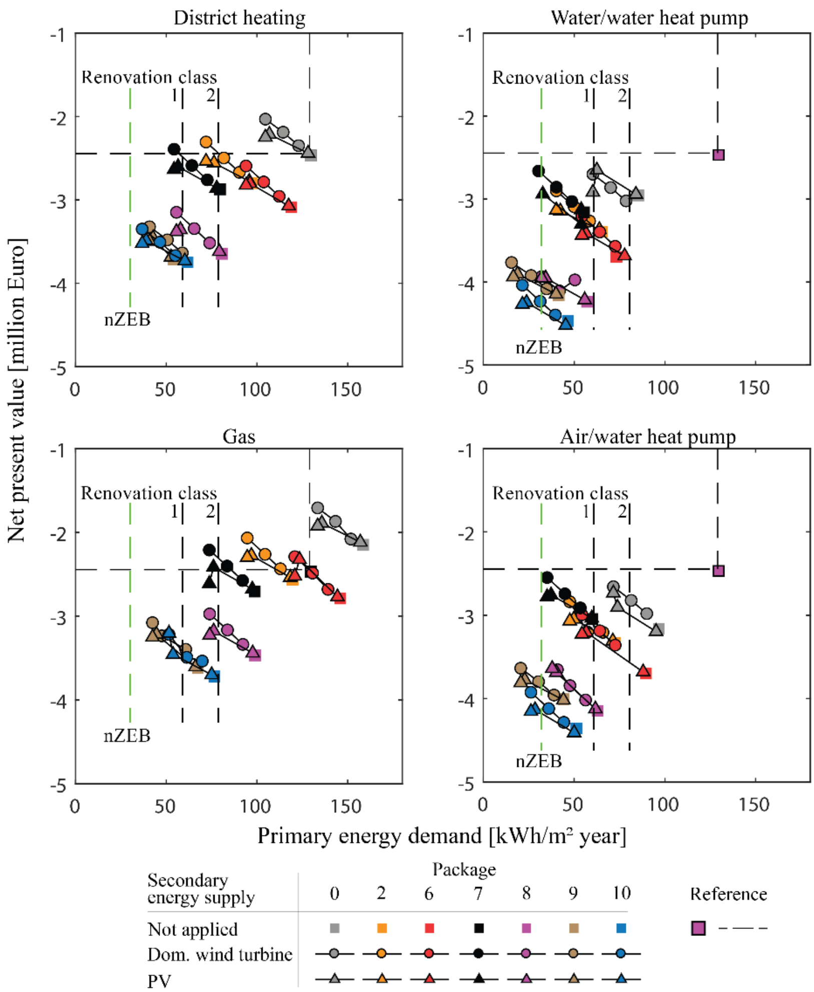


Figure 12 Net present value and primary energy demand of renovation packages and renewable energy-producing (secondary) systems. Combined with four different (main) energy supply systems. Source [3].

4

4. SENSITIVITY AND ROBUSTNESS

For clarity, it is necessary to specify the terms “sensitivity” and “robustness.” In this paper, sensitivity refers to studying how the uncertainty in the output can be allocated to different variations in the model's inputs. On the other hand, robustness is the ability of the least-cost method (LCM) to tolerate disruptions in the inputs whilst providing satisfactory results, leading to the cheapest packages closest to the nearly Zero Energy Building (nZEB) standard.

The LCM is broad, general and combines several individual measurements, analysis and calculation techniques. In principle, each of those parts accommodates a certain level of uncertainty, which may cause changes in the results of the method. To investigate and test the overall robustness of the LCM, two separate studies targeting different parts of the method are performed. At first, a sub-study in **Paper [3]** tested the reliability of the proposed cost-effectiveness parameter (CEP) by comparing this to the net present value-based (NPV-based) ranking for the same energy efficiency measures. Secondly, the sensitivity of the Life Cycle Cost (LCC) inputs and their effect on the outputs is investigated by a study described in **Paper [4]**. Lastly, the robustness of the LCM is evaluated. The respective studies and their findings are summarised in sections 4.1, 4.2 and 4.3, respectively.

4.1. COMPARISON OF THE COST-EFFECTIVE PARAMETER AND NET PRESENT VALUE

As defined in the previous chapter, the CEP represents the cost of achieved energy savings by the different renovation alternatives. The parameter considers the implementation cost (from the building owners’ perspective), lifetime and achieved energy savings of the solution. In contrast, LCC calculations are widely applied to evaluate renovation solutions, consider different calculation inputs and represent global costs over the calculation period. In addition to the lifetime, energy saving and implementation cost for a solution, LCC calculations further integrate forecasted indicators for price developments, interest rates, maintenance and a replacement for the investigated solution.

Considering that **Paper [3]** proposes a compilation of packages based on sorting the solutions according to the CEP, it was decided to compare the relative distribution of renovation actions evaluated by the CEP and the same calculated by LCC. This was carried out to test if the simplified CEP has limitations when comparing renovation actions to the LCC approach with NPV as an output indicator. For this purpose, all single renovation actions in **Paper [2]** are further analysed with LCC and compared in Figure 13. The x-axis on the top graph in Figure 13 depicts the CEP in Danish kroner per kWh saved, while the bottom depicts results for NPV in millions of Euro for a 50-year calculation period.

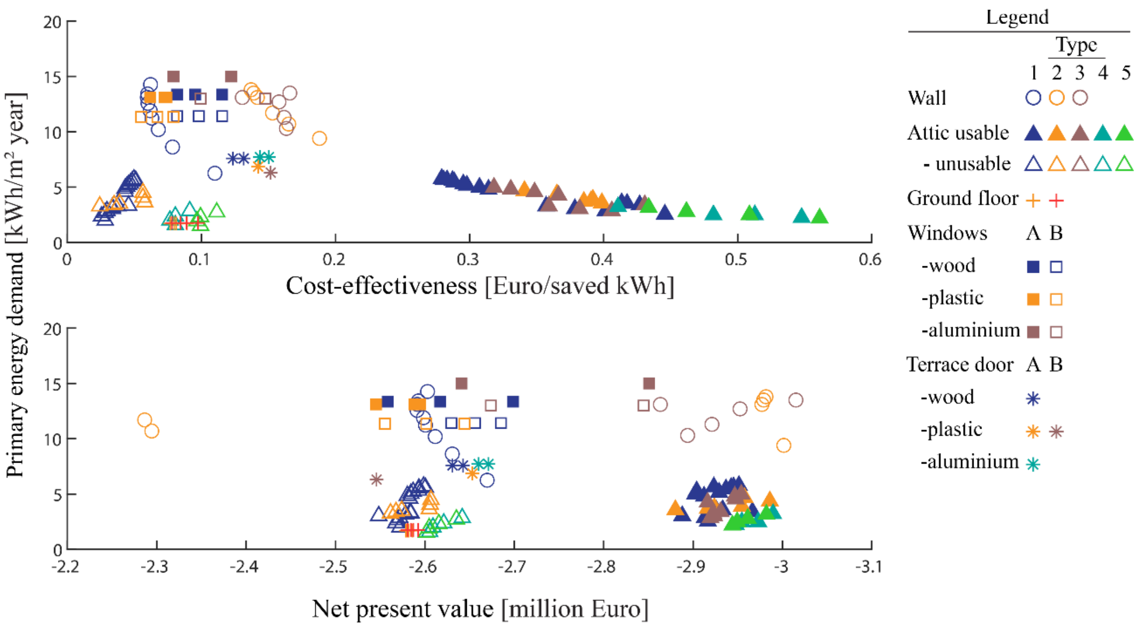


Figure 13 Comparison between the cost-effectiveness parameter (CEP) and Net Present Value (NPV). Adapted from [3].

The relative positioning between the solutions in the two cases (the CEP and NPV) is evaluated to indicate the applicability of the CEP for the compilation of the lowest cost packages. It is important to note that the comparison should not be made on the absolute values of the CEP and NPV due to the difference in their units. Instead, the relative positioning of the different renovation solutions is analysed [3]. Overall, Figure 13 shows more similarities than differences when comparing the relative position of renovation measures with the CEP (top) and NPV (bottom) in Figure 13.

Paper [3] concluded that most of the solutions in Figure 13 retain the same positioning, regardless of the parameter used. The main differences exist for two of the external wall solutions and one of the attic solutions. Despite the differences between the CEP and NPV (discussed in more depth in Paper [3]), the consistent positioning of most investigated solutions led to the conclusion that the CEP is a suitable evaluation criteria for renovation actions. This was also confirmed as the renovation package composed by individual soring of actions on a CEP-basis turned out to be in the cost-optimal Pareto front [3].

4.2. SENSITIVITY OF LCC INPUTS

Sensitivity analyses are performed for the third stage of the LCM - evaluation of package solutions. As described previously, renovation packages are evaluated based on the primary energy demand and the LCC. Both energy and LCC calculations employ several input parameters to derive the desired output. In the proposed LCM, the outputs are the energy demand (primary and final) and NPV. The input parameters for the mathematical models deriving the sought outputs are characterised with uncertainties, which can lead to considerable changes in the result. As pointed out in **Paper [4]**, the study is limited to the sensitivity of LCC parameters.

Paper [4] explores the relationship between input-related uncertainties and their effect on the output through one-at-a-time (OAT) and Monte Carlo (MC) parameter variation methods. The approach used for the analysis is illustrated in Figure 14, while the overview of the baseline models, applied analysis and key results are presented further in this and the next section.

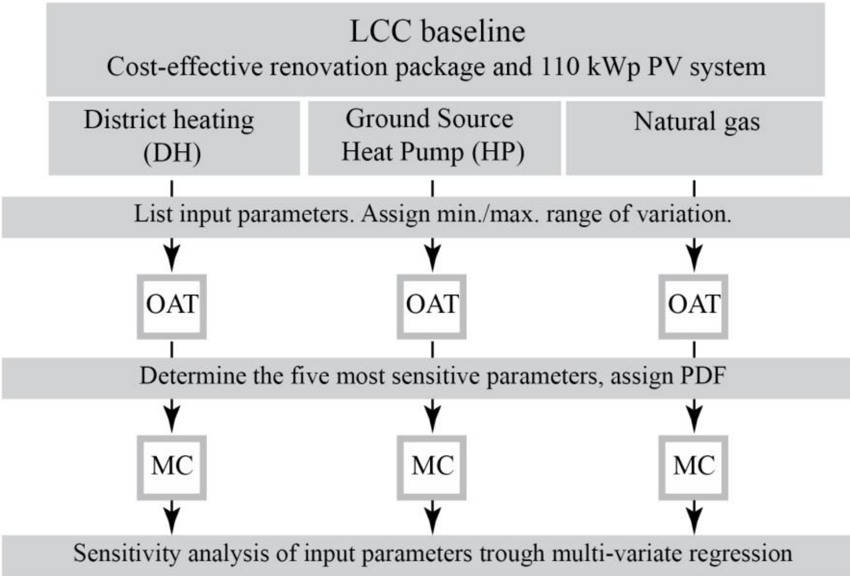


Figure 14 Conceptual illustration of the sensitivity study of LCC calculations. Source [4].

For the purpose of the study, the most cost-effective package (7) identified in **Paper [3]** is selected as a baseline for the analysis. The baseline consists of the following building-related elements:

- A roof-mounted Photovoltaic (PV) system with a 110 kWp capacity
- External wall insulation and cladding
- New windows
- Attic insulation
- Re-insulating pipe distribution network for space heating and domestic hot water (DHW)
- Change of DHW circulation pump

As indicated in Figure 14, the baseline is analysed in combination with three different building systems for the supply of heating and DHW. Those are:

- District heating sub-station (DH)
- Condensing gas boiler
- Ground-source Heat Pump (HP)

All cases consider the energy demand for space heating and DHW for the complete building found through the compliance tool BE18. Electricity demand is also considered for the complete building. Electricity demand for the operation of the building is derived from BE18. Private consumption (for the apartments) is determined during the energy audit described in **Paper [2]** (Figure 9, page 24). The energy demand for the building is dependent on the system under consideration. For example, with HP as a supply system, only electricity is present as an energy source. In contrast, baseline models with DH and gas contain two energy sources - electricity and DH or electricity and gas.

LCC calculations are performed using the calculation tool LCCByg. Each of the previously listed parameters bears building-related and system-related model inputs defining the unit cost, amount, lifetime, maintenance and replacement cost. The input attributed to the energy supply is the quantity and unit cost of the energy source; however, a specific price development can be applied; which is discussed and investigated in greater detail in **Paper [4]**. As noted in Figure 14, a list of all input parameters for the three baseline models is compiled and possible variations of each input are defined. Then, all model inputs are variated with a maximum and minim value using the OAT method. A sensitivity index is then calculated for each parameter according to the difference between the output values obtained from the minimum and maximum variation. The sensitivity index determines the individual (local) impact each parameter has on the output and ranks the parameters in ascending order. The ranking allowed the most influential parameters to be determined. The five most sensitive inputs further variated by the MC method are listed in Table 2. Before the computation of the MC method, Paper [4] looks at the available sources and reasons for the applied distribution functions and variation of each input.

Table 2 Five most sensitive parameters determined by OAT variation.

	Rank according to the OAT-based sensitivity index.				
Model	1	2	3	4	5
District heating	unit cost electricity	unit cost attic insulation	unit cost roof PV	amount attic insulation	unit cost new windows
Heat pump	lifetime heat pump	unit cost electricity	unit cost attic insulation	amount attic insulation	unit cost roof PV
Gas	unit cost natural gas	unit cost electricity	unit cost attic insulation	amount attic insulation	unit cost roof PV

The most sensitive inputs identified in Table 2 are further variated together using the MC method, with sampling based on the quasi-random Sobol method. Varying all parameters together allowed a determination of how sensitive the output (NPV) is to the applied variations and identify the combined or interactive (global) effects of the variated inputs. The relationship between the output and inputs is quantified by applying a multivariate regression and sensitivity analysis of the resulting Standardised Regression Coefficient (SRC). The SCR method applied in **Paper [4]** determines the sensitivity and the relative importance of the five parameters (for each energy supply system) based on the results from the multivariate regression. Moreover, the R^2 value is used to indicate the linearity of the model. Table 3 summarises the results for the three variated models, while the complete regression results for each model are included in Appendix A in **Paper [4]**.

Table 3 shows the global sensitivity for all parameters variated by the MC method. The sensitivity index is calculated from the derived regression coefficient (also noted in Table 3) by dividing each coefficient by the absolute sum of all five coefficients for each model. The first four variables in Table 3 are variated in all three models with different supply systems, while variables 5, 6 and 7 are included only in the DH, gas and HP scenarios, respectively.

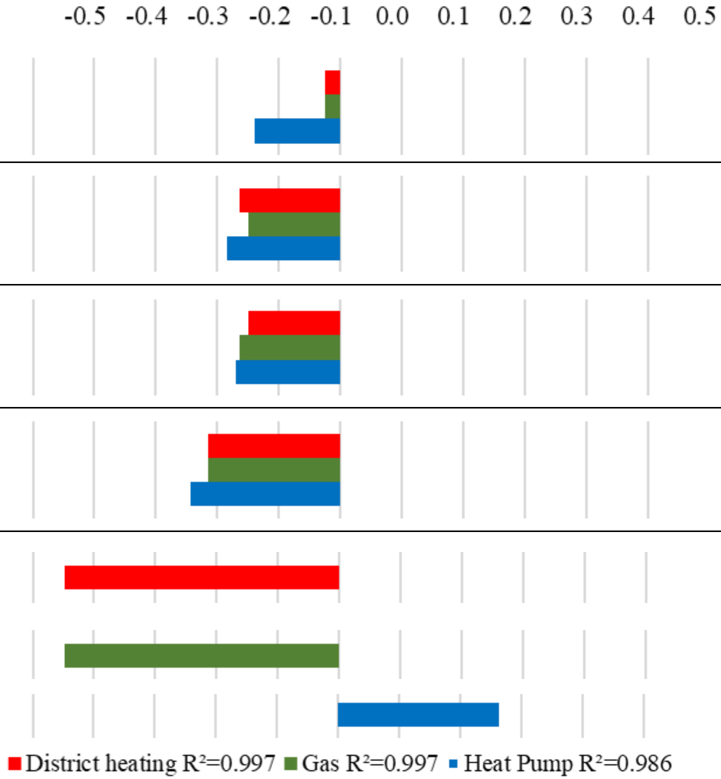
The results show that SRC for all variables (except the lifetime of HP) are negative. Since the LCC models consider expenses and disregard positive cash flow, the resulting output (NPV) is negative. A negative SRC means an increased variable value lowers the output (the solution becomes "more costly"). This is an expected result as an increase in the unit cost should result in greater global costs overall. The positive sign of the regression coefficient of HP's lifetime is also expected as the high value of the parameter (longer lifetime) results in increased NPV ("cheaper" solution) due to fewer replacements of the heat pump over the calculation period.

When looking at Table 3, it can be noted that the output for the respective system types is most sensitive to parameters 5, 6 and 7. At the same time, the unit cost of electricity is the least sensitive regardless of the supply system. The amount of attic insulation is the second most sensitive in all cases. The price of attic insulation is superior to roof-mounted PV for the case gas boiler as a heating supply system. Interestingly, the order of importance derived by an OAT analysis is not consistent with the order from the MC variation in Table 3. This is partially caused by the different ranges and distributions types. However, it may also indicate the effects of the interaction of the input variables on the output.

Paper [4] further applied the variations obtained by the MC method to determine the robustness of the LCM, discussed in Section 4.3.

Table 3 Summary of linear regression results for the three investigated space and DHW heating systems. Source [4]

Nr.	Variable	Sensitivity	Standardised Regression Coefficient (SRC)		
			DH	GAS	HP
1	Electricity unit cost		-0.029	-0.067	-0.303
2	Attic insulation unit cost		-0.299	-0.447	-0.400
3	PV unit cost		-0.237	-0.408	-0.366
4	Attic insulation amount		-0.393	-0.588	-0.526
5	**Model DH:** New windows unit cost		-0.823		
6	**Model: Gas** Gas unit cost			-1.229	
7	**Model Gas:** Lifetime of HP				0.57



4.3. ROBUSTNESS OF THE LEAST-COST METHOD

As specified previously, the term “robustness” refers to the method's ability to tolerate disruption in the inputs whilst providing satisfactory results, leading to the cheapest packages closest to nZEB. Namely, the robustness check is performed to evaluate the confidence of the LCC calculation model and thereby the ranking of renovation packages. The investigation is performed by representing the results from the MC method with a box plot, showing the range of variation and comparing it to the positioning for the global cost of other investigated packages.

Figure 15 shows the resulting distribution of variated data from **Paper [4]** as a boxplot and compares it to other renovation packages from **Paper [3]** for the cases with DH, gas and HP. The median value of the resulting NPV is depicted with a horizontal line in the middle of the box plot. The box limits represent the first and third quartile for the results, while the whiskers denote the minimum and maximum data point, excluding outliers. The outliers are included as dots along with the box plot.

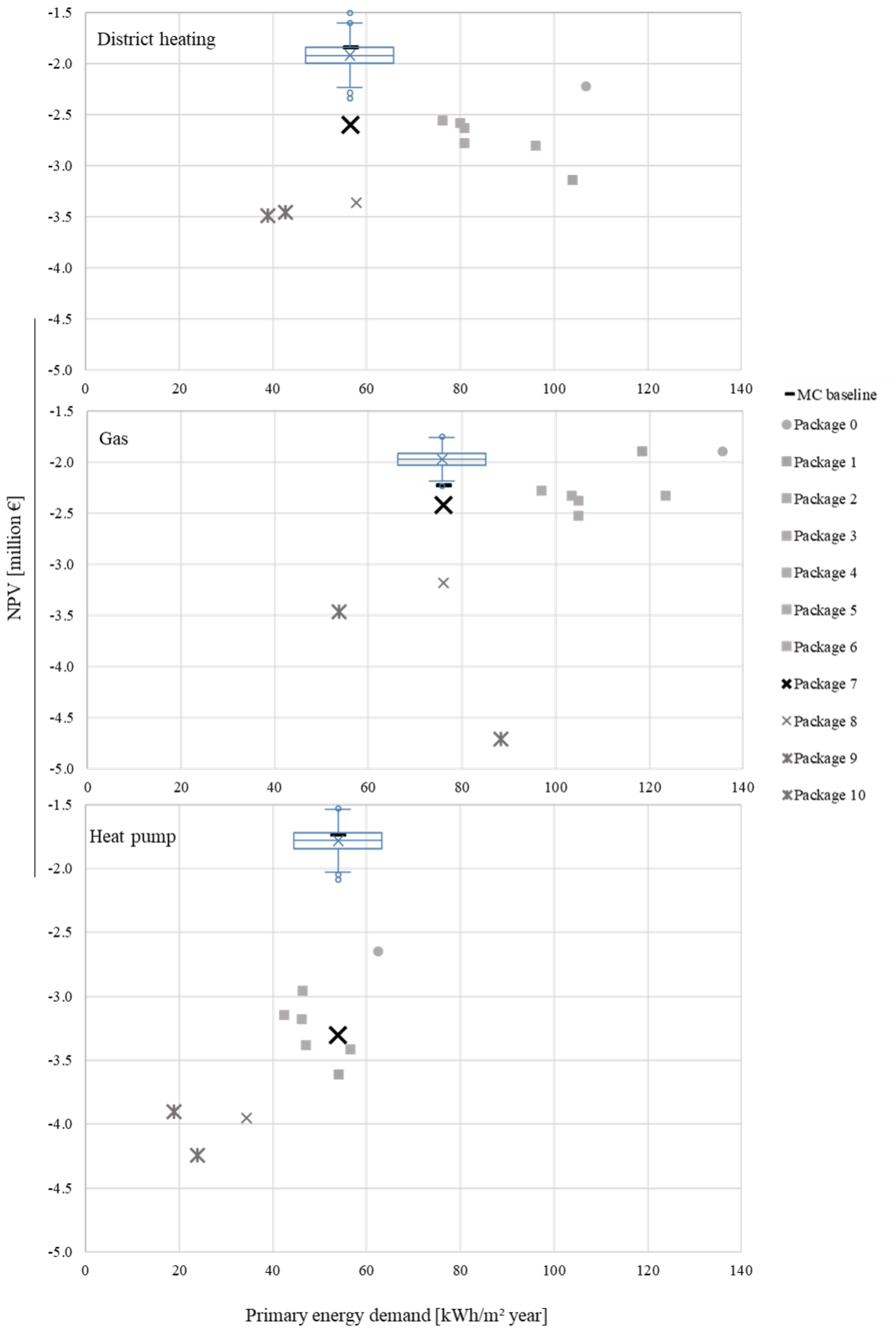


Figure 15 Cost robustness of the least-cost method.

Comparing the three box plots for DH, gas and HP in Figure 15, it can be noted that the scenario with gas has the smallest variance spread, while DH has the greatest. A more significant difference is noticed between the median NPVs for the analysed baseline in **Paper [4]** and the NPV results for package 7 in **Paper [3]**. In theory, two values should be the same as the mathematical models are identical. As pointed out in **Paper [4]**, the considerable difference stems from lowered discount factors that are to be used in LCC calculations. The analysis in **Paper [3]** adapted regulatory values imposed by the Danish Ministry of Finance from 2018, while for the analysis in **Paper [4]**, the financial assumptions for the calculation were lowered in 2021. The lowered discount factors result in a higher ("cheaper") NPV, which was also the intent of the updated financial assumptions [4,30]. As noticeable from Figure 15, The HP scenario exhibits the most considerable cost reduction due to updated financial assumptions, followed by district heating and gas. This result aligns with drivers and expectations of [30] for a lower LCC of more capital-intensive solutions such as HP. In addition, the results are also in agreement with a sensitivity study on the financial assumptions of renovation-related LCC calculations [31].

Overall, the results in Figure 15 for all three energy supply systems suggest that the method is quite robust. This declaration is based on the cost ranges determined by the box plots and the relative positioning to the cost of other renovation packages. Suppose the difference caused by politically-controlled financial assumptions is corrected. In this case, the variation range of Package 7 defined by a whisker falls within the cost range of less energy ambitious renovation packages (Package 1-6 of **Paper [3]**). Moreover, the uncertainty defined by the box plots does not overlap with the cost of more expensive energy renovation packages (Package 8, 9 and 10).

That means that even in the case of a faulty LCC calculation assumption for one or more input parameters, the order of the packages in respect to cost would be conserved. While this is true for the observations from Figure 15 for the baseline (Package 7), further analysis should determine the validity in cases with more ambitious renovation packages as they typically contain a higher number of individual actions. Thus, there is a chance that the uncertainty of packages with higher energy saving potential would be greater than packages with lower energy savings. More ambitious renovation packages typically include more individual solutions, thereby a higher chance for an additive interaction between the actions and faulty or uncertain input values in the calculation models.

5

APPLICATION OF THE METHOD IN A REFURBISHMENT ASSESSMENT PLATFORM

This chapter provides a condensed outline of the achieved integration of the least-cost method (LCM) into an online renovation assessment platform developed through the RECO2ST project.

5.1. INTEGRATION OF THE METHOD IN THE PLATFORM

The platform[2] was developed as part of the EU Horizon 2020 research project RECO2ST by various project partners contributing to different stages of the development. The idea of the platform is to allow the combination of outputs from software tools used for the assessment of one or another topic within renovation. Currently, the platform accommodates direct import from the cost-analysis tool EPIQR+, energy-savings tool PEIK and total energy balance tool LESOSAI. Data import to the platform is realised by a JSON file extension; thereby, any software capable of providing this can utilise the platform. The platform's functionality and application are presented in **Paper [5]** and outlined in the following sub-section.

The platform and LCM were developed in parallel; thereby, the platform structure reflects the method. The platform consists of three main sections (pages) relates to the three stages in the LCM.

The platform's home page is shown in Figure 16 and includes few sections for navigation, editing and data input of the building in question. The main navigational banner is located on the left-hand side of the home page. The user can go back and forth between the different levels of the analysis (building, actions or scenarios) and create customised reports. The homepage relates to

[2] https://epistimmo.com/#/

the LCM's Project Definition stage as it allows define the project building(s) its existing energy demand.

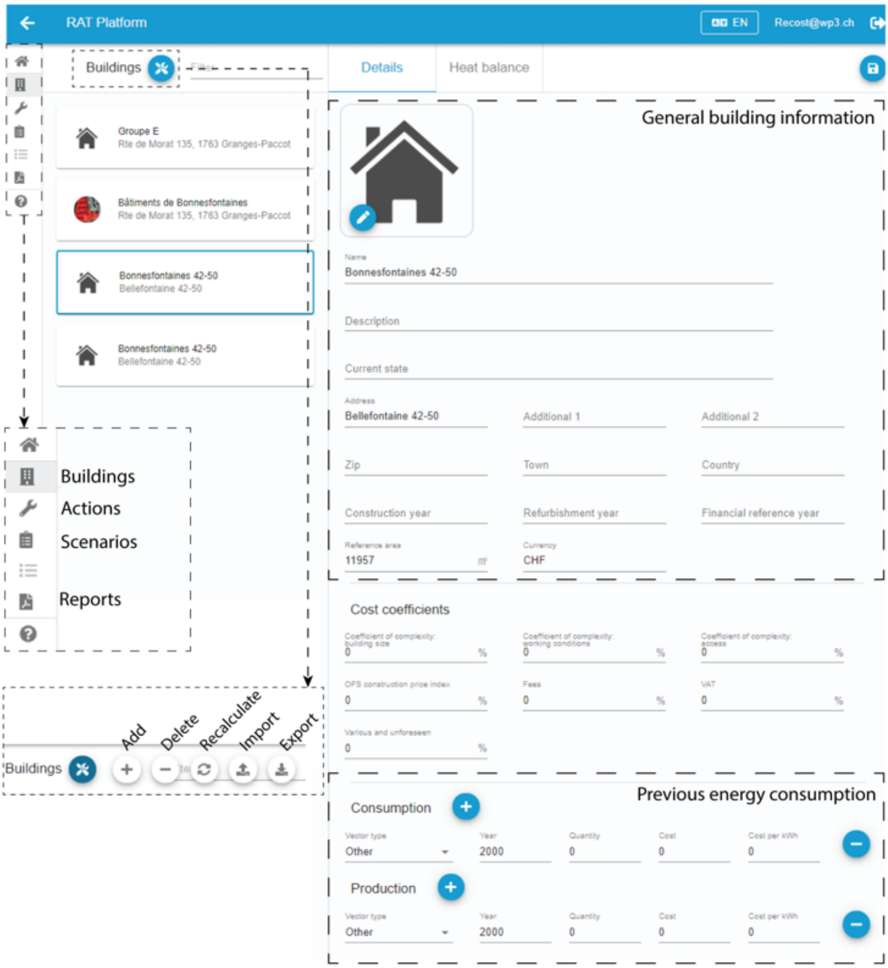


Figure 16: Home page of the refurbishment assessment platform, developed through the RECO2ST project. Source [5].

The "Buildings" toolbar located on the top left corner of the home page serves to add, remove, edit existing buildings and import or export building data. The "Recalculate" button is applied to calculate an indicator for every renovation action defined in the platform, inspired by the cost-effectiveness parameter (CEP) and discussed ahead. As depicted in Figure 16, the right-hand side of the page consists of generic building information and specifying the type of energy and existing consumption.

Figure 17 shows the page for defining the considered renovation "Actions", which reflects the second stage of the LCM. Input fields accommodate general description, technology-related and energy-saving inputs. Technology-related (action-related) related fields include the total investment cost, type, priority and payback of the renovation action. In addition, environmental indicators such as CO_2, Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP) fossil can be specified. The latter are directly imported when cost-analysis is carried out using EPQR+ [5]. In the current version of the platform, total cost, energy savings, and GWP can be applied as sorting criteria for compiling renovation scenarios.

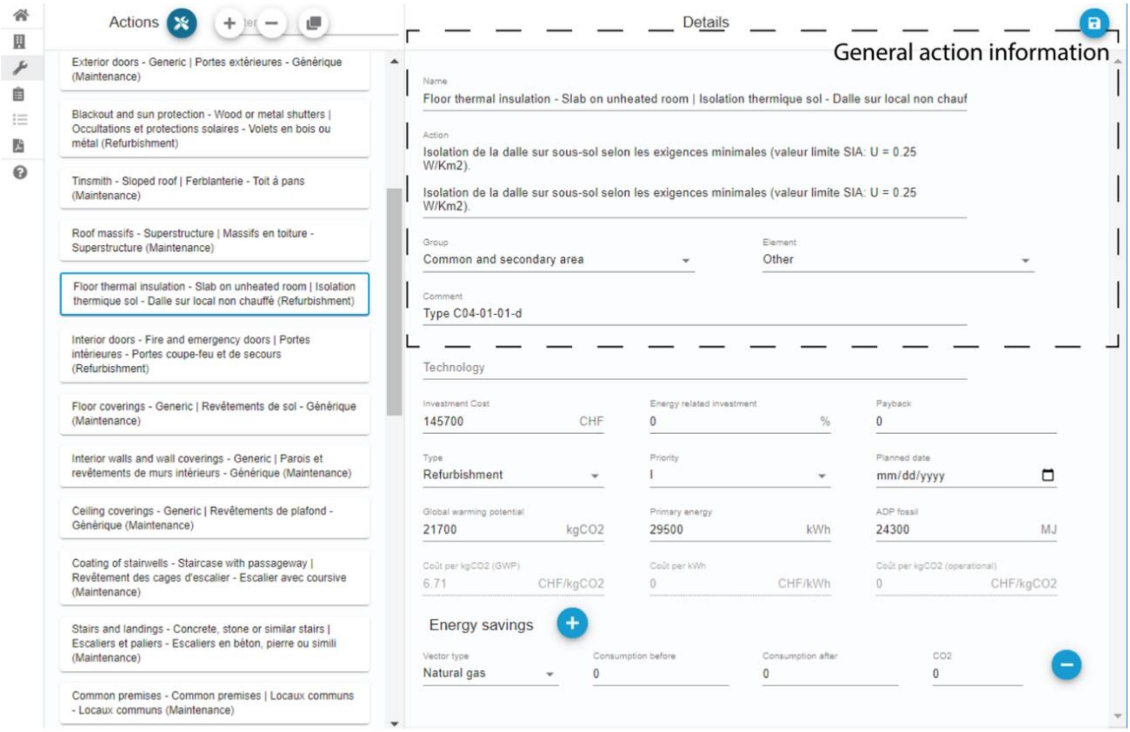


Figure 17: "Actions" page for the refurbishment assessment platform, developed through the RECO2ST project. Source [5].

The page dedicated to the compilation and evaluation of renovation scenarios (packages) in the platform is sown in Figure 18. The-right hand side lists all created scenarios by name, total cost, energy savings and GWP. The scenario (package) contents are selected from a list of all actions available on the right-hand side of the page. The list is interactive and can be arranged by type (energy-related and non-energy related actions), group (envelope, systems) or specific building elements or systems (wall, roofs, windows).

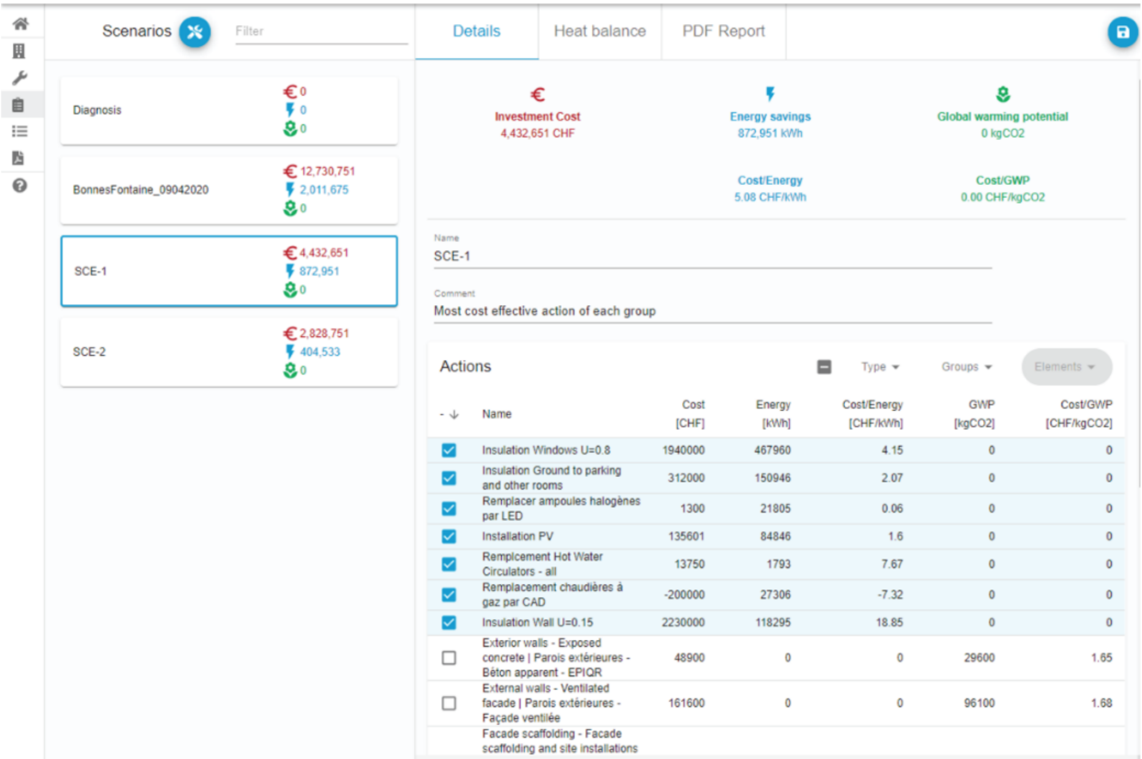


Figure 18: “Scenarios” page in the refurbishment assessment platform, developed through the RECO2ST project. Source [5].

The platform does not consider the lifetime and thus it simplifies the CEP indicator to “Cost/Energy” and “Cost/GWP”. The simplified indicators sown in Figure 18, are generated for every defined renovation action. The indicators are included in the current stage of the platform to test its ability to calculate simple indicators by inputs from different tools and rank actions based on the results.

As discussed in **Paper [5]**, the activities on the platform are limited to the compilation and evaluation of scenarios (packages) based on the contribution of single actions - the second stage of the LCM. At this stage, the platform does not cover LCC and the primary energy demand (global-for the whole package/scenario). Despite this limitation, the platform allows the comparison of single and package renovation solutions and for combining, handling and storing data from different tools [5].

Since the platform and LCM were developed alongside, they have many indirect similarities. For instance, the process in the platform follows the first two stages and evaluates single renovation actions separately. While the method surpasses the platform with regards to the evaluation of the LCC and global energy demand of packages, the platform provides additional criteria in the environmental domain. Moreover, the platform is still under development, and current works focus on applying LCC for the investigated solutions.

5.2. LESSONS LEARNED

Throughout the process of developing and applying the LC, several insights were obtained. The most significant lessons learned during the process are pointed out in this sub-section.

One of the essential lessons is the differences between the practical and theoretical (academic) approach applied to select the renovation strategy. The literature review found various methods for determining an "optimal" renovation package, most of which apply a combination of economic, environmental and social selection criteria. In practice, however, efforts are focused on more straightforward approaches that are usually concerned with the investment cost of renovation. Moreover, practitioners tend to focus on optimising the selection process for "what to renovate" by reducing the required time for auditing and analysing the existing condition and energy use. Also, in practice, there is a strong focus on applying well-known (lean) techniques and tools for arriving at a renovation proposal (for the client).

Another tendency found in literature is that a large share of renovation assessment methods apply a LCC analysis when considering economic evaluation criteria. However, owners of multi-family apartment buildings are yet to familiarise themselves with and understand the benefits of the life cycle approach. During the PhD project, this was confirmed on a number of occasions when conversing with practising engineers, representatives of real estate consortiums and social housing associations[3]. However, as discussed in **Paper [4]**, LCC is soon to be mandatory in Denmark. Thus, one of the main focus areas in [4] was to shed light on the most influential LCC input parameters, determine their impact and possible interactions.

Renovation is a vast research area and therefore, many tools, guides, roadmaps and methods exist to support the renovation process. The sheer number of available aids can be overwhelming. Moreover, combining and bookkeeping the relevant results from different tools is a rather hefty task. In this regard, the RECO2ST platform showed promising first tests and results.

[3] As part of discussions during RECO2ST project meetings and guest stays in consulting engineering companies in Switzerland.

6

CONCLUSION

This PhD project was motivated by reducing the gap between the required and actual rate of deep renovations. The research was centred on proposing a flexible and practical-oriented method to assist professional building owners, renovation experts and practitioners in assessing and selecting renovation strategies for residential buildings. The proposed framework is designed to stimulate the target audience in finding cost-effective renovation packages leading to nearly Zero Energy Building (nZEB) classification. The structure of the method allows tailoring the renovation assessment to specific building projects. It provides a roadmap for performing practical-oriented tasks and activities while respecting national or regional regulations and European trends in renovation assessment.

Conclusions on the PhD project are provided for each research objective, defined at the beginning of the project. The following sub-section revisits the ambitions stated in Section 1.3 and provides a concise conclusion on the outcomes related to each goal

6.1. REVISITING THE RESEARCH OBJECTIVES

1. *Investigate the essence and scope of existing RAMs. Identify if any of these methods have established frameworks for cost-balance between energy renovation measures and investments in renewable energy.*

A targeted literature review identified many methodologies for the assessment of renovation. The majority of the methods integrate energy demand and cost calculations for the selection of a cost-optimal renovation package. Moreover, methods identifying cost-optimal solutions relied heavily on Life Cycle Cost (LCC) calculations, which are yet to become common practice in Europe. Despite the wide range of methods, the literature review determined a need for a structured approach that evaluates contributions from individual renovation actions and a systematic selection of the contents of a renovation package.

> 2. *Propose flexible assessment methodology for the least-cost renovation of existing residential buildings to nZEB; targeted to practitioners, renovation experts, professional building owners and builders.*

This PhD project proposed a method that considers national nZEB regulations and practical-oriented tasks and considerations from the start. The main contributions of the method are the least-cost approach for the selection of the contents of a renovation package. The approach takes a preliminary step to LCC calculations based on a proposed cost-effectiveness parameter (CEP). The CEP accommodates an individual assessment of energy-saving and energy-producing actions before building a renovation package. The motivation for the CEP was to appeal to renovation consultants, building owners and practitioners by inhering terms and parameters that are well-known to the target audience, like implementation costs, energy savings and a lifetime of studied entities.

The overall flexibility of the proposed method relates to two areas. Firstly, the method does not oblige specific tools for determining assessment criteria or specific nZEB requirements. Instead, a generic framework for arriving at a final renovation solution, satisfying nZEB, is proposed. The user is free to apply preferred tools and methods for determining the necessary indicators. The second main flexibility feature relates to the application of the method in the developed assessment platform. Since both were developed in parallel, the platform follows the principles in the proposed method. Furthermore, it provides the user with opportunities to:

- Combine results from different assessment tools.
- Obtain an interactive list of renovation actions and associated evaluation criteria.
- Select preferred ranking criteria for single actions. For instance, total cost or energy savings; cost-, CO_2- or LCA-effectiveness.
- Create and compare renovation packages quickly and interactively.

> 3. *Test the robustness of the method and obtain a better understanding of the relationship between input and output parameters of LCC calculations.*

At first, the application of CEP is validated by comparing it to NPV results for single actions. The comparison showed that CEP-based and NPV-based rankings are nearly the same for the majority of elements.

The robustness of the method's results is assessed by performing a sensitivity analysis of the mathematical LCC model. The sensitivity study provided an insight into the relationships between an LCC model's output and input parameters. A regression applied to the sensitivity results revealed a linear relationship between building-related inputs and the output. Moreover, the obtained results quantified the output's range of expected fluctuation caused by uncertainties of the inputs. The results showed that even with extreme fluctuation in the input, a renovation package based on CEP would maintain its relative ranking compared to more investment-heavy packages.

The application of the least-cost method to different buildings with contrasting targets yield promising results. However, future work should focus on applying the proposed method to additional buildings for further validation. Further work is also required in the application of the refurbishment platform to case studies in practice. While the scope of the method in this PhD project was limited to two parameters, cost and energy savings and trials of combining CEP with other environmental or social evaluation criteria would expand the method and provide a more holistic renovation assessment

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APPENDED PAPERS

Paper 1: "Development of energy renovation packages for the Danish residential sector."

Paper 2: "Methodology for Evaluation and Development of Refurbishment Scenarios for Multi-Story Apartment Buildings, Applied to Two Buildings in Denmark and Switzerland "

Paper 3: "Novel Methodology toward Nearly Zero Energy Building (NZEB) Renovation: Cost-Effective Balance Approach as a Pre-Step to Cost-Optimal Life Cycle Cost Assessment."

Paper 4: "Investigations of building-related LCC sensitivity of a cost-effective renovation package by one-at-a-time and Monte Carlo variation methods."

Paper 5: "Methodology and platform for NZEB renovation of residential buildings "

PAPER #1

Development of energy renovation packages for the Danish residential sector.

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Development of energy renovation packages for the Danish residential sector

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Abstract

The work presented in this paper is developed as a part of the Horizon 2020 EU project REFURB. The number of deep energy retrofits is falling behind the EU ambitious targets. The REFURB project aims at finding technical and nontechnical solutions that match the demand and supply side of the residential building renovation market. Due to the multiple significant differences at the national level, compelling offers are developed specifically for each country participant. This paper elaborates only on the Danish approach. The Danish approach to create compelling offers for pre-selected homeowner target groups is based on (I) selection of dwelling segment with high impact and energy saving potential, (II) sequenced approach in creating renovation package solutions, (III) compelling offer to be proposed with specific timing. This paper focuses mainly on the second listed component, namely, development of the renovation package solutions. The paper only briefly highlights the selection of dwelling segment and does not present the creation of compelling offer due to the length of the paper. Initially, developed renovation packages are optimized purely focusing on the least-cost optimal, theoretical, energy savings. As a result, very rational packages were developed that were not met with acceptance from the building sector stakeholders. After several surveys and meetings with renovation market stakeholders such as building owners, energy renovation contractors, financial institutions, and energy consultants, the initial renovation packages were redefined in order to take account for factors such as securing investment in the renovated real estate, comfort, architectural aesthetic, and "low hanging fruit" energy saving solutions. Finally, ten different customized renovation packages were developed ranging between up to 7.500 and 62.000 € and bringing theoretical primary energy savings between 30 and up to 80%.

Selection and peer-review under responsibility of the scientific committee of the 10th International Conference on Applied Energy (ICAE2018).

Keywords: energy renovation; energy conservation; renovation packages; compelling offer

1. Introduction

The European Commission has set strict targets in relation to CO2 and energy reduction by 2020, 2030 and 2050 [1]. The upcoming goal for 2020 with which member states must comply is to reach 20% reduction of CO2 compared to levels in 1990. The building sector is responsible for 36% of the total CO2 emissions in the European Union, which mainly comes from the existing building stock [2]. Because of that, the European Union is more and more interested in stimulating the renovation of existing buildings so they comply with current standards for energy use and efficiency. On the local level, some member states offer financial incentives to homeowners to renovate their home. Similarly larger cross-border projects as REFURB [3] aim to find a more holistic approach to support and encourage the renovation of selected building types.

As indicated in [4] energy saving in the majority of the cases is not the key factor that drives building owners to renovate their building. The motivation to execute renovation is much more complex and includes several aspects such as improvement of indoor comfort, and family economy to secure investment, esthetics, energy savings, simple urge to replace old and worn element with the new one, and single events such as new child in the family or children moving out from their family home.

What is more, majority of the homeowners wish to receive a renovation that, to some extent, is tailored to their specific wishes. On the other hand, they lack or have just limited overview of the sequence and scope of necessary renovation tasks to gain synergy in the entire renovation project. Home owners often experience the renovation process as very turbulent with many unexpected events, more costly than initially assumed and lacking quality assurance. This combined with a blurry expectation of the outcome with respect to return on investment, property value, and improved comfort lead many to drop their projects.

Solving barriers and deciding on what the best case is for the available investments is a challenge both for homeowners themselves, but also for the industry. Recent studies made by [5] suggest that adopting a tailored package renovation approach provides greater possibilities for reaching deep renovation, especially when separate technical solutions are in good synergy. The more and deeper renovations are reached, the greater the reduction of CO2 and energy within the building sector.

New business models specifically developed for renovation including renovation packages are also emerging throughout northern Europe [6]. In the study by [6], assessment of such business models concluded that even though the business potential is big, it is still hard to run companies sustainably, based on such business model. According to the authors this is due to the barriers such as trustworthiness between customer and company, policy instruments for the initial phases of the process, greater support for renovations that strive for complete building solutions versus single component solutions, etc.

This paper presents the methodology to develop renovation packages for a single-family house built in the 1960-1976 period. It should be kept in mind that the presented packages are specifically tailored to the need of the selected case building; although these are a good representation of what can be expected from similar buildings from the same period. Moreover, methodology can be extruded to other building topologies.

A REFURB renovation package is defined in [7] as:

1) An easy-to-understand commercial offer to an end-user, written in non-technical language, which satisfies his/her requirements for comfortable living but at a higher energy-efficiency of his/her dwelling.

2) An offer comprising the optimum combination of solutions/technologies to be installed in the most logical sequence, tailored to the type of dwelling, the state of the building, the geography in which the dwelling is located, and socio-economic parameters.

3) An offer that unburdens the end-user, so he/she is assured of an agreed higher energy efficiency without worrying about individual technology choices.

2. Methodology

2.1. Selection of dwelling segment

In the project each participating country has selected one or more dwelling segments representing a large share of the building stock with significant energy saving potential. In Denmark, single-family houses constructed in the period 1960-1976 are selected. These houses represent approximately 25% of the residential sector in Denmark [8]. They have typically energy label ranging from G – for houses that were not energy modernized since their erection – and up to energy label C – for houses with some improvements undertaken. These buildings are often well located in the cities and are presently at the age when the first major renovation is likely to be required. Comparing to the present building legislation and compliances, these buildings perform rather poorly with regard to energy use and indoor climate. In the Danish scenario, two dweller types with high potential for energy renovation were identified: empty nesters (EN) and young families (YF). ENs are older couples whose children have recently moved out. This opens up for new possibilities for rearranging and energy renovating the home. Second target group is YF who just bought their first house and got children. They want to renovate/rearrange the old house to the new family needs and standards. They would often seek for better indoor environment.

2.2. Sequence approach – renovation package development

The renovation packages are addressed to homeowners that might have very different professional background, thus they should be made available, usable, and understandable to all targeted homeowners. Therefore, they should be presented in a non-technical manner and still include technical methodology and knowledge behind them [7].

The process of development of renovation packages was initially very rational and focused only on documentable energy saving criteria. Cost efficiency calculations are made with the purpose of sorting the proposed renovations and solutions in respect to investment cost, lifetime, and theoretical energy saving that could be documented through energy compliance calculation. The sorting was used to choose which technical solutions are going to be included in the packages and in which order. The priority was given to technologies with high cost efficiency, see Table 31 in [9]. The initial aim was to develop five packages with value starting from 25,000 € (shallow renovation up to 40% energy saving) up to 135,000 € (deep renovation up to 80% energy savings). To achieve synergies in the renovation, the cost optimum methodology is applied alongside engineering considerations related to construction processes. For example, if the external wall is insulated, then the insulation of the foundation and change of windows is prioritized as activities would be happening in the same area of the building.

The method for selection of a renovation package is as follows:

1) Select the most cost-efficient option as presented in Table 31 [9]

2) Check the investment cost of the selected technology in Table 32 [9]

3) Compare the cost of the technologies with the available amount of funds in the package.

Investment cost of each solution proposed is elaborated in detail in [9]. The calculation is performed for the typical case house constructed in 1973 that is presented in detail in [9]. Fig. 1 presents the amount of energy saved by implementing each of the considered technical solutions. For the current calculation, lifetime of the considered technologies are taken from [10] Annex 6. Cost of proposed technical solutions is calculated using Danish Molio price database for renovation projects.

Cost efficiency is calculated by (1) and (2). Fig. 1 presents the example results from the calculation for all technologies and for the case house.

$$Annual\ investment\ cost = \frac{Investment\ cost}{Lifetime} \left[\frac{€}{year}\right] \quad (1)$$

$$Cost\ Efficiency = \frac{Investment\ cost\ per\ year}{Saved\ energy} \left[\frac{€}{year} per\ saved\ \frac{kWh}{m^2}\ per\ year\right] \quad (2)$$

Fig. 1 shows the saved energy obtained by each 'one-at-a-time' renovation as a function of its cost efficiency. As seen in Fig. 1, some of the renovated elements have more than one cost. This is the result of the different technical solutions provided for the same energy improvement but with different costs.

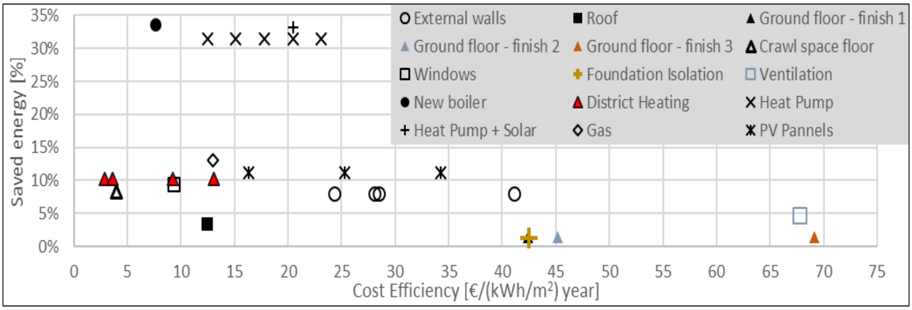

Fig. 1. Saved energy of each technology as a function of cost efficiency.

From this point on, there are few possible outcomes depending on the available funds and investment cost of the technology. Those are as follows:

1) If the cost of the technology is lower than the available funds in the package, new iteration to select additional technology can begin (as described above).

2) If the cost of the technology is equal or ± 15 % of the available funds for the representative package, the package is fulfilled and formation of the next package can begin.

3) If the cost of the technology is greater than the available funds of the package, the next most cost-effective technology is chosen and its investment cost is compared to the available funds in the package. This is done as some of the technologies may have low cost efficiency, but also low investment cost.

The initial renovation packages were subjected to a number of discussions between the Danish partners in the project. Furthermore, a stakeholder meeting with the renovation/construction industry representatives was held in order to receive feedback regarding the different renovation concepts. The following bullet points summarize these feedbacks:

• Even though gas boilers are not "green", these were included in the packages or stages when district heating (DH) was not an option. This is done on the basis that a gas boiler can be considered a transition solution for the period until 2050, and then exchanged with more sustainable option. Furthermore it was yet unknown if and to what extent the biogas would replace gas.

• Heat pump is proposed for those without DH connection and with sufficient budget for this expanse.

• At that stage, there was no distinction made between houses with and without the possibility to connect to DH. It was assumed that house has its own source of heat, e.g. boiler.

• Healthy indoor climate was listed as important parameter highly valued especially by YFs. Therefore, mechanical ventilation is prioritized higher than some more cost-effective measures.

In the consequent revision rounds several more issues were identified. These are listed below:

• Very promising low-hanging fruit solutions; for example, changing lighting to LED. Installation of radiator thermostats were omitted at the beginning since they are either not included in the compliance calculation or they require specific knowledge of the house. Supply side stakeholders indicated that those low-hanging fruits are first to be welcomed by the building owners due to low complexity of the job and relatively low cost. These low-hanging fruits are included in the final packages, presented in 3. Results.

• Despite the uncertainty of the price for different DH locations, it is integrated as a technical solution for renovation. As DH in Denmark is considered a green solution with primary energy factors lower than 1, it would be considered as one of the first steps in the renovation process. Given that in suburban areas DH network is not available, but in urban areas it usually is, there are two scenarios developed, one with and one without DH.

• Windows were moved up on the list of priorities. This decision was made as windows are fairly easy to replace. Moreover, they contribute not only to energy reduction, but also to better comfort and to architectural value of the building, significantly increasing the value of the house.

• Gas boiler was not included as a heat source possibility even though it is still allowed to install one. The reason for that is that Denmark is presently in the transition period towards free fossil energy generation and gas boiler would be only a temporary solution. Instead, a heat pump was proposed.

• Insulation of the external wall (except case with cavity wall insulation) was removed from the packages. The insulation of the external wall to nZEB level would be very costly due to the fact that in many cases requires demolition of existing external façade and its replacement with the new highly insulating solution. Although quite positive from an energy saving point of view, this activity was considered drastic and, therefore, could cause many house owners to drop their renovation plans.

• Including house owners in the renovation "journey" became one of the key identified aspects to an increased number of energy renovation projects. The financial factor is recognized as one of the major barriers to start energy renovation. Therefore, the price of the first renovation package is decreased to 7,500 € for a house without DH connection option and to 12,500 € for a house with DH connection option.

Creation of renovation packages in total included five major revisions. The presented conclusions were implemented afterwards in the final version of the renovation packages.

3. Results

This section presents the final 10 renovation packages (5 for DH connected and 5 for buildings without DH). Those were developed taking into account listed in previous chapter issues. Fig. 3 presents the final packages.

	Comfort	Arch. value	Pack. 1	Pack. 2	Pack. 3	Pack. 4	Pack. 5
LED light			✓	✓	✓	✓	A la carte
Pipe insulation			✓	✓	✓	✓	
New circulation pump			✓	✓	✓	✓	
Radiator thermostats	↑		✓	✓	✓	✓	
District heating connection			✓	✓	✓	✓	
Roof insulation			✓	✓	✓	✓	
Wall cavity insulation	↑		✓	✓	✓	✓	
New windows	↑	↑		✓	✓	✓	
Mechanical Ventilation	↑			✓	✓	✓	
Floor above crawl basement insulation	↑			✓	✓	✓	
Heat pump with integrated storage					✓	✓	
Floor on the ground insulation	↑	↑			✓	✓	
18 m² PV cells						✓	
Smart heating control system	↑					✓	
Energy saving no district heating (up to)			15%	30%	70%	80%	
Energy saving with district heating (up to)			40%	45%	50%	70%	

Fig. 3 Final, renovation packages – with and without DH.

4. Discussion

Fig. 3 presents renovation packages with their recommended technical solutions towards nZEB. The content of the renovation packages is developed gradually, creating so called renovation steps. The package approach is expected to appeal more to YFs who would rather execute renovation and move in as fast as possible. The step approach is expected to appeal better to ENs who have more time and would rather gain trust in the process and gradually observe consequences of their choices.

As seen in Fig. 3, the energy saving potential for the proposed packages ranges between 15 % for the smallest package and up to 80% for the large package. What is more, for a house with DH connection the potential theoretical savings seem much more promising for the first two packages than in the case where the house has no option for DH connection. This is because the connection to DH is not too expensive and there is budget for that action starting from the smallest packages. Furthermore, energy saving refers to primary energy use, and in the Danish context DH is rewarded with primary energy factor of 0.8. The situation changes for packages three and four as soon as there is budget to install a heat pump in the house without possibility of DH connection. A heat pump due to its competitive coefficient of performance (COP) is a feasible alternative to old boilers, which are used in the calculation as a reference. However, installation of a heat pump is costly and, therefore, is not recommended in the first packages. Moreover, installation of the heat pump is recommended first after completion of energy improvements to the house envelope. A decreased required energy for heating automatically results in savings related to purchase and installation of the smaller heat pump.

5. Conclusions

This section presents focal conclusions drawn throughout the process of developing the renovation packages:

1) Securing the renovation journey for the house owner is the key factor to decrease number of dropouts. It is believed that transparent process based on package solution is the right manner to communicate renovation scope and objectives. Packages, however, must be presented in nontechnical manner that is understandable to the majority of house owners.

2) Energy saving is not sufficient motivation for people to renovate. Rational scientific/economic approach oriented on energy savings has a low success rate since people base their decisions on other aspects such as comfort, securing healthy environment for the family, real estate value assurance, and architectural aesthetics.

3) Developed packages support the renovation process and should be considered as tools to gain the house owner's interest and awareness regarding energy renovation. However, they do not provide final tailored solutions. This paper presents methodology rather than ready solutions. These solutions should still be specified for a particular business model and with the assistance of an energy consultant.

4) Indoor climate has become a strong driver for energy retrofit in Denmark, and it is expected that in upcoming years it might be the key important driver for energy retrofit in buildings.

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PAPER #2

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

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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.

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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 CO2 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, CO2 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 (CO2)

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], CO2 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 CO2 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 SOC	ECO	ENV	Renovation Level
[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 evaluationof 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 CO2 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.

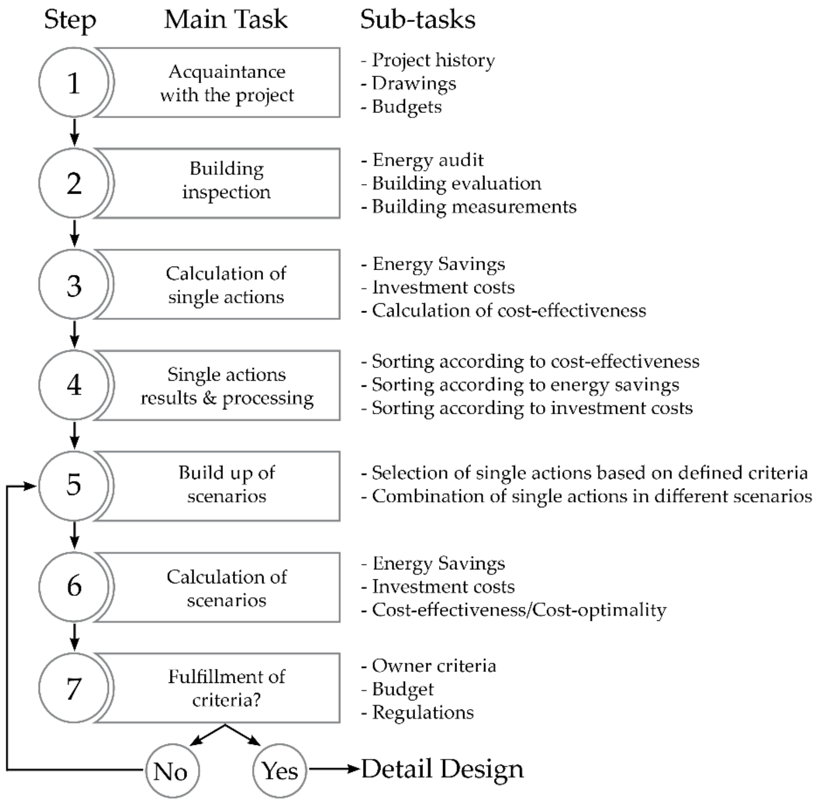

Figure 1. Methodology steps and main activities associated with each step.

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 oftenconsidered. 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).

$$\boldsymbol{Cost-effectiveness}\ \left[\frac{€}{\boldsymbol{saved\ kWh}}\right] = \frac{\boldsymbol{Annual\ investment}\ [€/\boldsymbol{y}]}{\boldsymbol{Saved\ energy}\ [\boldsymbol{kWh}/\boldsymbol{y}]} \quad (1)$$

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.

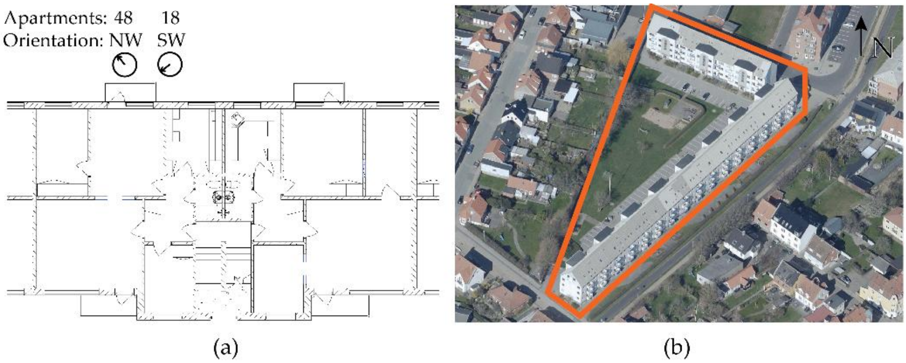

Figure 2. (a) Plan and orientation of the Danish case study building complex; and (b) overview of the building complex and its surroundings.

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.

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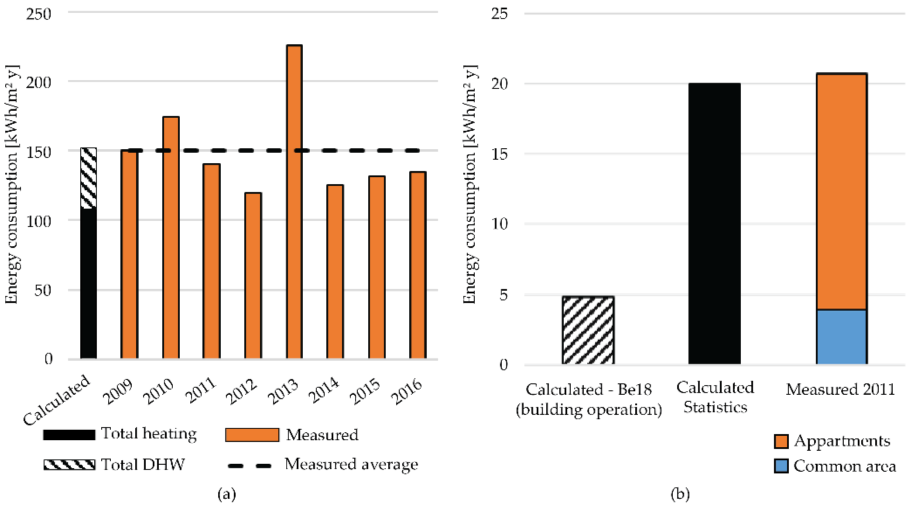

Figure 3. Energy demand of the Danish case study. Comparison of total calculated and measured: heating (a); and electricity (b).

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.

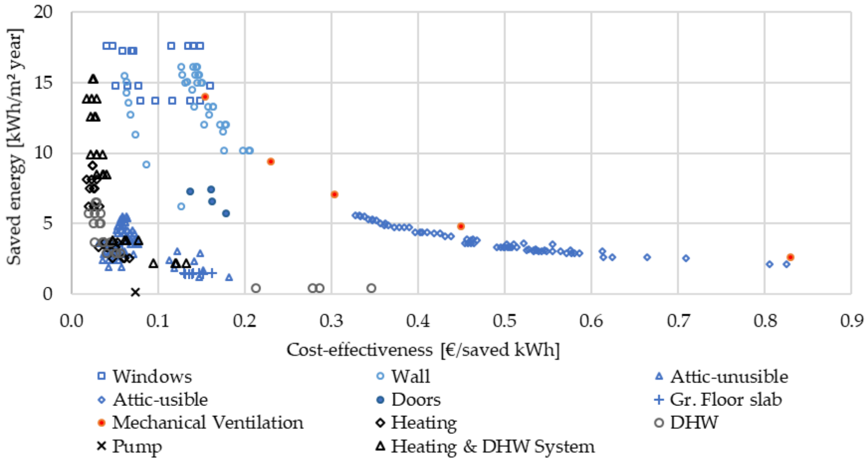

Figure 4. Cost-effectiveness of single renovation actions investigated for the Danish case study building.

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.

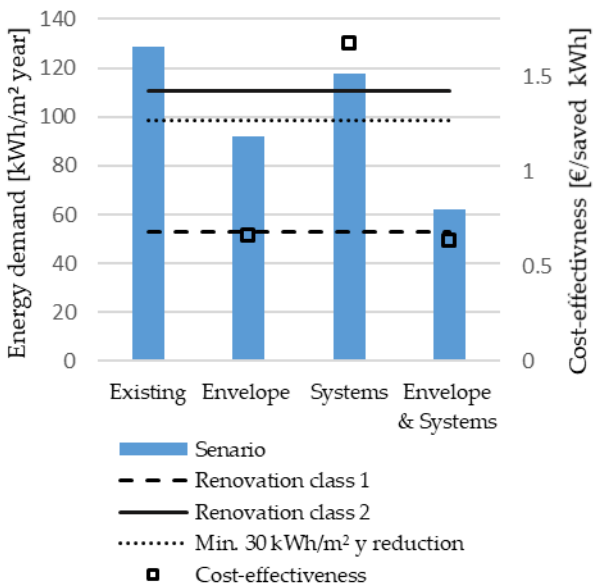

Figure 5. Results of primary energy demand for existing state and applied global renovation packages. Global cost-effectiveness values (right y-axis) and limits for renovation classes according to Danish building regulations 2018 (horizontal lines).

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.

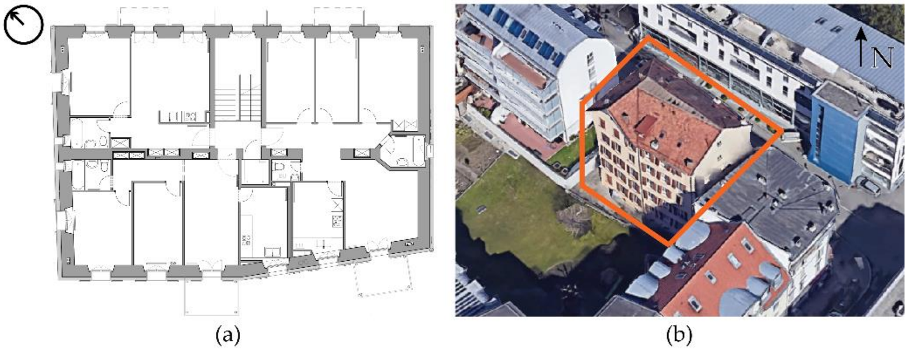

Figure 6. (a) Plan and orientation of the Swiss case study building; and (b) overview of the building and its surroundings.

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 labelling 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.

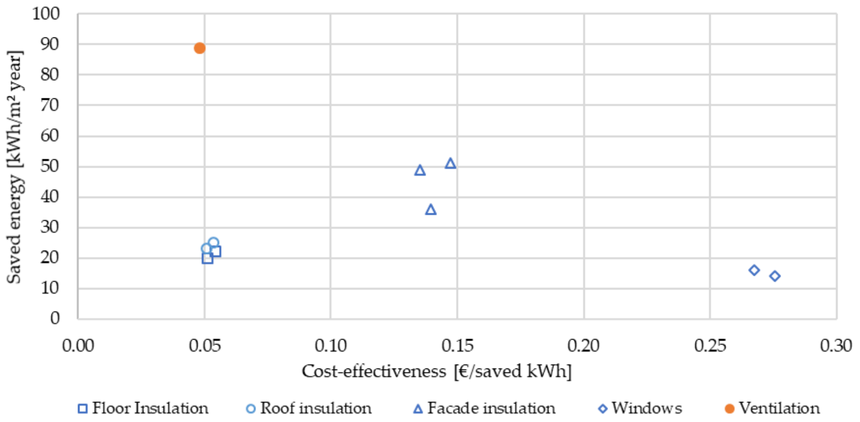

Figure 7. Cost-effectiveness of single renovation actions investigated for the Swiss case study building.

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 m3/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.

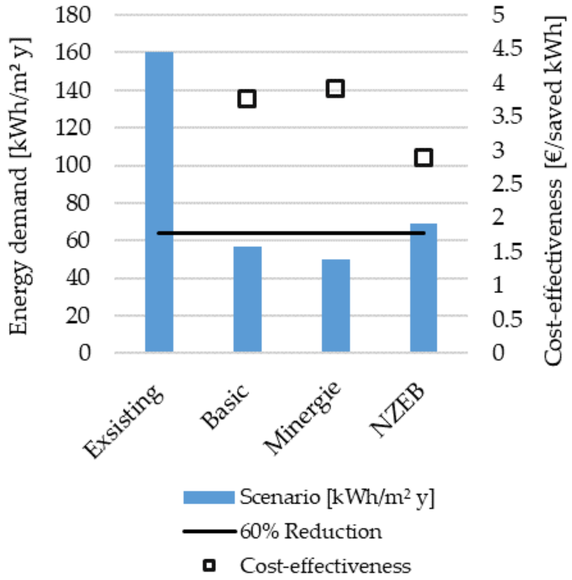

Figure 8. Results of primary energy demand for existing state and applied global renovation packages. Global cost-effectiveness values (right y-axis) and target limit for the renovation (horizontal line).

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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PAPER #3

Novel Methodology toward Nearly Zero Energy Building (NZEB) Renovation: Cost-Effective Balance Approach as a Pre-Step to Cost-Optimal Life Cycle Cost Assessment.

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Featured Application: The proposed method can be applied to a specific building renovation project for evaluating and selecting energy efficiency and renewable energy production measures, with the aim of reaching the NZEB standard

Abstract: Reaching environmental targets set by the European Union (EU) requires a constant renovation of the existing building stock to nearly Zero Energy Buildings (NZEB) in a cost-optimal manner. Studies show that the renovation rate of the existing building stock is more than two times less than what is necessary to reach the targets. Furthermore, the majority of performed renovations across the EU reach just a small amount of energy savings, whereas NZEB renovations are rarely achieved. This paper proposes a methodology for the evaluation of renovation measures, aiming to provide decision support related to the selection of what to renovate and to what extent. The proposed method is rooted in the well-established cost-optimal methodology, yet it suggests a pre-step to package evaluation. This is done by means of a simplified cost-effective parameter (CEP), linking cost, lifetime, and energy savings. The methodology is demonstrated using a case study building in Denmark. The results show that the CEP provides good grounds for the compilation of single actions to packages. Further developments could focus on the sensitivity of the model inputs and integration of additional evaluation parameters to cost, such as environmental, architectural, comfort, risk, etc.

Keywords: NZEB renovation; cost-effective renovation; assessment method; energy efficiency cost; renewable energy cost; residential renovation

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1. Introduction

On a global scale, buildings are responsible for more than one-third of the final energy and global CO2 emissions, and 55% of the total electricity consumption [1]. The 2030 Climate and Energy Ambition of the European Union (EU) establishes a target of 55%emissions reduction by 2030 compared to 1990 [2]. The building sector is pointed out as having the largest potential for cost-efficient reduction of emissions [2]. An explanation for that can be contributed to the large share of aging and inefficient buildings. It has been reported that residential buildings in the EU account for about 75% of the total building stock, where more than half were built prior to 1960 [3]. It has been estimated that reaching the environmental targets requires 3% of the building stock to be renovated annually [4]. While it is rather complex to measure, study [5] reports annual rates for renovation in the period 2012–2016 to be just 0.2% for deep renovations (above 60% energy use reduction) and 1.1% for medium renovations (between 30 and 60% energy use reduction).

To accelerate the process and ensure an increase in renovation rate and depth, the EU Commission has published a renovation wave communication [6]. The objective of the communication is to at least double the annual rate of energy renovation in the EU by 2030 and accelerate deep energy renovations. A number of initiatives are established to speed up the progress and boost the renovation sector across all levels. Communication [6] underlines the need for long-term renovation strategies on a national level to convert existing buildings to nearly Zero Energy Buildings (NZEB).

The recast Energy Performance for Buildings Directive (EPBD) defines NZEB as a building with low energy demand that is mainly covered by renewables [7]. The EPBD recast establishes NZEB as a standard for all new public buildings from 2020. The definition remains the same in the latter published Directive 2018/844 [4], which has a strong focus on renovation of existing buildings. While the overall definition is established on the EU level by the aforementioned directives, Member States have the responsibility of defining and implementing national definitions [8]. Reports show that only a few Member States have generated policies for stimulating cost-effective NZEB renovation [9].

Quite extensive research has been carried out in the area of NZEB renovation [10,11]. As the renovation field is quite vast, multiple aspects related to NZEB have been investi-gated. Definitions and indicators have been reported for specific countries [12] or building types [13–16]. Studies have also focused on the evaluation of specific solutions for building parts to reach NZEB standard. Aparicio-Gonzalez et al. [17] presents a rooftop extension as a solution; Assimakopoulos et al. [18] analyze the addition of sun spaces, or rooms to the exterior wall, while variations of facade additions are studied in [19–21]. In addition to solutions for reaching NZEB, studies have also investigated the gap of expected and achieved energy performance [22]. Possible financial discrepancies that can be caused by occupant behavior are studied in [23], while study [24] investigates the investment gap between cost-optimal and NZEB solutions by macroeconomic scenarios.

Hamid et al. [11] conducted an extensive literature review of 234 studies, concerning the renovation of multi-family buildings in temperate climate. The authors found that the most occurring strategies for residential renovation consider energy efficiency, whereas other represented topics, such as economic, environmental, architectural, comfort, or risk are also applied to a different extent and depth. The large share of methodologies involving energy and economic factors is partially caused by the well-established cost-optimal approach, incorporating Life Cycle Cost (LCC) calculations. The cost-optimal method was proposed by the EU Commission for the evaluation of minimum energy requirements on the national level [25] and further developed throughout Annex 56 on the building level [15,26,27]. The method has been applied in varying scope across different building types, e.g., schools [28], dwellings [29–31], or combination of building types covering a given share of the building stock [15,32,33].

Studies have also established optimization methods for the selection of an optimal solution. It is noticed that such optimizations are more often applied to a complete build-ing renovation or packages [29,31,32], than to a specific component or element of the renovation [34,35]. In addition to the widely applied cost-optimal approach, there are studies that focus on other parameters and/or methods for the evaluation of NZEB renova-tion [16,32,36].

A literature review presented in [37] focused on renovation methods and criteria, indicating that the majority of the methods compare different packages or various social, economic, and/or environmental indicators, rather than the contribution of the individual elements and systems. This is in agreement with the conclusions reported by Hamid et al. [11] for the need of further evaluation of cost-effectiveness and energy savings of each individual renovation measure. An approach for evaluation of the individual contribution of diverse renovation measures was proposed in [37]. The main limitations of the approach were that it disregarded actions related to change of energy source and renewable energy production; moreover, it does not extend to LCC package evaluation.

This paper presents an assessment methodology for decision support and the selection of renovation strategies to reach the NZEB standard for a specific building. The suggested procedure considers economic and energy indicators, seeking cost-optimal balance between investments in energy savings and renewable energy production. The economic impact of each improvement to the building is first assessed individually and then as a combination of improvements (packages).

The individual assessment is done by a previously proposed cost-effectiveness param-eter (CEP) [37], coupling primary the energy savings, implementation cost, and lifetime of individual renovation measures. The CEP is adapted to assess renewable energy-producing systems and used to select cost-effective renovation packages. Packages are evaluated using LCC calculations in accordance with DS/EN 15459-1:2017 [38] and the cost-optimal approach [25], taking into account supply and renovation cost. To establish the validity of the CEP, it is compared to a Net Present Value (NPV) derived by LCC calculation. Demon-stration of the method is made using a case study in Denmark consisting of residential social housing complex from 1949, which was previously analyzed in [37].

This contributes to accelerating renovations to NZEB standards by defining the nec-essary activities, decisions, tasks, and analysis needed to assess an existing residential building and convert it to the NZEB standard by selecting cost-optimal renovation package. The main novelty of the paper lies in the suggested evaluation and selection of which renovation measures to be included in renovation packages.

2. Method

An overview of the complete process included in the proposed methodology is shown in Figure 1. The procedure considers a renovation project of a specific building(s) and asso-ciated renovation targets. The method does not include the securing of financing schemes or state incentives; however, when in place, the specifics of such can be accounted for.

The methodology is outlined as a flowchart with three main stages. The starting point is the project definition stage, followed by evaluation of single actions and finally, evaluation of selected renovation packages (scenarios). A detailed design of the selected renovation package is beyond the scope of the proposed method.

The main aspects of the stages lay in the title of each of the three sections. The project definition stage includes activities and tasks related to obtaining all available information about the building, e.g., building dimensions, envelope and system characteristics, available documentation, historical energy use, local requirements, targets and wishes of the client etc. In addition, in this stage, a designer identifies any missing and necessary data and calculations required for completion of the next stages. Those are described in further detail in Section 2.1. The second stage—single actions—is where a designer evaluates the individual contribution of the building elements considered for renovation. This can be considered as a pre-step to the well-established cost-optimal approach, which is the main aspect in the last stage that deals with the evaluation of package solutions. Each of the three sections and their corresponding tasks, activities, and analysis are explained in the following sub-sections.

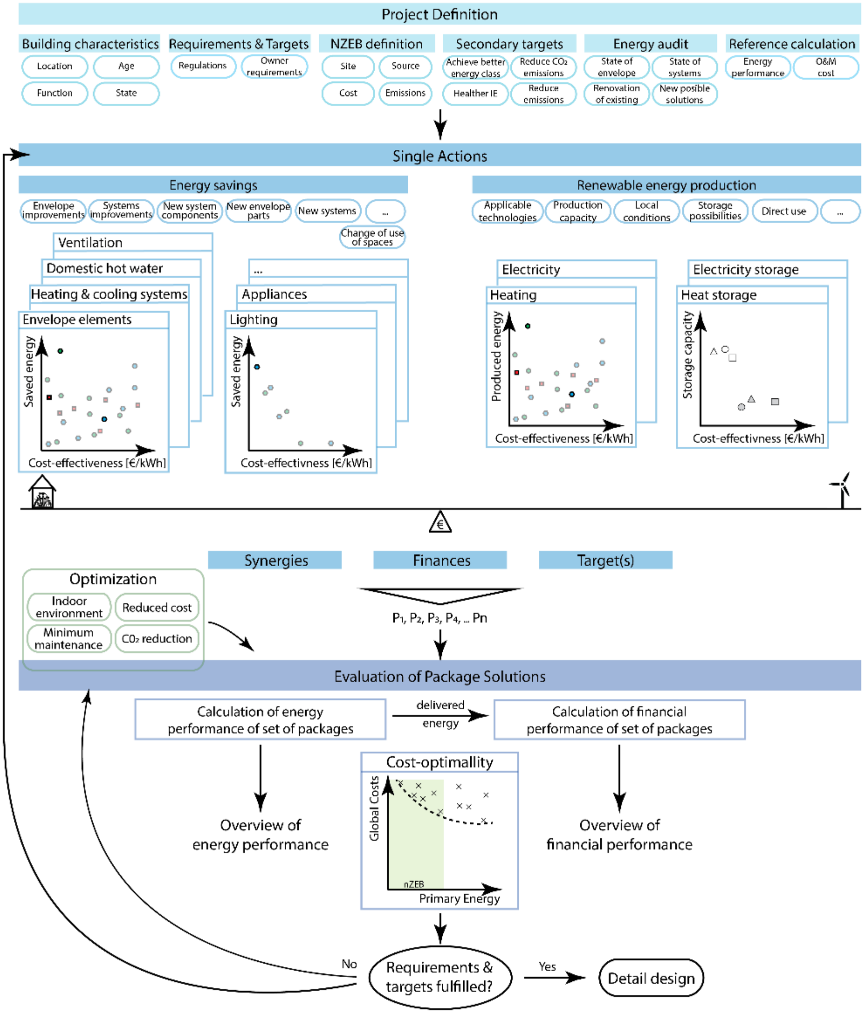

Figure 1. Overview of methodology for obtaining least-cost renovation scenarios for specific building projects.

2.1. Project Definition

In addition to the general project information, another essential part of the project definition stage is performing an energy and building audit. During the audit, a designer can evaluate the state of envelope elements and systems, and if those need replacement, renovate to a given extend, or readjust the set points and operation parameters of the renovate to a given extend, or readjust the set points and operation parameters of the systems. Furthermore, ideas and considerations of the possible solutions for each build-systems. Furthermore, ideas and considerations of the possible solutions for each buildingpart can be initiated and discussed with the property manager, building owner, and/or building users. An audit will also provide knowledge for the actual energy use under real conditions. If available, historical energy use of the building can be used to calibrate the reference energy model and thus obtain more realistic results for potential energy savings from the different renovation interventions.

In order to identify the potential energy savings of a component or complete renova-tion package, it is necessary to create a reference energy model, reflecting the actual energy performance of the building before renovation. This can be performed using a number of methods ranging from simple—single zone (steady-state seasonal/monthly methods) to complex—multi-zone, dynamic methods (finite element, finite volume, gray, or black box approaches). Most EU Member States follow standardized modeling methods with sup-plementary national annexes. The required detail and depth level of the reference energy model is also dependent on parameters related to the specific project. Such parameters can be available time for the design phase, purpose of the model, or available resources for compiling an energy model. For example, in projects where the reference energy model is used for documentation purposes only, the client may be less interested in investing additional time for achieving better accuracy of the model than the minimal requirement. However, there are projects where the accuracy of the reference energy model is of greater importance. Such could be projects with energy reduction guarantees, or cases where the reference model is the basis for evaluation of renovation actions and/or scenarios (as proposed in this method).

As the focus of this method is reaching NZEB, the specific local requirements need to be established. The type of indicator and its limit value for achieving an NZEB vary from country to country [8]. The definition plays an important role in establishing a balance between renewable energy production and energy efficiency investments. Moreover, the way NZEB is defined will predetermine the actions to be included and the focus of the analysis. As a result of the evolving nature of the NZEB definition, the methodology presented in Figure 1 does not target a specific NZEB definition or a main indicator; rather, it is designed to assess necessary building parameters needed to fulfill a given NZEB requirement. This paper applies the definition of low energy building from the Danish regulations for achieving NZEB classification: namely, a highly efficient building with a maximum of 27 kWh/m^2 year primary energy demand, accounting for heating, cooling, ventilation, and domestic hot water. Furthermore, part of the energy demand must be covered by renewable energy production [39].

2.2. Evaluation of Single Action

Following the completion of the project definition stage, it is proposed that applicable single renovation actions are evaluated separately. The goal is to obtain an overview and compare how different renovation actions perform in terms of potential energy savings and costs. A methodology for linking cost, energy savings, and lifetime, described in [37], is applied in this paper and further developed to include renewable energy systems. A brief summary of the methodology is provided in the following paragraph.

The methodology proposed in [37] evaluates investments in energy efficiency based on a parameter termed cost-effectiveness. It links implementation cost, primary energy savings, and lifespan of the evaluated actions. The cost-effectiveness parameter (CEP) of each action is calculated using Equation (1) and represents the cost of saved kWh primary energy.

$$\text{CEP}\ [(€\,|\,\text{Kr.}\,|\,\$)/(\text{saved kWh})] = (\text{Implementation cost}/\text{lifetime}\ [€/\text{y}])/(\text{Saved energy}\ [\text{kWh}/\text{y}]) \quad (1)$$

The different lifespan of investigated improvements is taken into account by dividing the implementation cost by the expected lifespan of the action in question. The implementa-tion cost at this stage includes all costs necessary to implement an action. Those can be the removal and disposal of old materials, equipment and person-hour expenses, investment for new materials and components, etc. This way of representation allows the building owner to obtain a direct overview of the value for money that each action yields. Moreover, knowing the implementation cost for different actions grants a possibility of working with the budget, ensuring there is enough funds to implement a given improvement.

Applying the CEP parameter results in a rather simplified approach to evaluate the contribution of single actions, comparing to global cost (NPV) obtained using Equation (2)

$$\text{GC} = \text{CO}_{\text{init}} + \sum_{j}\left[\sum_{i=1}^{\text{TC}}\left(\text{CO}_{\text{a(i)}}(\text{j}) * \left(1 + \text{RAT}_{\text{xx(i)}}(\text{j})\right) + \text{CO}_{\text{co2(i)}}(\text{j})\right) * \text{D\_f}_{(\text{i})} + \text{CO}_{\text{fin(TSL)}}(\text{j}) - \text{VAL}_{\text{ft(TC)}}\text{t}(\text{j})\right]. \quad (2)$$

Equation (2) follows the representation defined in DS/EN 15459 [38], where GC is global cost, while different cost types are denoted with "CO" and accompanying subscript that specifies the type of cost (init—initial; a—annual; CO2—emission cost; fin(TSL)—disposal cost). The calculation takes into account possible residual value (VALft) and discount factor (D_f) for the calculation period (tTC).

The CEP parameter includes only implementation cost and disregards price increase, residual value, and discounting, which simplifies the calculation in comparison to LCC. Furthermore, the CEP evaluates the contributions of studied solutions for the duration of their lifespan, while LCC are calculated for a defined calculation period. At this early stage of the renovation process, such simplification can prove valuable to obtain a quick overview and grounds for comparison of different solutions without diving into details of appro-priate assumptions for the additional parameters required for LCC analysis. Moreover, determining the NPV for each alternative may prove to be a task requiring extensive time and resources for the purpose of evaluation of individual contributions from renovation measures. Furthermore, the process of determining CEP acquires a solid background of all the parameters necessary for LCC calculations, which is performed in the next step of the method on the package level. To investigate how CEP ranks the different single actions in comparison to ranking based on LCC, single actions investigated in [37] are further evaluated using the LCC approach.

A drawback of the methodology presented in [37] is that it is solely applied for energy-saving actions. The evaluation of renewable energy-producing systems requires further development. It is proposed that the cost parameter for investments in renewable energy production is with the same unit as the CEP of investments in energy efficiency. This is done with the aim of obtaining grounds for direct comparison of cost-effectiveness between energy-producing systems and energy-efficiency improvements. The evaluation cannot be completely the same, as investments in energy efficiency yield energy savings, while investments in renewables result in the generation of energy. Therefore, they are contrasting by definition and require different considerations for estimating their benefits and costs.

Operation and maintenance cost throughout the lifetime of an energy-producing system can add up to a considerable amount, compared to the cost of purchasing and installing the system [40]. Therefore, operation and maintenance cost are included in the cost-effective evaluation. Furthermore, different types of systems run on different fuel, which is with distinct cost. Thereby, fuel costs are estimated on an annual basis considering the fuel type and the amount necessary to cover the demand of the building. For heating systems other than district heating connection and electricity, it is necessary to use a calorific value of the fuel for calculating the required total amount. Examples of such fuels are natural gas, coal, wood, and its by-products. The analysis in this paper considers only natural gas with a calorific value of 11.36 kWh heating per m3 of gas. Still, CEP for renewable energy systems is also calculated using Equation (1), and the annual investment includes the aforementioned cost types, while the energy is produced instead of saved. In a similar manner, when energy storage systems are evaluated, the stored amount of energy is used instead of the produced energy. The analysis in this paper accounts for energy storage only when it is an inseparable part of a system and not a separate energy-saving measure. Therefore, energy storage options are not discussed at the individual level in this paper.

To obtain an estimate for the investment cost of an energy-producing system, it is also necessary to know the capacity (or size) of the system. In the present work, the necessary capacity is determined by the reference calculation during the project definition stage. In principle, a system dimensioned according to the demand of the building prior to energy renovation would be able to cover the building's energy demand without implementing further energy-efficiency measures. By implementing energy-efficiency measures to the building, a reduction of the energy demand is achieved. As a consequence, it may be possible to reduce the required system size and with that its investment cost. In cases where there is no necessity for the implementation of energy-efficiency actions, but the heating system needs replacement, it would be appropriate to dimension the new system in accordance to the reference demand. All considered systems in this paper are based on the reference demand with the aim to obtain a relative comparison between the options. The specific system dimensioning and resulting costs can be taken into consideration in the next stage when all renovation actions are selected.

The two previous paragraphs relate to systems that deliver energy on demand through-out the year (e.g., district heating connection, heat pumps, boilers on varying fuel type). Those are an inseparable part of a residential building and for ease are further referred to as the main energy systems. While there are some cases where the only required renovation measure is changing the main system, those are quite few. Moreover, given that all the main systems in this paper are dimensioned with the same energy demand, evaluation of CEP for main systems becomes redundant, as it is dictated by implementation and fuel cost. Instead, all main systems are evaluated by LCC both individually and in combination with secondary (renewable) energy systems.

Renewable energy systems that run on fluctuating natural driving forces cannot provide energy on demand. Therefore, such can be considered as secondary production systems and can be installed independently of the main system (e.g., producing and selling all of the energy to the grid) or work in combination with it (producing part of the energy that the main system runs on). Since it is more likely for a secondary system to be applied as a single improvement to a building, those are evaluated both individually using CEP, and together with main systems by LCC analysis. The CEP parameter for renewable systems is assessed on the basis of data available in technology data catalogues provided by the Danish Energy Agency [40,41]. It accounts for investment, fixed, operation, and maintenance cost, where produced energy is calculated on an annual basis using average operation hours and technology specific design parameters, which are specified in [40,41].

2.3. Balancing Energy Efficiency and Energy Production

This is the pivotal point of the methodology as all previously acquired information is used in making viable package solutions. In addition to the main target, the designer has to take into account synergy of actions, finances of the project, and dependence of actions on the result. In addition, the designer also needs to anticipate other unforeseeable factors as rebound effects (likelihood of behavioral change of the occupants), implementation complexity, time, etc. The approach for investigating the cost balance between renewable energy and energy reduction via renovation is performed in the following way:

1. Compare cost and energy performance of single actions in order to establish the most cost-effective solutions. For that, the results for single actions established in [37] and the energy-producing systems analyzed in this paper are compared.

2. Sort single actions according to CEP, from more to less cost-effective. The sorting can be done on several levels, e.g., on a component level where only investigated actions for the specific component are included in the sorting. Another possibility is to sort by function, e.g., envelope or system-related actions, or sort across all investigated actions regardless of their function.

3. Combine single renovation actions into renovation packages and determine their global cost and energy performance. In this paper, the combination of single actions into packages is done both with and without regard to the CEP, aiming to evaluate its ability to construct cost-optimal packages. The objective is to constitute packages in-corporating different levels of energy savings using a different approach for selection of what a package consists of.

4. At last, all renovation packages are combined with each of the main and secondary energy-producing systems in a one-at-a-time manner. Once computed, the global cost and energy performance are assessed by comparing the results with the reference case. Results for combinations are also compared to respective solutions without renewable energy production or change of the main supply system. This is done with the aim to evaluate the individual effect of each secondary renewable system.

2.4. Evaluation of Renovation Packages

The last stage of the method consists of computing energy and LCC calculations for the selected renovation packages. For consistency and comparability reasons, results from the calculations are represented following the cost-optimal methodology introduced in the EPBD [7].

The cost-optimal method consists of obtaining an overview of energy and financial performance of each selected package by plotting the resulting global cost (NPV) versus the energy performance, as indicated in the bottom part of Figure 1. This visualization allows the designer to see how the different packages compare in terms of global cost and if they satisfy NZEB demands or not. Plotting results for global cost and primary energy savings in the proposed way typically results in a Pareto distribution, as indicated by the dashed line in the cost-optimality plot in Figure 1. In the provided example, NZEB requirements are defined by a maximum limit for primary energy; however, it can be replaced with the parameter valid for the country or region so long as it is not primary energy.

Energy calculations in this paper are performed using the national Danish compliance tool BE18. The software employs a quasi-steady-state monthly method [42], which is also in accordance with national and European standards. The output of the software is heat balance and primary energy demand for the modeled building, which is compared to limit values for energy classes set by Danish Building regulations 2018 [39]. Results from BE18 are further used as supply demand input to LCC models. The final heating and domestic hot water demand is obtained from the heat balance, which accounts for transmission and ventilation losses as well as solar and internal gains. The electricity demand for operation of the building is also acquired from BE18, while demand for private apartments has been estimated based on historical data and verified with statistical data for households in Denmark [37]. The calculations are limited to cost concerning total energy demand (heat and electricity), improvements to building parts, and the addition of main and secondary supply systems. BE18 is used to assess the contribution from renewable energy sources by applying the investigated solutions to the selected building case study. The model adapts the same technical specifications as in the evaluation of singe actions; however, it accounts for local conditions and limitations such as space, orientation, inclination, etc. The produced renewable energy is calculated in the software and automatically integrated in the primary energy output. The obtained total produced energy is subtracted from the corresponding final energy demand and used for LCC analysis.

Computation of the LCC calculations in this paper is done with the software LC-CByg [43]. The tool provides pre-set templates with economic assumptions for different projects types. The presented analysis follow guidelines and assumptions set out by stan-dard DS/EN 15459-1:2017 [38]. The suggested calculation period for residential buildings is 50 years. A set of decreasing discount rates and price development assumptions, which are mandatory for public projects in Denmark, are applied in all calculation models. In this set of assumptions, the discount rate is reduced from 4 to 3% after year 36, while individual price developments ranging from −0.5 to 2% are applied for the different energy sources (natural gas = −0.5%; district heating = 1%; electricity = 1.5%).

If a satisfactory package is found, the last step of the methodology is to check if the selected package fulfills all primary and secondary targets of the project. If that is in place, the process can continue with optimization and detailed design of the selected package. If some of the requirements and targets are not fulfilled, the designer can perform a second iteration, either by selecting a different package or creating a new set of packages from single actions defined in the previous step.

3. Results

Results from the three main stages of the methodology are presented in three following sections. The proposed method is applied on a case study building complex consisting of 66 apartments housed in two detached buildings and located in Frederikshavn, Denmark. The building complex is in use since 1949, and no major renovations have been undertaken afterward. Even though there is no specific project budget or target for renovation of the building, its age and state allow for a wide range of improvements to the different building parts.

3.1. Project Definition

This section describes the outcome of applying the first stage of the methodology on the selected case study. As the state and energy performance of the case study have been reported in [37], this section outlines the main findings in relation to building characteristics and defines the additionally studied energy-producing systems.

The primary energy demand for the building in its existing state is found to be 129.6 kWh/ m^2 year by the BE18 reference energy model. It considers energy demand for heating, cooling, ventilation, domestic hot water, and electricity for operation of the building. The energy model has been developed and validated by the energy audit described in depth in [37]. The total heated floor area of 5250 m^2 is divided equally between the apartments, 48 of which are oriented to the west and 18 are oriented to the south. Both buildings are three storeys in height with unheated attic, basement, and utility room. Thermal characteristics for the main building envelope elements are shown in Table 1.

Table 1. U-values of building envelope elements in existing state prior renovation. Adapted from [37].

Building Element	U-Value [W/m^2K]
External wall	0.58
Windows	2.9
Attic slab	0.35
Basement/ground floor slab	1.48

To achieve NZEB in the Danish context, the primary energy demand must be lower than the limit value of 27 kWh/m^2 year and partially covered by renewable production [39]. For this specific building, the primary energy demand needs a reduction of nearly 80%. Moreover, it has been reported that heating and domestic hot water demand is covered by district heating sub-station, which is common for both buildings [37]. The sub-station consists of two heat exchangers (one for heating and one for DHW), which are installed when the building was constructed. Ventilation commences naturally through windows and ventilation openings in the bathrooms.

Considering that the existing district heating sub-station is quite outdated, it is worth considering its replacement. This can be either the re-establishment of a new substation or switching to a different energy system. This, combined with the requirement in Danish building regulations for a share of renewable energy production, can have a large effect on the economic and energy performance, as different systems bear distinct characteristics. Here, it is important to consider local conditions and possibilities, e.g., the availability of district heating or a gas network, space for vertical or horizontal ground-source heat exchangers, available roof area and orientation, etc.

The energy source for a system is a determining factor for defining it as renewable. For example, district heating should not be considered renewable if the source is coal. On the other hand, district heating plants operated on biomass, geothermal, or other renewable sources can be considered renewable. In fact, in Denmark, more than half of district heating plants are powered by renewable sources [44]. Some renewable energy-producing systems cannot deliver energy on demand, as there are reliant on fluctuating natural driving forces. Therefore, such are better suited to supplement a main energy system that is capable of delivering energy on demand. The produced energy by the secondary renewable system may be used to power the main system directly, stored, or sold to the grid.

This study investigates four main energy supply systems for heating and domestic hot water and two secondary renewable energy systems. The main supply systems included in the analysis are a district heating sub-station, a natural gas boiler, a Water-to-Water (W/W) heat pump, and an Air-to-Water (A/W) heat pump. Investigated secondary supply systems are the addition of a Domestic Wind Turbine (DWT) and photovoltaic panels (PV). The selection of the investigated system types and sizes hinged on acquiring necessary input data for economical and energy performance analysis. The associated cost and technical specifications for the main and secondary energy-producing systems are accessible in Technology Data Catalogues by the Danish Energy Agency [40,41]. To investigate a possible effect of the DWT and PV system size and thereby production, three sizes deemed suitable for the building energy demand and available space are considered. For DWT, the selected system capacities are

5, 10, and 25 kW. In regard to PV, the studied sizes are 6.1, 110, and 150 kWp, corresponding to 30, 500, and 930 m^2, respectively [40,41].

3.2. Single Actions

This section provides results related to the evaluation of single renovation actions for the selected case study. The results are presented in three sub-sections. The first sub-section presents a comparison of the resulting ranking of renovation actions, based on CEP and global cost (NPV). The second sub-section presents the CEP of the investigated renewable energy-producing systems. The third and final sub-section shows a relation of global cost and primary energy for the individual main energy supply systems and their combination with secondary (renewable) systems.

3.2.1. Comparison of CEP and NPV of Single Actions

Figure 2 compares single energy-efficiency actions represented in terms of the CEP from [37] to the same actions, evaluated using the LCC method and represented by NPV for a 50-year period. The comparison is made on all actions proposed in [37], but for clarity purposes, only envelope actions are shown in Figure 2. A complete list of all results is provided in Appendix A, while the detailed cost structure of each action is accessible through the Data Availability Statement. As it can be observed in Figure 2 and in the appended information, there are multiple solutions of the same element and type. These are cases with several solutions for a given element type. For example, an external wall type one with nine variations of insulation thickness or windows of the same material and class, but different opening mechanisms.

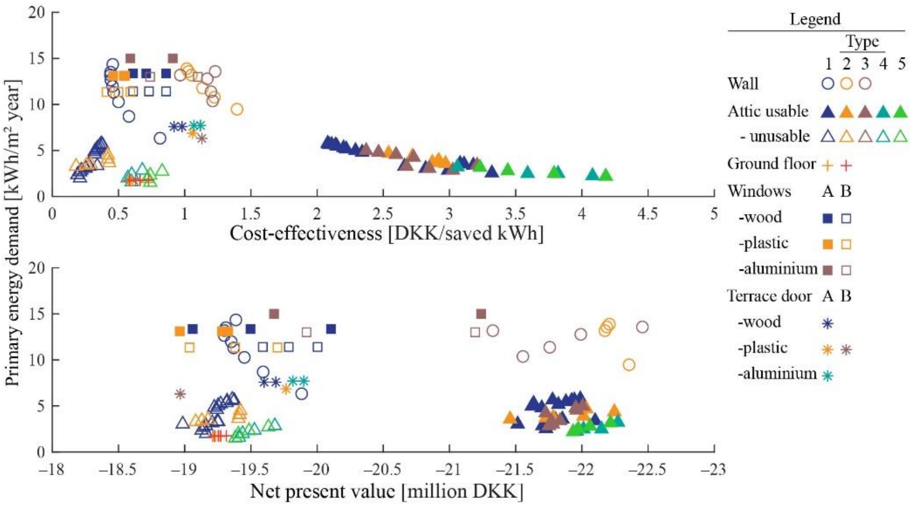

Figure 2. Comparison between the cost-effectiveness parameter (CEP)

adapted from [37] (top) and net present value (bottom) for selected energy efficiency actions.

By comparing the graphs in Figure 2, a few similarities and differences can be noted. By comparing the graphs in Figure 2, a few similarities and differences can be noted. The most significant differences are the change in slope of the usable attic solutions, wallThe most significant differences are the change in slope of the usable attic solutions, wall type one and two. While their CEP decreases with increase of energy savings (increased type one and two. While their CEP decreases with increase of energy savings (increased insulation thickness), the NPV for those elements increases. Furthermore, the NPV ofinsulation thickness), the NPV for those elements increases. Furthermore, the NPV of wall types two and three are comparable to the usable attic solution. This is not the case wall types two and three are comparable to the usable attic solution. This is not the case when the CEP is applied. Nevertheless, the remaining actions maintain similar dispositionwhen the CEP is applied. Nevertheless, the remaining actions maintain similar disposi-tion (relative to each other), when applying either the CEP or NPV. For example, it is (relative to each other), when applying either the CEP or NPV. For example, it is evident that wall type one, windows, attic solutions, terrace doors, and ground floor insulation all preserve the same distribution.

While the CEP represents the cost of saved kWh for a given solution over its life-time, NPV determines the total cost over the calculation period. Furthermore, CEP considers only implementation cost, lifetime, and saved energy by the solution. In ad-dition to that, NPV takes into account inflation, price increases, interest rate, mainte-nance, replacement cost, and residual value at the end of the calculation period. Even though those parameters are an inseparable part from global solution (package) evalu-ation, the comparison in Figure 2 shows that omitting them seems to have a limited effect on the ranking of single actions. At this relatively early stage of the methodolo-gy, it is valuable to identify actions with low investment relative to the obtained sav-ings rather than find the solutions with the least required investment over a defined period of time. Moreover, the majority of building owners are still not completely clear on the practical use and application of LCC calculations, and its uptake is still rather weak [45]. Regarding those considerations, in combination with the great difference in calculation methods for the CEP and NPV, it can be argued that the CEP provides sat-isfactory results for this stage of a renovation project, despite its simplified approach.

3.2.2. CEP of Renewable Energy-Producing Systems

Figure 3 presents the CEP results for the secondary renewable energy-producing systems. The figure shows the CEP in Danish kroner per produced kWh as a function of produced energy. Both parameters are calculated using the method explained in Section 2.2 and data available in [40,41]. The energy produced by a renewable system is dependent on various technical, local, and operational parameters. The results pre-sented in Figure 3 consider the average number of operational hours, technical and ef-ficiency system parameters as specified in [40,41], but excludes site and system opera-tion specifics. Thus, results in Figure 3 can be considered as an example of how differ-ent systems compare in terms of energy production and cost with optimal conditions. As the operational conditions are often limited by site characteristics (e.g., building orientation, location, roof area and slope, etc.), the produced energy is likely to be low-er than that suggested in Figure 3. The CEP of the systems may also change if there is financial incentives or regulations, supporting specific types of systems.

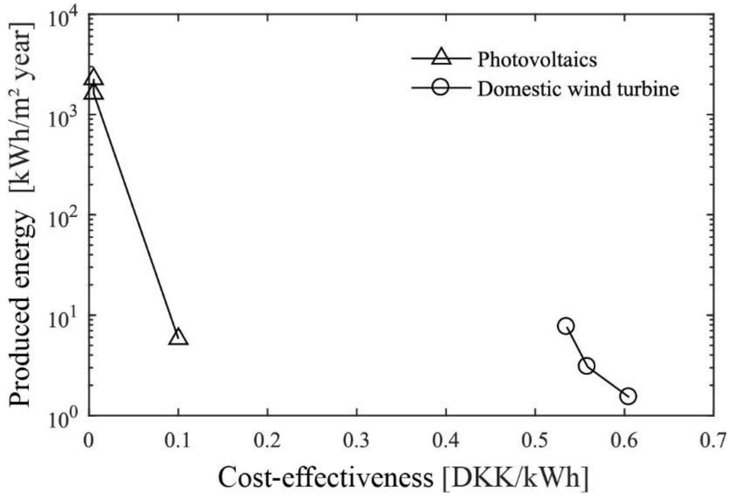

Figure 3. The cost-effectiveness parameter (CEP) for renewable energy-producing technologies.

By comparing the CEP of renewable energy production systems (Figure 3) and this of envelope actions (Figure 2), it can be stated that renewable energy production systems are more cost-effective than implementation of renovation to the building. The least cost-effective system—DWT—is comparable to the most cost-effective enve-lope options. The most cost-effective system in accordance to Figure 3 is the photovol-taic panels (PV), where even the smallest system is more cost-effective than any of the investigated envelope solutions. Both PV and DWT systems exhibit a reduction in the CEP with increase in capacity; thereby, the implementation of a larger system should result in reduced total cost compared to the implementation of a smaller system. Fur-thermore, considering that every produced kWh reduces the necessary purchased en-ergy (if utilized directly on site), the implementation of a renewable energy system should result in a reduction of energy demand and global cost.

To check if that is true, renewable options are applied to the reference energy model (before renovation) as a secondary energy supply and investigated for both global energy and cost performance. In addition to the secondary renewable energy supply options, the reference model is also fitted with four different primary supply options, as defined in Section 2.2.

3.2.3. Global Cost and Energy Performance of Main and Secondary Energy Systems

Figure 4 shows primary energy demand and global cost for the main and secondary supply options. Global cost is presented using the NPV indicator for the applied calculation period of 50 years, while primary energy demand is found using the com-pliance tool BE18. Primary energy and NPV for the reference case are represented by a vertical and a horizontal dashed line, respectively (~130 kWh/m^2 year and −18.22 mil-lion DKK). With that representation, cheaper solutions than the reference appear above the horizontal reference line. Consequently, solutions with lower energy de-mand are located to the left of the vertical reference line. The limit values for reaching NZEB, as well as voluntary renovation classes 1 and 2, are denoted by three additional vertical dashed lines. Renovation classes 1 and 2 are stated in Danish building regula-tions and correspond to 52.8 and 70.4 kWh/m^2 year, respectively [39]. As defined in Section 2.1, reaching NZEB in a Danish concept is equivalent to 27 kWh/m^2 year, which is marked by the green vertical dashed line. This representation is applied to all fol-lowing figures comparing NPV and energy demand.

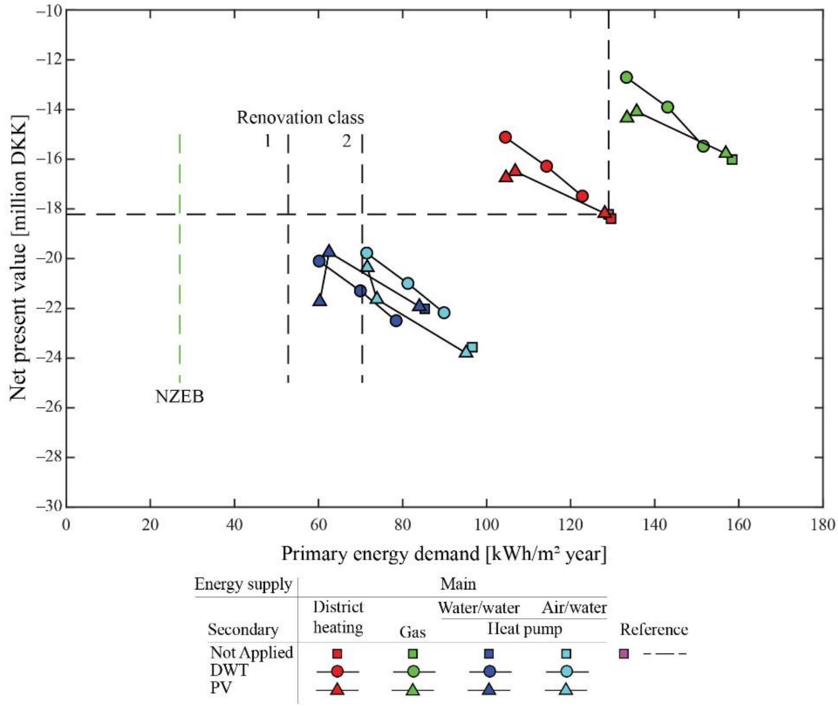

Figure 4. Comparison of the four studied main supply options, combined with secondary renewable energy-producing systems. No energy-saving measures applied.

The different scenarios of main energy supply are first computed without any ap-plication of secondary renewable energy production. Then, each renewable system is added in a one-at-a-time manner. Figure 4 shows that the cheapest option is to run the building on natural gas; however, using gas results in higher primary energy than the reference case. As the required heat demand for district heating and gas scenarios is equal, the increase of primary energy is solely due to the applied national primary en-ergy factors. A factor of one is applied for natural gas compared to 0.85 for district heating and 1.9 for electricity. As a consequence, in cases where the target is reaching NZEB, the natural gas case is not favored in the Danish context.

Switching from district heating to either a Water-to-Water (W/W) or Air-to-Water (A/W) heat pump results in lower primary energy demand. Given that the primary energy factor for electricity is higher than this for district heating and gas, the reduction is a consequence of the "free" energy produced by the heat pump's high Coefficient of Performance (COP). The COP of the investigated W/W heat pump is higher (4.2) than that of the A/W heat pump (3.65); thereby, the

W/W heat pump realizes higher primary energy savings. Although the W/W heat pump is approximately 55% more expensive than A/W in regard to acquisition and replacement cost, its higher efficiency brings 17% lower supply demand and 6.5% lower global cost compared to A/W. In spite of their differences, the two heat pump types are comparable. Both scenarios yield lower primary energy demand and higher NPV in comparison to the reference. Nonetheless, the cost increase is relatively small related to the achieved primary energy savings; hence, heat pumps are favored as the main heating supply solution for NZEB renovation.

Figure 4 shows that the addition of renewable electricity production results in a reduction of cost and energy demand, regardless of the system type and size. This can be explained by the assumption that all produced energy is used on site. This simplification is made, as the goal of the analysis is to identify the potential of each system rather than find the exact amount energy used on-site. Produced on-site electricity is modeled to cover the necessary demand for building operation and common spaces first, while excess production is assumed to be utilized by private apartments.

For all scenarios including DWT, increasing the system size results in a reduction of primary energy and NPV. The investigated wind turbine is cheaper than the PV systems in all scenarios, except W/W heat pump. For gas, district heating, and W/W heat pump as the main supply, the second largest PV system (110 kWp) exhibits the lowest cost. The only scenario where the largest capacity PV plant is the cheapest of the three investigated sizes is in combination with the A/W heat pump. It is also noticed that the cost difference between the two larger PV sizes is greatest for the W/W heat pump.

Overall, the performance of the studied PV and DWT systems is comparable both in terms of cost and energy production. However, the installation of a DWT requires space and a number of regulatory requirements, which cannot be fulfilled in most cases. Even so, the results indicate that if space and regulations are in place, DWT can be a viable supple-mentary supply option. It must be noted that both the economic and energy performance for all renewable technologies vary considerably depending on technology specifications, local conditions, legislation, funding incentives, costs, calculation methods, etc.

3.3. Compilation and Evaluation of Packages

This section provides a description for the approach used to compile renovation pack-ages and presents the results. Furthermore, the resulting global cost and primary energy demand for the selected packages alone and in combination with main and secondary systems are presented and analyzed.

Having determined the individual effect on energy demand and knowing the cost for applying various energy efficiency actions, different energy supply sources, and renewable energy production systems, we can now use the acquired data to sort the actions and com-pose renovation packages. The objective of this study is to combine renovation packages based on different approaches for the selection of what a package consists of. Moreover, we identify if using cost-effectiveness as a sorting parameter can yield cost-optimal packages.

The compiled renovation packages are differentiated in three target groups, based on the predicted amount of energy savings, which are expressed in percent reduction from the reference. The level of energy savings is set to approximately 20, 40 and 60%. Naturally, packages with lower target have wider selection of possibilities, as less actions are required to reach the target. Therefore, six packages are compiled for target savings of 20%, and two are compiled for 40 and 60%.

The approach used to select the contents of packages 1–6 is to include a variety of rather random building elements, adding up to 20% savings. This is done to mimic cases where the elements to be renovated are pre-selected, but the specific solution is not. The selection of the specific element type, insulation thickness, or class is made on the basis of the energy savings and CEP. The sorting is performed on an element level, as grouped in Tables A1–A6 in Appendix A. Then, a selection of the specific element type is made from one or more of the tables, depending on the goal of the package. For packages 1–6, CEP and energy savings are considered to make up packages, which are expected to provide approximately 20% energy savings while still comprised with one of the most cost-effective elements.

Alternatively, the elements included in package 7 are selected on the basis of global CEP sorting, across all investigated actions. This is done with aim of identifying if selection solely based on CEP provides cost-optimal packages. Package 8 considers the same level of savings as package 7, although it focuses on reaching the target by implementing fewer building elements with large individual energy savings. For this package, the first priority is to select the building elements with large individual savings and then select the specific type based on element-sorted CEP.

Packages 9 and 10 consist of a 60% energy reduction target. Package 9 is compiled by CEP sorting on an element level, and then including all needed elements to reach approximately 60% savings, prioritizing those with large savings first. Lastly, package 10 includes all investigated elements but for the compromise of lower energy class windows and terrace doors. The resulting packages and their content details are presented in Table 2, whereas a list of all elements and their CEP value is available in Appendix A. The last two rows in

Table 2 provide the predicted savings by the sum of individual contributions of renovation actions and the achieved global savings by the package.

Table 2. Contents and classification of investigated renovation packages. Included building elements in a renovation package are marked with “X”, which is located with respect to the variated element properties.

		Energy Reduction %		20						40		60	
Element	**Material**	**Insulation**	**Class/Type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Wall	Timber finish	220 mm								X	X		
		245 mm	class 37	X	X	X						X	X
		315 mm					X						
Attic	Timber floor finish	465 mm	class 37	X			X		X				
		95 mm	class 34							X			
		490 mm	class 37									X	X
Ground floor	Timber finish	45 mm	class 37	X					X				
		45 mm	class 34										X
Windows	Plastic	N.A	class A					X				X	
			class B		X					X	X		X
Terrace door	Wood	N.A	class A			X							
	Plastic	N.A	class A					X			X	X	
		N.A	class B										X
Heating and DHW	Pipe network	40 mm	universal						X	X			
		50 mm	matts									X	X
DHW	Pump	N.A	circulation							X		X	X
Ventilation	0.175		decentral								X		
	0.15		with heat									X	
	0.1		recovery										X
Sum of individual actions			% savings	20	25	21	20	20	18	39	52	64	66
Global savings of package				11	25	7	20	20	8	39	39	58	52

The results for NPV and primary energy demand for each of the specified renovation packages and their combination with main and secondary energy supply are presented in Figure 5. Similarly to the cost-optimality plot shown in Figure 1, all studied combinations and the resulting Pareto curve are presented for the purpose of observing the complete solution space. As the differentiation in Figure 5 is made only by the package and main supply option, there are seven identical symbols appearing for each package. Those correspond to the three studied DWT and PV systems and the main supply systems as stand-alone systems, which are all discussed in detail throughout this section. Package zero represents a change of energy-producing system and/or the addition of renewables, as presented in Figure 4.

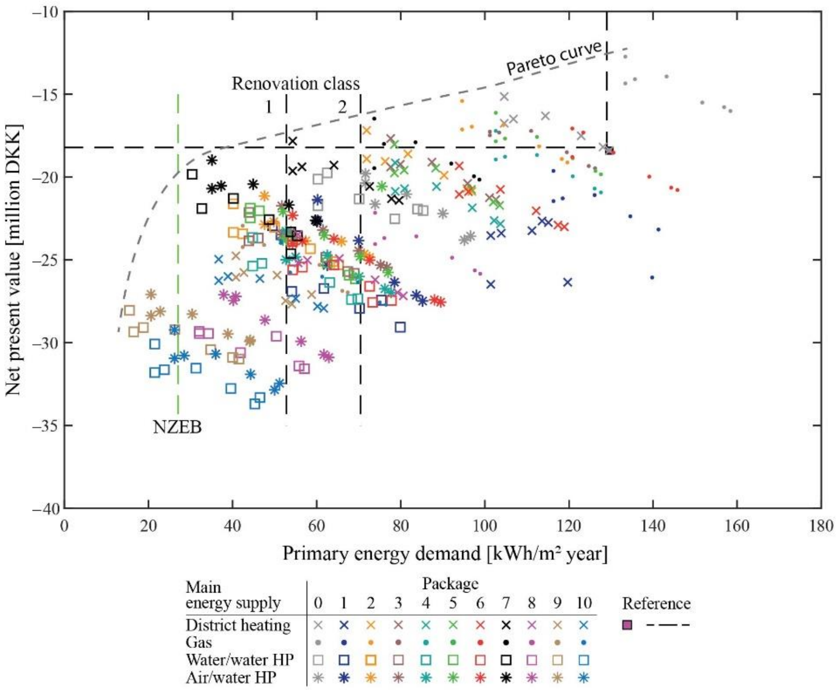

Figure 5. Primary energy as a function of net present value for all investigated packages (308 + reference).

Given the selected boundary conditions for the calculations, 12 of the 308 studied cases satisfy NZEB. Seven of those have W/W heat pumps as the primary supply and five A/W heat pumps. There are 56 solutions lying between the NZEB requirement and renovation class one, while those between the limits for renovation class one and two are 79.

As observed from Figure 5, there are a number of cases that are rather close to the NZEB target value of 27 kWh/m2 year but do not reach NZEB. Those have the potential to reach the target by means of model optimization on either the envelope or the pro-ducing system's side. Figure 5 reveals a general tendency of increasing global cost with reduction of primary energy demand. Nevertheless, there are also solutions with sig-nificantly lowered energy demand that are comparable to the reference case total costs. The results are further analyzed for each main supply system in two ways. First, the addition of renovation packages alone is presented in Figure 6. Second, the packages are combined with the secondary energy production systems in Figure 7. Figure 6 presents the resulting energy demand and NPV by applying the renovation packages defined in Table 2 to the reference energy model. The results are shown for each main supply type, where packages with energy-saving targets of 20, 40, and 60% are marked with an "x", a diamond, and a star, respectively. If district heating is kept as the main supply, packages 1–6 (target savings of 20%, based on sum of individual element contributions) provide global savings in the range of 8–25% compared to the reference. As indicated at the bottom of Table 1, for some of the packages, the addition of individual savings and resulting savings based on global energy balance are equal, while for others, they differ. This confirms that the sum of savings of individual actions is not always equal to the global savings. In fact, the comparison between expected and achieved results in Table 2 shows a tendency for greater difference between the results with an increasing number of elements in a package. This is evident as packages 2–5 all constitute of two renovated elements and only for one of these are the global savings lower than the sum of individual actions. Furthermore, a mismatch between global saving and sum of individual elements is also present for packages 1 and 6–10, which comprise three or more elements. On the contrary, package 7 consist of five elements and has equal global and summed energy savings, while package 3 consist of two elements but the sum and global savings differ. This indicates that both the type and number of elements included in the package an influence on how close the expected and achieved savings are.

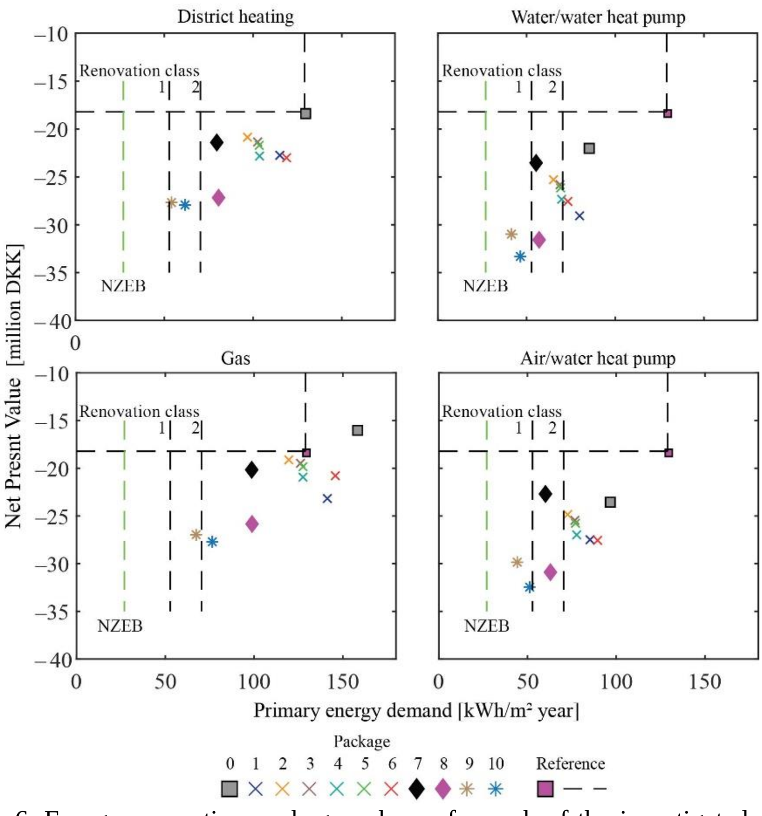

Figure 6. Energy renovation packages, shown for each of the investigated primary energy supply options.

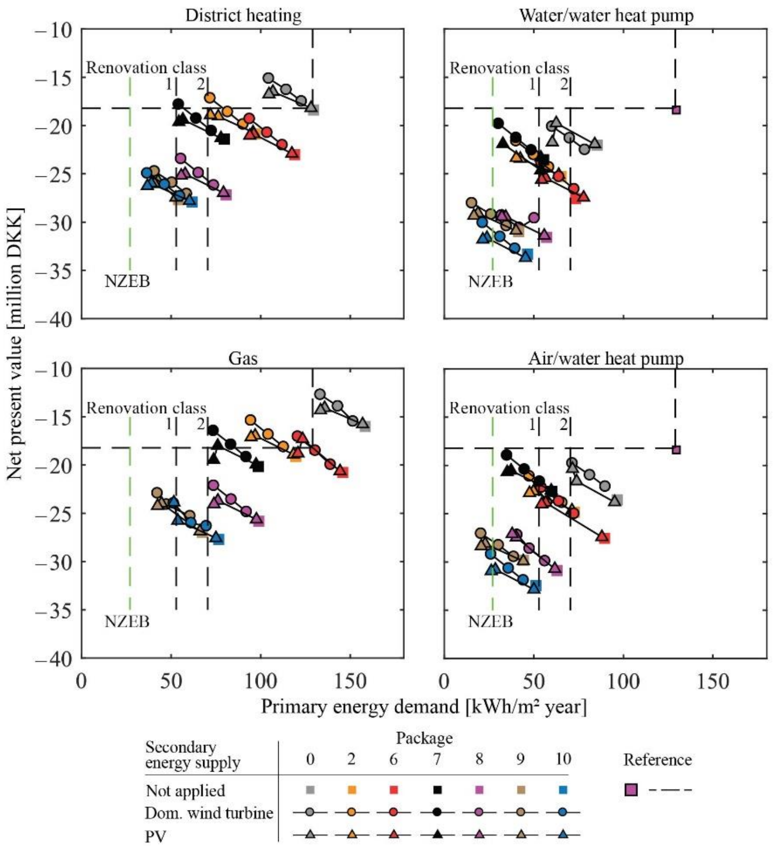

Figure 7. Selected renovation packages shown for each main supply option.

Analyzing the packages with 20% target savings, it can be noted that package 2 provides the most savings for the least cost-increase (25% energy savings for 14% higher NPV compared to reference). Package 6 is the least efficient and the most ex-pensive of the six packages, providing 8% energy reduction but 26% global cost in-crease. Packages 3, 4, and 5 provide comparable energy savings of approximately 20%, but they vary in NPV. Respectively, there is a 17, 25, and 19% increase in NPV for packages 3, 4, and 5. Package 1 provides an 11% primary energy reduction and 24% in-crease in NPV.

Even though the relative relationship between packages 1 and 6 is similar for all other supply systems, it is noticed that the type of main system can influence their or-der in respect to cost and energy savings. For example, packages 1 and 6 are nearly equal in terms of energy savings and cost for scenarios with district heating and A/W heat pumps, while for scenarios with gas and W/W heat pumps, their cost differs no-ticeably. As expected, scenarios with heat pumps bring the largest energy savings compared to the reference (35–50% savings), where in the case of W/W heat pumps, this is enough to satisfy renovation class 2.

From Figure 6, it becomes apparent that packages 7 and 8 perform equally in regard to energy reduction but with considerably different NPV values. Regardless of the applied supply system, package 7 is substantially cheaper than package 8. A possible explanation of the great cost difference can be contributed to the addition of mechanical ventilation with heat recovery to package 8. It can also be noticed that for scenarios with heat pumps, package 7 is the cheapest of all packages, while for district heating and gas, the cost and achieved savings of package 7 are comparable to those of packages 1–6. Higher energy savings outweigh the additional implementation and running cost for package 7 compared to packages 1–6. This shows that higher energy savings does not necessarily mean greater global cost; moreover, how energy savings are achieved can have a large influence on the total global cost. Considering that the approach for compiling package 7 is purely based on the CEP, sorted across all investigated elements, it can be argued that the approach can yield cost-optimal packages.

Packages 9 and 10 compare well in terms of economic and energy performance. Both of the packages include mechanical ventilation with heat recovery; thereby, they are most the expensive and comparable in cost with package 8. In all cases, package 9 is cheaper and more energy efficient than package 10. The cost difference is larger for the two heat pumps scenarios, in which case package 9 is also cheaper than package 8.

Finally, all renovation packages are combined with each of the studied renewable energy systems. Figure 7 presents the resulting energy demand and NPV, where for clarity, only the best and worst performing packages with 20% target savings are shown. The tendencies observed in Figure 4 for the addition of renewable systems alone remain unchanged when they are further combined with renovation packages. Namely, PV and DWT lower both the global cost and energy demand. The present analysis excludes the potential reduction of system capacity, resulting from achieved energy savings by a given renovation package. Further considerations in this regard may lower the global cost of energy-producing systems as a consequence of lower investment, replacement, and possibly operation and maintenance cost.

For district heating as the main supply option, only package 2 achieves renovation class two when combined with the largest sizes of PV and DWT. It is noticed that global costs for the largest DWT are also lower than the reference. Neither of the cases incorpo-rating package 6 result in renovation class classification. Packages 7 and 8 in combination with two of the DWT or PV solutions satisfy renovation class two, where the larger system sizes reach the limit for renovation class one. The offset in global cost between packages 7 and 8 appears to remain unchanged. Despite the relatively large savings obtained from packages 9 and 10, reaching NZEB with district heating is still not possible, even with the addition of renewable secondary supply.

As explained previously, natural gas and district heating have equal heating demand; however, due to the higher primary energy factor for gas, these scenarios observe higher primary energy demand. Hence, the only solutions satisfying any of the denoted building renovation classes are also the ones with the highest savings. In fact, only a few solutions combining gas and large DWT or PV systems surpass requirements for renovation class one. The results in Figure 7 confirm that natural gas would likely not be the favored solution for cases in Denmark where the target is NZEB, even with the addition of renewable energy production. However, natural gas could be applicable if the target is global cost reduction.

Nearly all solutions incorporating heat pumps and renovation packages satisfy renova-tion class two. Actually, when the more efficient W/W heat pump is combined with larger PVs or DWT, renovation class 2 can be achieved without the addition of energy-saving measures (marked in gray in Figure 7). This is also true for the A/W heat pump, although only for the largest PV and DWT systems. It can be noticed that for both heat pumps types, package 7 combined with 25 kW DWT is the cheapest solution of all. Although package 7 combined with either PV or DTW does not satisfy the NZEB requirement, it can be foreseen that a small optimization of selecting one or more elements in the package with higher energy saving could make that possible. Additional reductions of about 4 and 10 kWh/m^2 per year are needed for W/W and A/W heat pumps to reach the limit value, respectively. Most solutions involving packages 9 and 10 in combination with heat pumps and secondary renewables lay in the region between 27 and 52 kWh/m^2 year. The solutions satisfying the NZEB requirement consist of A/W heat pumps combined with packages 9 and 110, 150 kWp PVs, or 25 kW DWT. In the case of W/W heat pumps, both packages 9 and 10 combined with the aforementioned renewables fit with the NZEB limit.

4. Discussion

The suggested methodology gives the opportunity to consider a wide variety of necessary activities and select a renovation strategy based on a structured approach. The different stages link regulatory and computational considerations for the comparison and selection of renovation actions, considering energy demand and costs.

The methodology is demonstrated using case study buildings that require extensive renovation and energy savings (80% reduction) to reach the NZEB standard. The exiting state of the selected case study provides the possibility for the application of a wide range of energy-efficiency measures and requires a substantial energy reduction. Thus, the selection of which building parts to be renovated and to what extend is crucial for reaching a cost-optimal NZEB solution. The case study results showed a number of different ways for reaching the NZEB target. Furthermore, the applied method helped to identify solutions that have the potential to reach the NZEB target with significantly reduced cost.

While the targets for the specific project at hand can vary, the method is refined for renovations targeting the NZEB standard. Currently, an NZEB is defined in the EPDB [7] as "[a] building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby." In most Member States, the limit value of how low the energy demand of the building needs to be is defined by the maximum primary energy. The limit value varies greatly from country to country in both magnitude and the way the indicator is determined. In some Member States, the indicator is a non-dimensional parameter relative to a reference building [8]. In a few countries, carbon emissions is the main indicator, while in others, emissions are used as a secondary indicator to primary energy [8]. Since the release of the EPBD, recast various definitions and calculation methods for NZEB have been applied [46]; moreover, the definitions are still evolving and changing. Therefore, the fact that the methodology is not tailored to a specific limit value but rather focused on activities to acquire and evaluate the parameters in question is considered as a strength.

For the demonstration of the method in this paper, single actions are evaluated based on cost and energy savings. The suggested approach is flexible toward the specific energy modeling method. While the presented work adopts a simple, standardized approach, it is possible to be done using other calculation methods tailored to the project needs or local requirements. The accuracy of derived energy savings is dependent on the selected method and accompanying assumptions.

Similar statements can be made for the estimation and calculation of costs. Nowadays, this is a much less regulated topic compared to energy performance, but it can be noticed that this is changing with the implementation of new emerging standards [38] and expected EPBD revision before July 2021 [47]. The suggestion for addressing costs, first on a single element level and then by LCC, is in line with a number of the key principles communicated in the Renovation Wave [6]. Addressing single actions in a simplified way may also help bridge the gap of practitioners understanding life cycle thinking.

Regardless of the applied approach, any cost results will be dependent on the depth of the analysis and the sources for prices of the different actions (database, specific tender offer, selected websites/companies, product catalogues, etc.). As discussed in Section 2.2, some cost reductions may also occur as a result of the contents of a renovation package. Especially for packages with large energy savings, the total cost may be reduced due to synergies of the performed actions and reduction of the required system capacity.

Figure 8 gives an example of the corresponding investment cost (left) alongside the operation and maintenance cost (right) as a function of system capacity. Data for each of the four compared systems are obtained from the Danish technology data cat-alogues [4140,4241]. The comparison shows that for some systems such as district heating and gas, there would not be great differences in the resulting investment or operation and maintenance cost due to reduction of the required capacity. This differs for heat pumps, as an evidently considerable investment cost reduction can be achieved by reducing the size of a heat pump. The strongest cost-dependence on the size is observed for W/W heat pumps. Operation and maintenance costs for the two heat pumps are equal and remain the same for 160 and 400 kW systems, but they de-crease for systems smaller than 160 kW.

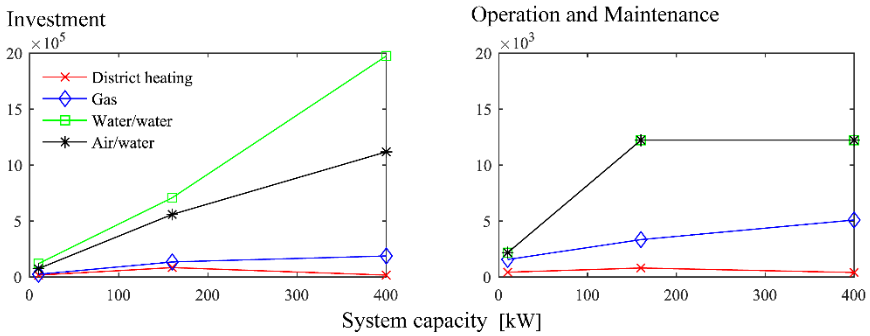

Figure 8. Investment (left) and operation and maintenance (right) costs as a function of system capacity for selected energy-producing systems.

The investment, operation, and maintenance costs are only a couple of the param-eters involved in the methodology. To identify which model parameters have the highest impact on the CEP and LCC results, a sensitivity analysis of energy and cost calculations is necessary. Furthermore, such will determine the robustness of the solu-tions and the methodology overall.

The comparison of CEP and NPV of individual building elements showed the same disposition for nearly all investigated elements. This suggests that a selection of package contents based on NPV would not be very different to a selection based on CEP. However, as presented in the paper, the two parameters are obtained by different methods, where NPV requires a greater number of inputs and arguably grater com-plexity and time. The CEP provides the possibility for choosing actions by considering the cost of saved kWh and gives the possibility of applying different approaches for compiling a package. Sorting on an element level, one can apply the CEP to select spe-cific types from a range of options. The applied methodology for the compilation of packages showed that selected actions vary with different project goals. Sorting across all possible investigated options provided the package with the most savings for the least cost.

Comparing the methodology proposed in this paper with the work presented in [24], it can be argued that the CEP parameter helps to reduce the economic gap between cost-optimal and NZEB solutions, as it seeks to implement a package that delivers the most energy savings for the least investment. While the aim of the study [14] was to find building system configurations that comply with a minimum share of renewables in an Italian setting, the achieved results for applicable renewable systems are in good agreement with those found in this paper: namely, heat pumps combined with PV systems and small solar heating plants. In a similar manner, results related to cost-optimality presented in [31,32] have a comparable composition of optimal package, as found in this paper. In fact, both papers found that interventions of multiple building parts and systems are necessary to reach NZEB. In [31], the cost-optimal package consists of basic insulation of all building elements, a heat pump or gas boiler, and renewable production. A number of similarities can also be observed between results for the cost-optimal renovation of a Finish apartment building provided in [29] and this study. First, mechanical ventilation and additional insulation were not cost-effective solutions, despite the large share of saved energy. In addition, heat pumps provide the best economic performance, whereas PVs are especially recommendable due to the achievable reduction of global cost and energy demand.

However, neither of the papers evaluate single actions in the same manner as proposed in this paper. A comparable approach that considers environmental impact, instead of global cost, is presented in [34]. The method ranks thermal insulation and finds that there are several solutions significantly reducing energy demand, but those are also characterized with different environmental impacts.

Association of the proposed method with a more comprehensive Multi-Objective Parametric Analysis (MOPA) [35] can also be drawn. The MOPA method is divided in three stages, which are different in essence from the stages presented here; however, the approach is generally similar. Although MOPA is applied to lightweight addition instead of the whole building, the first stage consists of analyzing components separately and then performing analysis for obtaining optimum design parameters. The third stage deals with the analysis of renewable energy resources. Indeed, MOPA is a parametric methodology that provides a much wider range of solutions. On the contrary, those solutions stem from the parameter variation, rather than real-life products, as is the case in this method.

The proposed method can be used as template for guiding the building owner through the tasks, activities, and decisions needed for the selection of a renovation plan to reach the NZEB standard. Furthermore, consultants and energy-saving companies could also apply it to compose renovation scenarios. Currently, the method accounts for energy and economic indicators only, but it can be expanded to account for additional indicators describing CO2 emissions, life cycle analysis, comfort, etc.

5. Conclusions

The paper presents a methodology for the selection and evaluation of renovation alternatives with the nearly Zero Energy Building (NZEB) target. The outline of the method can serve as a flowchart that presents steps for data acquisition and handling in a structured manner, with the aim of simple, transparent, and justified decision making. The methodology is applied to a case study, where the performed analysis points to the following conclusions.

The cost-effectiveness parameter (CEP) can be useful for estimating cost–benefits of various energy producing and saving actions. Although some discrepancies are noticed when comparing single action ranking based on the CEP and NPV, most actions retain their relative order.

The CEP can be used for the sorting of renovation actions across different levels, depending on the focus of the project. As demonstrated, soring across pre-selected building element types, or all elements, yields different contents for renovation packages. The results also showed that creating a package, solely based on the CEP, provides a package with the largest savings for the least cost increase. Although the results in this area are promising, further research including a higher number of packages is needed.

Even though the selected case study buildings require an energy demand reduction of about 80%, applying the proposed method converged several solutions satisfying the NZEB target. This can partly contribute to the large amount of energy-saving measures applied in this study; however, in cases where the initially determined single actions are limited and none of their combinations satisfies the targets, the user can iterate back to creating one or more single actions or variants of the already determined actions.

Analyses related to renewable energy production show that in nearly all cases, it is cheaper to implement a renewable energy system than do nothing. A considerable difference in both energy and cost is noted for the investigated main supply systems. Heat pumps prove to be most favorable when the target is

NZEB. It was shown that the primary energy factor plays a big role in reaching a limit value for building energy class.

Further studies should explore the robustness of the proposed method and the sen-sitivity of the different economic and energy parameters. Another viable topic could be to expand the current methodology with more evaluation parameters beyond economics and energy efficiency. Those could be related to a reduction of CO_2 emissions, greenhouse gases, or comfort indicators for the occupants.

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Appendix A

Please refer to the full version of the article, readily available at: https://doi.org/10.3390/app11094141

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PAPER #4

Investigations of building-related LCC sensitivity of a cost-effective renovation package by one-at-a-time and Monte Carlo variation methods.

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Abstract

Nearly Zero Energy Building (NZEB) is becoming a standard for new and renovated buildings throughout the European Union (EU). While the approaches and definitions are widely varying in the EU Member States, the elements included in the NZEB definition are universal throughout the EU. Those are high-energy efficiency, healthy indoor climate and renewable energy production systems covering a high share of the energy demand of the building. Furthermore, through the ongoing implementation of Directives related to energy efficiency and NZEB buildings, the EU commission has established that newly constructed NZEB and conversion of existing buildings to NZEB shall be done cost-effectively. This is assessed by linking Life Cycle Cost (LCC) and energy demand calculations, representing them in a cost-optimality plot and finding the optimal solution from the resulting Pareto front. Given that the results of an LCC calculation are quite dependent on the elements considered in a calculation model and its scope, this study takes an explorative approach to determine the most influential parameters in LCC calculations for a pre-selected cost-effective package. This is achieved by varying inputs using local and global variation methods. The local variation approach consists of a variation of one input while keeping the rest inputs at their baseline value. With global variation, all selected parameters are variated simultaneously. The one-at-a-time (OAT) approach identified the amount and unit cost of utility supply (district heating, electricity and gas) as the most influential parameters to the output. Moreover, OAT results are further used to rank the next five most sensitive parameters and perform global sensitivity analysis using Monte Carlo (MC) simulations. Linear multivariate regression, applied to MC results, revealed high R^2 values (≥ 0.98), suggesting a linear correlation between output and variable inputs. Sensitivity analysis applied to standardised regression coefficients of each variated parameter determined the unit price of attic insulation, gas price and the lifetime of the Heat Pump (HP), as the most sensitive parameters in the three investigated models.

Keywords: *LCC, NZEB renovation, robustness.*

Nomenclature

Acronyms	
NZEB	Nearly Zero Energy Building
EU	European Union
LCC	Life Cycle Cost
PDF	Probability Density Function
OAT	One-at-a-time
MC	Monte Carlo
HP	Heat Pump
DHW	Domestic hot water
DH	District heating
PV	Photovoltaic system
GC	Global Cost
NPV	Net Present Value
DR	Interest rate
PD	Price Development
TDC	Technology Data Catalogue
SRC	Standardised Regression Coefficient
SI	Sensitivity Index

1. Introduction

In a recently published Directive 2018/884 [1], the European Commission calls upon the Member States to develop national, long-term renovation strategies for cost-effective conversion of existing buildings to nearly Zero Energy Buildings (NZEB). Article 2a (b) of Directive 2018/844 further obligates the Member States to establish cost-effective approaches to renovate, respecting building type, location and potential trigger points during the lifecycle of the building.

In Denmark, for example, this is well-reflected in a new, voluntary sustainability building class that is to become mandatory from 2023 [2]. The new Danish classification includes social, environmental and economic sustainability criteria. Nine evaluation criteria are introduced, where parameters regarding occupant health represent the social category. The environmental and economic categories are expressed by Life Cycle Analysis and Life Cycle Cost (LCC) [3].

Besides that LCC is planned to be mandatory in Denmark, it has been widely applied to determine cost-optimal minimal energy demands in EU Member States and seek cost-optimal renovation strategies [4]. Cost optimality requires LCC calculations to determine global cost and compare the studied options, which allows for the selection of an optimal solution. Estimating the LCC of a solution requires financial and building-related parameters. Financial inputs and general boundary conditions are assumed based on national guidelines, standards, databases and/or historical data. Building-related calculation inputs depend on the scope of the analysis and sources of input parameters in the calculation. For instance, the more individual renovation measures are considered, the more input parameters must be defined.

When investigating the LCC for renovating an existing building, at least two aspects should be taken into account. Those are the energy demand necessary for operating the building to provide a healthy and comfortable indoor environment and the cost related to the applied improvements. Besides this, a calculation can include costs related to planning, management, administration, cleaning etc. Different revenue streams can also be accounted for. Those could result from non-recurring income, as governmental grants, or as recurring as tax deductions, rent instalments, or renewable energy sold to the grid.

Even though LCC can account for all of the costs mentioned above, revenue types, inflation and specific price development over the calculation period, their prediction accuracy is constrained by the certainty of input data. Furthermore, as discussed above, there are multiple parameters and values with different origins. For example, to calculate the contribution of supplied energy to global cost, one must estimate the necessary energy need and its cost. The energy need is typically determined by calculation tools, which pose certain uncertainty. Alternatively, the energy need can be determined using measured historical data; however, this approach also poses uncertainty as the measured amount is related to occupant behaviour, weather conditions and varies from year to year. Future energy costs are also uncertain parameters. Despite the predicted price developments and rather hefty information regarding energy unit cost, one can never be sure how close those forecasted trends would be to actual values.

Associated uncertainties in LCC can be quantified by design exploration methods and sensitivity analysis, where the input parameters are variated with pre-selected ranges and distributions. Such approaches are well-established when it comes to energy demand calculations, and their strengths, weaknesses and computational aspects have been comprehensively analysed and discussed [5–8]. Although sensitivity analysis of LCC calculations is not as widely researched topic as energy demand analysis, some publications have performed sensitivity on LCC with diverse objectives.

Financial assumptions seem to be the parameters in LCC analysis that are investigated the most. For instance, the impact of the energy price on a cost-optimal solution, found by the decision support scheme, is presented in [9]. Pallis et al. [10,11] perform a sensitivity study on the interest rate and energy price development for newly constructed single-, and multi-family NZEB buildings in Greece. The sensitivity of the same two parameters is also investigated in [12] for listed and non-listed multi-family buildings in Sweden located in different climatic zones. In [4], Ferreira et al. further include energy price as a parameter in addition to interest rate and energy price development. The uncertainty of seven energy-related inputs to LCC calculation is investigated in [13] for two scenarios, using the one-at-a-time (OAT) approach. The focus of study [14] is financial assumptions but uses an optimisation-based scheme to investigate many scenarios for a single-family house in Norway, including energy-saving measures, renewable energy sources, and systems. Another example of optimisation based schemes employing solution space exploration is presented in [15]. Such multi-objective optimisations are robust as the considered parameters' sensitivity is integrated into the method itself. However, a drawback of such methods is that they can be very time and expertise demanding practical implications.

There are also studies focusing on how a specific aspect of a renovation project affects a cost-optimal solution. For instance, [16] investigates occupant behaviour and its influence on cost-optimality. Nonetheless, the interest rate, energy prices and their expected developments seem to be in focus when it comes to sensitivity in LCC. Moreover, sensitivity analysis is often a secondary objective in research related to cost-optimal solutions. The main objective is the selection of an optimal package. To the authors' best knowledge in the time of writing, only study [17] performs uncertainty characterisation on 18 LCC input parameters. The study applies probabilistic methodology employing Sobol sampling combined with Monte Carlo (MC) approach. Convergence criteria are used to assess the sensitivity in a calculation concerning a single-family house in Italy. The case applies special economic consequences (penalties) for reduced usable floor area due to internal insulation with vacuum panels.

While most referenced studies seek and select a cost-optimal package, the main objective of this study is to define the input parameters of an LCC calculation and quantify their individual and combined influence on the output. This is accomplished using local - OAT and global - MC methods for variation of inputs of a pre-selected baseline model, representing renovation of a multi-family apartment building complex in Denmark.

The selected baseline model was found to be cost-effective in a previous work of the authors [18] (Package 7). It realised most energy savings for the least cost-increase compared to the studied alternatives. Using the method proposed in [18], renovation packages are compiled based on a cost-effectiveness parameter of individual energy-saving and energy-producing actions. As a final step of the method, the global cost for each compiled package is determined using LCC calculations and the cost-optimal package reaching (or closest to) NZEB can be identified. A secondary objective of this study is to test the robustness of the selected baseline in regards to global cost by comparing the remaining packages studied in [18].

This paper presents a local and a global sensitivity analysis applied to the selected baseline model. Local sensitivity (OAT) analysis is performed first for the model boundary conditions and then for building model inputs. The energy supply system for space heating and domestic hot water (DHW) in the baseline is also variated between three alternatives in order to investigate the influence of energy supply type on the results. For each energy supply system, an OAT analysis are applied to find the five input parameters with the most substantial influence on the output. Further, those are variated simultaneously, using the MC approach with quasi-random sampling to investigate possible interactions of the parameters and their correlation.

2. Method

The work presented in this paper aims to determine the impact of boundary conditions and model input on the output of LCC calculation concerning the renovation of a multi-family building located in Denmark. To do so, first, the origin and key details of the applied baseline are presented. Thereafter, section 2.1 provides a description of the applied LCC calculation method, where sections 2.1.1 and 2.1.2 depict boundary conditions and building-related model inputs, respectively. The local sensitivity of each model input is estimated by performing OAT variation, which is described in section 2.2. Global sensitivity is applied by the MC method, described in section 2.3. Finally, the sensitivity of the different parameters is analysed using methods described in section 2.4. Figure 1 shows a diagram of the approach used to define the input parameters and their sensitivity.

For this study, the case building investigated in [18,19] is used as a starting point for the analysis. The building has been operational since 1949 and houses 66 apartments with a total heated floor area of 5250 m^2. The existing source of heating and DHW is a District Heating (DH) substation. The primary energy demand of the building in its existing condition was determined by the Danish compliance tool BE18 and accounts to 130 kWh/m^2 year [18]. The selected renovation package, represented in the baseline model, provided approximately 40% energy savings and consists of re-insulation of the external wall, attic slab and pipe network for distribution of heating and DHW, new windows with energy class B, replacement of the circulation pump for DHW and 110 kWp roof-mounted Photovoltaic (PV) system [18].

As indicated previously, the baseline is suited with three different energy supply systems for space heating and DHW. The scenario with a new DH substation considers costs related to replacing the existing sub-station. In the other two scenarios, the existing DH substation is replaced with heat pump (HP) and natural gas boiler. Switching from DH to natural gas or HP as a supply source accounts for removing the DH sub-station and incorporating gas boiler or ground-source HP, respectively. Thereby, each of the three models would have common (renovation package-related) and individual (system-related) inputs parameters.

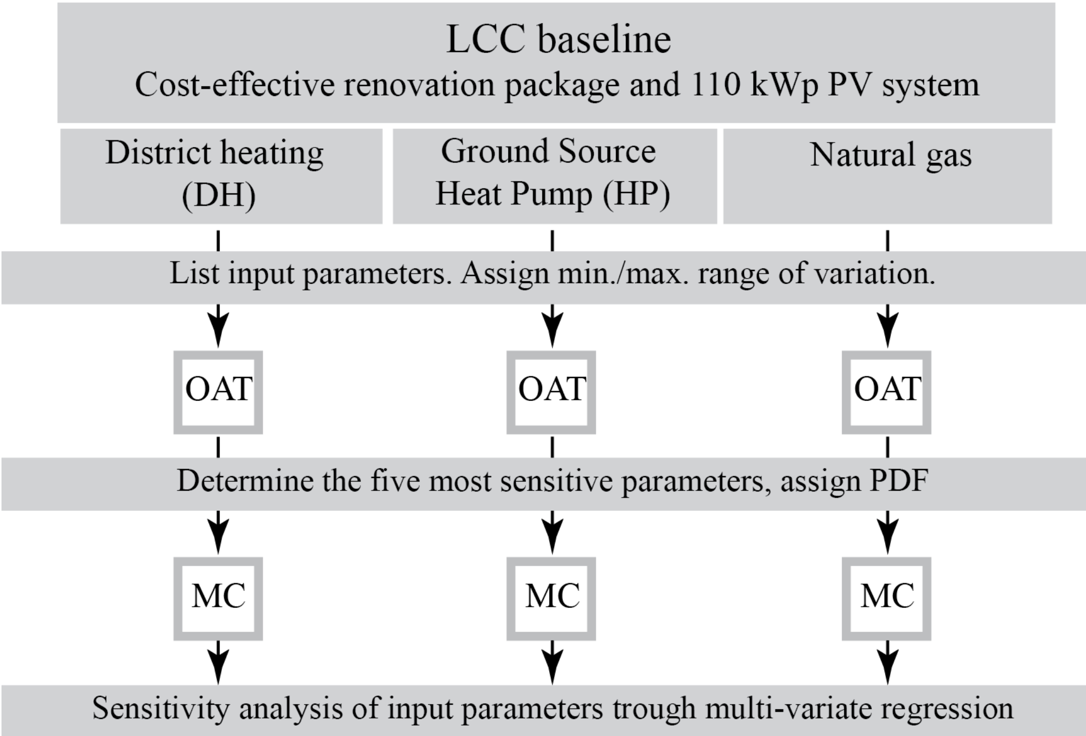


Figure 1 Diagram of sensitivity study applied in this paper.

The procedure and calculation methodology for LCC follow the standard DS/EN 15459-1:2017 [20]. Overall, a calculation model consists of boundary conditions and building-related model inputs. Boundary conditions include the calculation period and macro-economic factors for the calculation, i.e. interest rate and price development. The model input can be split into different categories, depended on the cost type. For instance: energy supply, acquisition, management, cleaning, component, recurring and non-recurring costs. Income from rent, incentives, loans or grants can also be integrated in an LCC calculation. Commonly evaluated outputs of LCC are global cost (GC), or net present value (NPV), depending on the objective of the calculation. Global costs are calculated using equation (1), shown with the same notation as given in standard [20]. The main difference between GC and NPV is that GC includes CO2 cost by definition. Those, however, are often excluded and thereby, NPV can be considered the same as CG. Carbon costs are excluded from the analysis of this study for the purpose of consistency and comparability to [18]; moreover, the monetary value of carbon costs and their future development is still quite uncertain.

$$GC = CO_{INIT} + \sum_{j} \left[\sum_{i=1}^{TC} (CO_{a(i)}(j) * \left(1 + RAT_{xx(i)}(j)\right) + CO_{CO2(i)}(j)) * D_{f(i)} + CO_{fin(TSL)}(j) - VAL_{ft_{TC}} t(j) \right] \quad (1)$$

CO – cost type (subscript: INIT – initial; a – annual; CO_2 – emission; fin(TSL) – disposal cost); VAL_{ft} – residual value; D_f – discount factor; t_{TC} - calculation period. RAT price evolution of parameter *i*-

To a great extent, the model inputs are dependent on the aim, scope and purpose of the performed study. As declared previously, this study adopts a baseline from previous research of the authors [18], and thereby the model inputs are pre-determined. The selected baseline model accounts exclusively for costs related to energy renovation of the selected package and building operation. That includes the cost for purchase of building components and associated energy supply systems, maintenance, replacement and operation (supplied energy). LCC calculations are performed using the free software LCCByg (version 3.2.14) [21]. The considered model output - NPV is used to determine the sensitivity and correlation of the variated input parameters.

1.1.1. Model boundary conditions

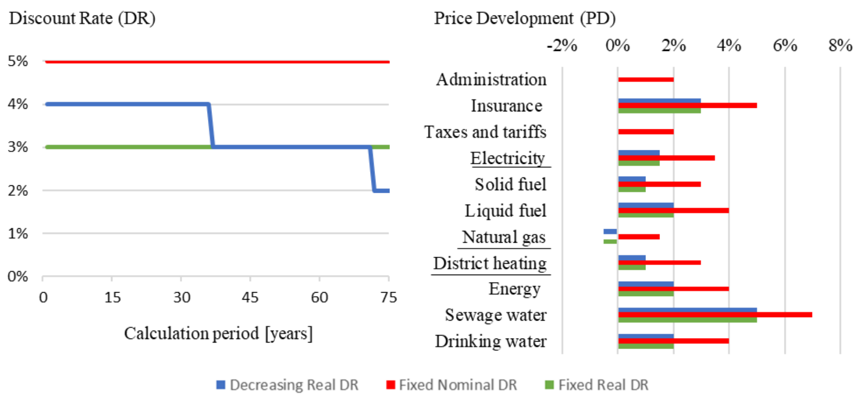
Boundary conditions in LCC refer to the calculation period and financial input parameters determined on a national level. In Denmark, the Ministry of Finance enforces discount rates (DR) and price developments (PD) for discounting future to present values. A guidance describing different DR types and their respective application was published on November 12, 2018, and recently updated on July 7 2021 [22]. The main difference in the letter being lowered DR with 0.5% point in the updated 2021 guidance, compared to 2018 values [23].

The guideline enforces a step-wise decrease of the real discount rate for public clients, as illustrated in Figure 2 (left). The applied LCCByg software provides two additional sets of assumptions – fixed real DR and fixed nominal DR. The respective values for each DR type are illustrated in Figure 2 (left), whereas, general description of the applicable building projects is outlined below.

- Decreasing real DR – This DR type is applied to public buildings, where a 1% decrease is applied after years 36 and 75. This DR type applies

fixed prices without inflation [23].
- Fixed real DR –Applied to projects concerning social housing organisations. As the name suggests, the discount rate and possible price developments are fixed and exclude inflation.
- Fixed Nominal DR – Prices and discount rates are stated in current prices, including inflation. This DR type is applied to projects requiring DGNB certification.

Optionally, a specific PD can be applied for different cost types considered in the calculation. Those can be observed in Figure 2 (right). If applied, the individual PD is used instead of the general PD (inflation). The origin analysis of the baseline models [18] applied PD to energy costs for operation and private energy demand, underlined in Figure 2 (right) and dictated by the applied energy supply system. For example, PD for gas and electricity in a scenario with natural gas boiler and only PD for electricity in the HP scenario.



rate types (left) and price development for different cost types (right) [22].
To investigate the impact of the three DR types on the resulting net present value (NPV), they are applied to the baseline model, using the OAT approach. Additionally, the impact of applying the optional PDs for DH and electricity is investigated by computing the DH baseline model with and without PD for each of the DR types.

2.1.2. Model inputs

A list of all calculation inputs included in the three variations of the baseline model is presented in Table 1. The table classifies the input parameters into five categories and depicts the baseline value and respective source. Model-specific parameters describing the variated energy systems are marked with a "*" before the parameter name and are the ones that are applied only in the appropriate models. The first three cost categories in Table 1 (operation, implementation and maintenance) are unit cost inputs. The last two are the lifespan of the elements and the amount (quantity) for each parameter.

Costs for energy renovation measures are obtained from the MOLIO price database for renovation works [24]. Cost related to energy-producing systems stem from Technology Data Catalogues (TDC); for individual heating installations [25] and energy-producing technologies [26]. The lifespan of envelope elements is taken from guidelines [27] and TDC [25,26] for energy supply systems. The energy demand for the operation of the building includes energy necessary for space heating, DHW and electricity (both building operation and private use). Building operation-related electricity is determined by the compliance tool BE18. Private electricity demand is determined through metered data at the building, collected during an energy audit described in [19]. The energy demand is calculated by the Danish compliance tool BE18 and already accounts for energy savings, achieved by the implementation of the renovation package and energy production by the roof-mounted PV [18]. The improved building element (m^2; m; piece) is determined through documentation and building audit, presented in [19].

The lower and upper bounds for the uncertainty range of the different parameters are shown in Table 1. Unit cost for represented energy sources is determined from available data in the price database, published by the Danish Energy Agency (DEA)[28] in 2018. The granularity of the different energy supply sources differs for DH, gas and electricity. The baseline model's district heating unit cost is determined by averaging the available data for 392 different locations across Denmark (2018 database). Electricity unit cost data is available as annual values, categorised concerning usage type (household or industry) and consumption range. The baseline unit cost for electricity is selected as the average annual household electricity price excluding VAT, taxes and levities, for the period 2007 – 2018 and lowest consumption range. Gas unit cost originates from the same period, though using monthly instead of annual data points. The unit cost of the different energy sources and the determination of their applied variation are discussed further in the following sections of this paper.

Table 1 List of input parameters

			Baseline		OAT	
Category	**Parameter**	**Unit**	**Value**	**Source**	**Range**	**Source**
Operation	*District heating	€/MWh	69.29		18-128	Database min/max
(energy supply)	*Gas	€/m^3	0.796	DEA [28]	0.635-0.913	
	*Electricity	€/MWh	230.1		210-330	Database min/max
	*Electricity-HP	€/MWh	93.54		-	
Implementation	*DH sub-station	€/system	15,600		12-20K	
	*Gas boiler	€/unit	24,600	TDC [25]	20-30K	TDC [25]
	*Heat Pump	€/unit	249,000		235-265K	
	Roof mounted PV	€/system	80,300	TDC [26]	49.5-134.2K	Assumed ±20%
	Ex. wall insulation	€/m^2	20.7		17-25	
	Ex. wall cladding	€/m^2	17		13-20	
	New windows	€/m^2	73	MOLIO [24]	69-88	Assumed ±20%
	Attic insulation	€/m^2	130		104-156	
	Pipe network ins.	€/m	11.8		9-14	
	Circulation pump	€/unit	1,098		879-1318	
Maintenance	*DH sub-station	€/year	136		108-189	TDC [25]
	*Gas boiler	€/year	651	TDC [25]	531-814	
	*Heat Pump	€/year	1650		1070-2850	TDC [25]
	Roof mounted PV	€/year	1,144	TDC [26]	781-1342	TDC [26]
	Ex. wall insulation	€/year	551		440-660	
	Ex. wall cladding	€/year	894		715-1072	
	Windows	€/year	1,147	LCCByg*	918-1376	Assumed ±20%
	Attic insulation	€/year	228		1814-2722	
	Pipe network ins.	€/year	373		298-447	
	Circulation pump	€/year	11		9-13	

			Baseline		OAT	
Category	**Parameter**	**Unit**	**Value**	**Source**	**Range**	**Source**
Lifespan	*DH sub-station	Year	25		20-30	
	*Gas boiler	year	25	TDC [25]	25-40	TDC [25]
	*Heat Pump	year	20		15-25	
	Roof mounted PV	Year	30	TDC [26]	25-40	TDC [26]
	Ex. wall insulation	year	50		40-60	
	Ex. wall cladding	year	120		95-145	
	Windows	year	50	sbi [27]	40-60	Assumed ±20%
	Attic insulation	year	50		35-65	
	Pipe network ins.	year	80		65-95	
	Circulation pump	year	25		20-30	
Amount	*District heating	MWh	483.37		387-580	
	*Gas	m^3	45,078			
	*Electricity- DH and gas	MWh	51,072	calculated BE18	41.6-62.4K	Assumed +-20%
	*Electricity – HP	MWh	216.8			
	Ex. wall insulation	m^2	2660		2128-3192	
	Ex. wall cladding	m^2	2660			
	Windows	m^2	1570	Measured	1256-1885	Assumed +-20%
	Attic insulation	m^2	1750		1400-2100	
	Pipe network ins.	m^2	3160		2528-3792	

LCCByg* - standard values in the software, based on sbi [27].

2.2. Local sensitivity analysis – OAT

Local sensitivity analysis in this paper refers to one-at-a-time (OAT) variation of input parameters. Having the baseline as a starting point, each input value is variated consecutively, while the remaining parameters are kept constant. The OAT analysis is performed in twofold, distinguishing between variations of boundary conditions (see section 2.1.1) and building-specific model inputs (see section 2.1.2).

The baseline represents a multi-family building owned by a social housing association. Ergo, respecting the DS/EN 15459-1:2017 [21] guidelines for such building type means applying decreasing real DR for 50 years. As previously pointed out, PD for energy costs have been considered in the respective models. However, to assess their direct effect on the output, PD for electricity and DH are variated in addition to DR type and calculation period.

First, the three different DR types described in section 2.1.1 are applied in turn to the baseline. For each of the DR types, the calculation is performed for a range of calculation periods from 10 to 60 years with a 10-year step interval. In addition, price development for electricity and district heating are applied individually and in combination for each DR type and calculation period. OAT analysis for DR types and specific PD were applied only to the baseline model that utilises district heating as the main supply for heating and DHW. This is done to quantify the difference between applied DR, PD and for variation of calculation period. In respect to DS/EN 15459-1:2017 [20], the calculation period to be applied for residential buildings is 50 years.

Given that the building is owned by a social housing association and provided that for this type of client (public), one must follow the Ministry of Finance [23], DR can be considered deterministic. This is as DR is determined by the standard meaning that a designer is obligated to apply a specific one, thus not variable. Thereby, boundary conditions are variated by OAT only, where the purpose is to quantify the possible output variation for the different DR types, price developments and calculation period.

The second step in the OAT approach consists of variating model input parameters related to the specific building renovation; in this case, the input parameters that make up the baseline. Two variations for each parameter are performed – one with the lower and one with the upper value of uncertainty, defined in Table 1.

As specified in Table 1, the ranges for different parameters are obtained from different sources. Costs related to energy supply and renewable systems are obtained by the two TDC published by the DEA. Cost related to renovation works and energy efficiency improvements originates from the MOLIO database, whereas the ranges are assumed due to a lack of a better source. Lastly, the cost for the operation of the building stems from the DEA's historical energy price database from 2018 [28]. The unit cost for energy types used in the baseline and variation ranges applied in the OAT calculations are determined as follows:

• District heating (DH) – the unit price for district heating is available for 392 DH plants across Denmark. There is great variation in the cost of delivered heat across Denmark. Because of that, cost data in [29] is given as annual values for 2018, found in the 392 different DH plants and not for historical values such as electricity and gas. The average price for 2018 from the different stations is 525 DKK/MWh and varies significantly from one DH plant to the next (±135 DKK/kWh). The range for OAT calculations is determined by the minimum and maximum value for the represented in the database values.

• Electricity – the unit cost of electricity is a quite complex and uncertain parameter. The final unit cost depends on the "raw" energy price and several other factors influencing the price. Some of the main factors are governmental fees and taxes, provider subscription expenses, network maintenance and fees. Moreover, some of those fees are fixed while others are added with respect to the building heating system and demand. For example, a general charge of 88.4 øre/kWh is added to the electricity price. If the building is heated by electricity, an additional 25.9 øre/kWh is owed by each client (building owner) [29]. Moreover, a variable "PSO (Public service obligation)" is added when forming the final electricity price. As all of those price elements are highly variable, and most of them are to be paid by private clients, the calculations exclude VAT, taxes and fees. In addition to all taxes and fees, electricity price is also dependant on the annual amount of purchased electricity by a "client" of the energy providers, e.g. building owner or apartment tenants. Clients of a supply company are classified into categories (usage intervals) from small – single-family homes to large - industrial clients. Naturally, the unit cost for large clients is lower than this for small clients. As the baseline considers a multi-family building, the baseline value was selected considering medium-size client (usage interval from 2.5 < 5 MWh) and determined as the average of available annual data for 2009-2018. It should be pointed out that the analysis presented in [18] and those presented in this paper account for the purchase of electricity for the whole building globally (e.g. building operation and private use in apartments are analysed as input). In reality, the building owner and each tenant would be individual clients to the electricity provider. Thus, tenants would be categorised/charged according to costs respective to low usage intervals, while the building owner would likely be categorised as a client in the higher usage intervals with lower unit costs. The range applied in OAT analysis represents the minimum and maximum annual values for electricity cost of different usage intervals to investigate the effect of this simplification.

• Gas – Unit costs for gas are also differentiated by client type (household or industry) and - the amount of purchased energy. A breakdown of household gas prices is provided on a monthly basis for the period 2009-2018. Each aspect contributing to the total gas price is represented individually. Given that the gas price has been rather stable [28] for the period 2009-2018, the baseline value was determined by average cost, while the OAT range as the minimum and maximum values for the whole period and excluding VAT. Gas prices are also available as annual values for different usage intervals (client sizes). Since in a scenario where gas is the source for centralised heating and DHW supply, the energy demand of the building would be a determining factor for the unit cost of gas. However, just as for electricity, governmental taxes and local subscription tariffs are also major determining factors for the total cost. Those are included in the OAT variation, as the baseline adapts average, minimum and maximum values in 2007-2018, excluding VAT but including government taxes and levies. Furthermore, baseline values were selected based on the smallest available usage interval (<20GJ gas).

Ranges for implementation, maintenance and lifetime of the energy systems are referenced in Table 1 TDC [25,26]. The variation ranges for energy efficiency improvements are determined as ±20% variation from the baseline due to the lack of a better source. The same ±20% are applied to the quantity of the different material input. These variations, for instance, could result from wrong quantity estimations related to different renovated building parts or insufficient documentation, leading to uncertain assumptions.

Once all variations are computed with their respective minimum and maximum values, the sensitivity index of each parameter is determined by equation (2). The parameters are sorted in ascending order with respect to the calculated sensitivity index. This procedure lists the most influencing to the output parameters first and allows for selecting the desired top five most influential inputs.

$$\boldsymbol{Si} = \frac{\Delta \boldsymbol{y_i}}{\sum|\Delta \boldsymbol{y_i}|} \qquad \textbf{(2)}$$

Where Δy_i is the difference between the output values obtained from the minimum and maximum variated input value of parameter *i*.

2.3. Global sensitivity – Monte Carlo (MC) method.

Contrary to OAT, the MC method allows for quantification of the combined (global) effect of the variated parameters. This is achieved by continuously reproducing calculations of the baseline model, where selected input parameters are variated simultaneously, based on random or quasi-random sampling techniques. The sampling applied in this paper is realised by Sobol sequencing for the selection of the quasi-random samples. Quasi-random sampling allows for better coverage of the solution space than random sampling, as clusters of closely distributed input values are avoided [8].

The sequence for a successive step in the analysis consists of generating the quasi-random value in the range of 0-1, which is then used to select the values for variated inputs via cumulative PDFs for each parameter. The procedure is done for the total number of chosen samples, which is 5,000 for each supply system. Once all sample inputs have been determined and saved into an input matrix, AutoIT script is applied to compute each set of inputs in LCCByg and export the result. The procedure is then repeated for all samples.

As previously explained in section 2.2 of this paper, the parameters variated in the global analysis are selected respecting their sensitivity index. Once the parameters are identified, the ranges and data availability used in the OAT approach are examined in detail. This is completed to assign appropriate PDFs for the parameters, respecting the parameter type, available data and identifiable forecasting trends. Performing such a study for all input parameters would be tedious, lengthy and, to some extent, redundant work. That is why a detailed investigation of applicable data is done for the pre-selected parameters by OAT only. The selected parameters used in the global sensitivity method and their distribution types and ranges are presented in section 3.2.1.

2.4. Sensitivity analysis (SA)

SA is applied to assess the relationship between input and output and compare models with alternative energy supply systems for space heating and DHW. Determining how each input contributes to the output is done by performing multivariate linear regression analysis known as Standardized (Rank) Regression Coefficients (S(R)RC). It is based on a standardised input matrix and output vector, done by equation (3) for each of the inputs (xi,j) and the output (yi,j).

$$\mathbf{std\_}\boldsymbol{x_{j,i}} = \frac{\boldsymbol{x_{j,i} - \mu_x}}{\boldsymbol{\sigma_x}} \qquad \mathbf{std\_}\boldsymbol{y_{j,i}} = \frac{\boldsymbol{y_{j,i} - \mu_y}}{\boldsymbol{\sigma_y}} \tag{3}$$

The standardised coefficients are then used for the regression model, which applies the least-squares method to calculate a line fitting to equation (4) for the five inputs ($x_1 - x_5$) and output data (y_1).

$$\boldsymbol{std\_y = b_1\, std\_x_1 \;+ b_2\, std\_x_2 \;+ \cdots + b_n\, std\_x_n \;\ldots + \varepsilon} \tag{4}$$

Where b_i is regression coefficients responding to each x_i parameter and ε is a constant.

The obtained regression coefficients (b_i) are used to determine the importance of the respective input, as its value quantifies its sensitivity. The larger the coefficient, the more sensitive it is. The sensitivity index (SI) is estimated as the relative share of each regression coefficient to the absolute sum of all coefficients, as illustrated by equation (5).

$$\boldsymbol{SI_{x(i)}} = \frac{\boldsymbol{b_i}}{\sum|\boldsymbol{b_i}|} \qquad \textbf{(5)}$$

Given that the applied regression model is linear, the standard coefficient of determination (R2) is assessed alongside to verify or disprove the linearity of the baseline model. The R2 value ranges from zero to one and represents the difference between estimated and actual y-values. R2 value close to one indicates a good correlation of the studied sample, thereby a linear LCC calculation model. On the other hand, if the R2 value is closer to zero, the linear regression is not suitable for predicting the output.

3. Results

3.1. Local sensitivity– One-at-a-time (OAT) approach

This section presents the results from the OAT approach, which is performed in two stages – one for boundary conditions and one for model-specific input. First, section 3.1.1 presents the results from the variation of discount rate (DR) types and calculation periods, defined in 2.1.1. After that, all building-related model inputs, variated with their minimum and maximum values and presented in section 3.1.2. This sub-section also presents the sensitivity of each parameter and which five are chosen for variation in the global Monte Carlo method.

3.1.1. Boundary conditions

The results concerning DR type and individual price developments (PD) are presented in Figure 3. The sensitivity index depicted on the y-axis of the figure is calculated using equation (2), where Δy for each case is calculated with respect to the financial conditions of the baseline - decreasing real DR, 50 year calculation period and disregarding specific price developments. Given this consideration, the positive sign index represents scenarios with a higher cost than the baseline. As evident from Figure 3, the variation from the baseline due to PD is relatively small (<0.1). When comparing the two different PDs to the baseline model (decreasing DR), it can be noticed that PD for DH has a higher impact than PD of electricity for all DR types when applied individually. The combined effect on the result when PDs for both energy sources are applied is slightly lower for real DR types and additive for fixed nominal DR.

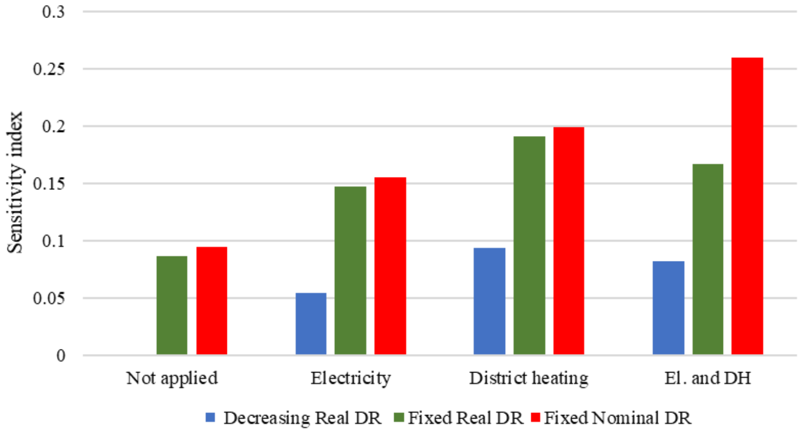


Figure 3 Sensitivity index for different discount rate (DR) types and price developments (PD) compared to the baseline (Decreasing DR and no applied PD), considering 50 year calculation period.

Figure 4 shows the sensitivity index for the DR rates calculated for different periods disregarding PDs. The calculation period affects the results nearly linearly, recognised due to a proportional change in sensitivity index with a change in the calculation period. The difference between the successive calculations steps is nearly equal, but an increase of the index is noticed for the shortest calculation periods. Overall, it can be stated that the calculation period is the boundary condition that will have the greatest influence on the final result, compared to DR and the application of PD. A 10-year difference in the calculation period would change the output more than applying different DR rates or PDs.

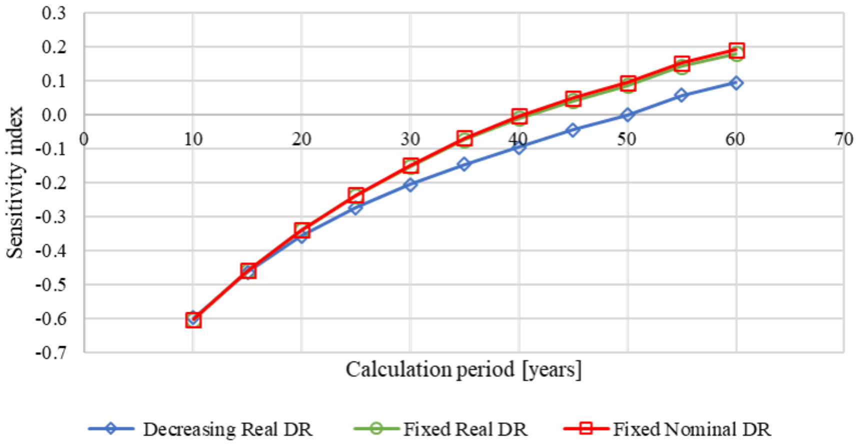


Figure 4 Sensitivity index for three discount rates as a function of calculation period.

3.1.2. Model inputs

The second investigation employing OAT methodology is applied to building-related model inputs, defined in Table 1. As described in section 2.2, OAT calculations of model inputs are used to identify the most impactful parameters for the output - in this case, NPV. Figure 5 shows the sensitivity index of each parameter for each investigated energy supply system. Sensitivity indexes depicted in Figure 5 are calculated in accordance with equation (2) for respective ranges stated in Table 1.

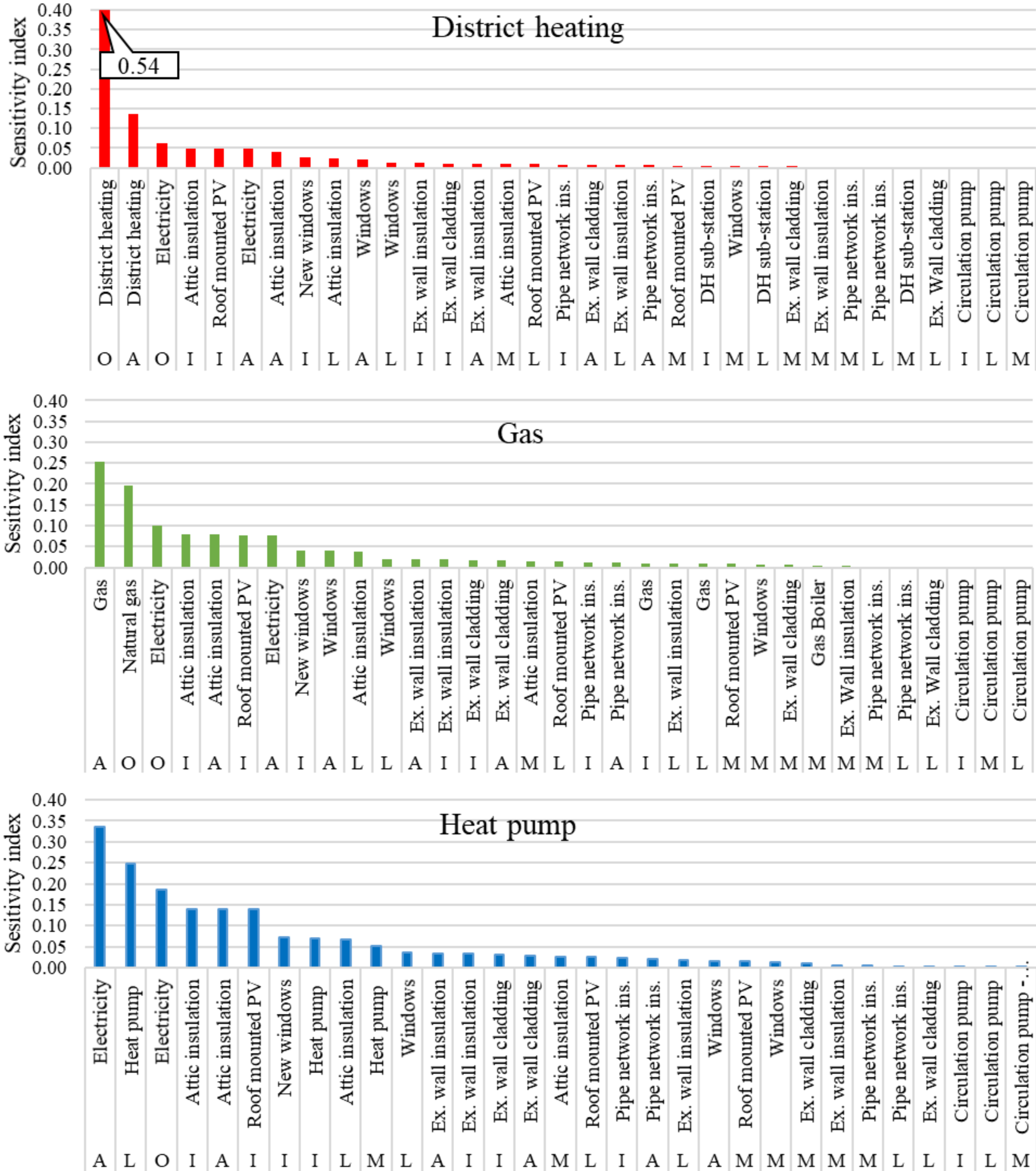


Figure 5 Results from variation input parameters using OAT approach.

For the three investigated systems, parameters related to fuel cost and amount rank highest. An exception makes the Heat Pump (HP) scenario, where the lifetime of the HP outranks electricity amount with the second-highest sensitivity index. A plausible explanation for that is the high investment (and thereby replacement) cost of HP. Applying the upper and lower limit values for the HP's lifetime in OAT variation results in one extra or less system replacement for the calculation period. The remaining parameters that follow fuel cost seem to be ranked (positioned), if not in the same order, then very close to the same order - all the way to the least sensitive inputs.

Despite their front-ranking position, parameters describing the amount of electricity, gas and district heating energy are excluded from variation in the global analysis. This decision is made, as the sensitivity of energy demand is a topic on its own that is highly dependent on the method for deriving the final value of delivered energy. The results in Figure 5 show that the amount of energy has a significant influence, regardless of the applied system. Therefore, one should be sure of the value's origin (or used method) when striving for high accuracy LCC.

In contrast, the unit cost of the different fuels is considered in the global sensitivity analysis. Energy unit costs are also a rather uncertain parameter. The main uncertainty in the development of fuel cost lies in national and local factors (subscription fees, local rates, building usage type) and can be quantified by historical and/or forecasted data. Price variation for electricity and gas is determined based on historical and forecasted values (described in further detail in the across the country, which operate on various sources and function on principles, characterised by different costs - evident from DEA database [28]. While the unit cost varies on a national level, the value for a specific building depends on the location. Thereby, the DH unit price is considered deterministic since the owner would have to pay the cost of DH for the region that the building is located. Regarding the results show in in in Figure 5, DH unit cost presents the single largest sensitivity index. In view of its deterministic essence, DH unit cost is not varied with the MC method; however, it is still accounted for in a differen manner. Accounting for the large national price variation is done by fixing DH unit cost at a low, medium and high value and variating the next five most impactful parameters. The low and high DH unit cost are chosen as 2σ from the mean value (low = 34, medium = 68, high = 108 €/MWh). In essence, three variations incorporating the aforementioned DH prices are calculated for the DH scenario. This method is applied to quantify the relative importance and possible interactions of the next five parameters with DH unit cost. Furthermore, identify if any changes occur in the relationship between inputs and output caused by the level of DH unit price. The parameters variated in MC analysis for each system type are summarised in Table 2 and discussed in detail in the following section.

Table 2 First five most sensitive parameters for each system, excluding the energy required for building operation.

	Rank according to sensitivity index				
	1	2	3	4	5
District heating	unit cost electricity	unit cost attic insulation	unit cost roof PV	amount attic insulation	unit cost new windows
Heat pump	lifetime heat pump	unit cost electricity	unit cost attic insulation	amount attic insulation	unit cost roof PV
Gas	unit cost natural gas	unit cost electricity	unit cost attic insulation	amount attic insulation	unit cost roof PV

3.2. Global sensitivity

3.2.1. Variated parameters

Table 2 summarises the top five ranking parameters (excluding amount of energy) for each scenario comprising of different energy supply systems. Four of the parameters are common for all scenarios: the unit cost of electricity, attic's insulation and roof-mounted PV's, and the amount (m^2) of attic insulation considered in the calculation. Besides the shared parameters, a model-specific parameter is identified for each of the three cases. For DH, that is the unit cost of the new windows; for HP- the lifetime of the HP and for gas, it is the unit cost of the fuel.

As discussed in the previous section, electricity price is a rather complex parameter to predict. Two of the determining factors being the annual amount of supplied electricity to the client and the type of heating system (e.g. electrical or another source for space building heating). In that sense, the "profile" of the building owner may change if switching from fuel-based to electrical heating system. Firstly, due to the larger amount of purchased electricity (usage interval). Secondly, due to additional fees if the building is heated on electrical energy [29]. The unit cost difference in the electricity price can be observed in Figure 6, which shows historical and forecasted data for two distinct usage intervals for electricity and gas. The figure collects data from the DEA price database [28] mentioned above and a more recent DEA publication on socio-economic calculations, including the cost of energy [30]. The latter provides forecast values for electricity and gas costs for the period 2020-2040. The forecast is based on 2019 values, and for electricity is provided for a single usage interval, whereas for gas, a forecast for several different intervals is available. Solid bars in Figure 6 represent electricity prices for the second-largest interval (<15 MWh), while the patterned addition depicts unit cost for the smallest usage interval (used to determine unit costs in the baseline model).

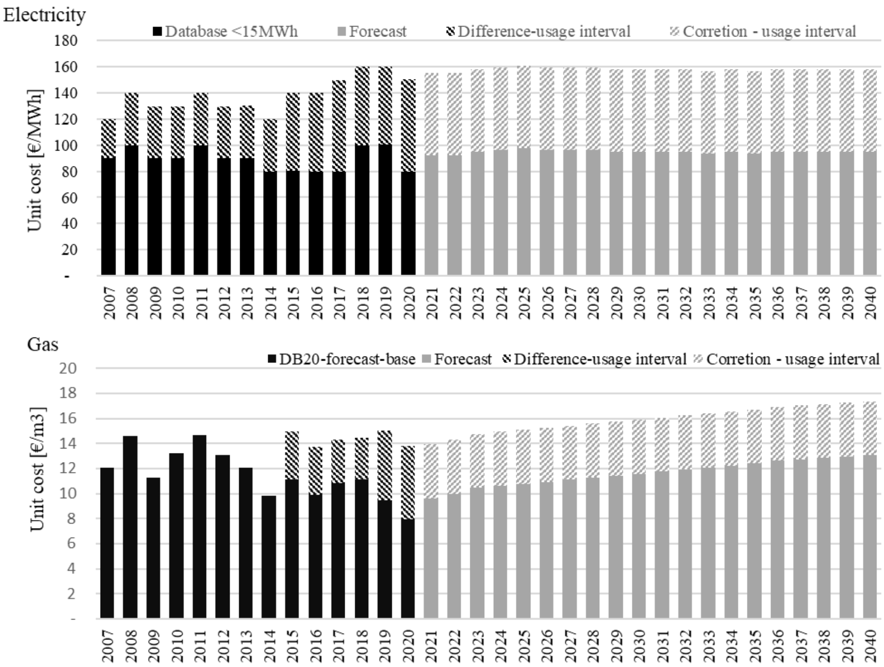


Figure 6 Historic (black) and forecasted (grey) values for electricity and gas. Diagonal pattern fill represents unit cost difference for relevant usage intervals. Forecasted values are corrected for the applied usage interval in the simulations.

The electricity demand in the LCC model is represented by a single input value accounting for the total building demand (operation and private). The majority of electricity need in DH and gas scenarios is attributed to private apartments, in contrast to the HP scenario where electricity for building operation accounts for approximately 80% of the total demand [18,19]. Thereby, for DH and gas scenarios, the majority of el would be "paid" at the highest price (low usage interval), where for the HP scenario, increased electricity demand (101 MWh/y) classifies the building owner in the highest usage interval (>15 MWh). For 2018 difference between the smallest and largest interval is 60 €/MWh el[4] (approximately 60%). This difference is not taken into account for HP scenarios in the analysis presented in [18]. From Figure 5 and Table 2, it is evident that the considered electricity price significantly impacts the output. Thereby, the work in this paper accounts for price difference by applying PDF derived from (low-interval <1 MWh; higher cost) models with DH and gas and from a high interval usage (>15MW; lower unit price) for HP scenario. The PDF in both intervals are shown in Figure 7 and are comprised of all forecasted data points and the last five annual historical data values (2015-2020) in Figure 6.

[4] DEA 2018 [28] exc. Excluding taxes and levies

Like electricity, the forecast for natural gas prices is provided in [28] for a higher usage interval than the one applicable to the investigated renovation package. Forecasted gas values are corrected (hatched pattern in Figure 6) in the same manner as those for electricity. Moreover, to increase the variation and anticipate the uncertain changes in the forecast, data for determining PDF and CDF of gas is from the same interval span as for electricity – all forecasted corrected values and historical values for the period 2015-20.

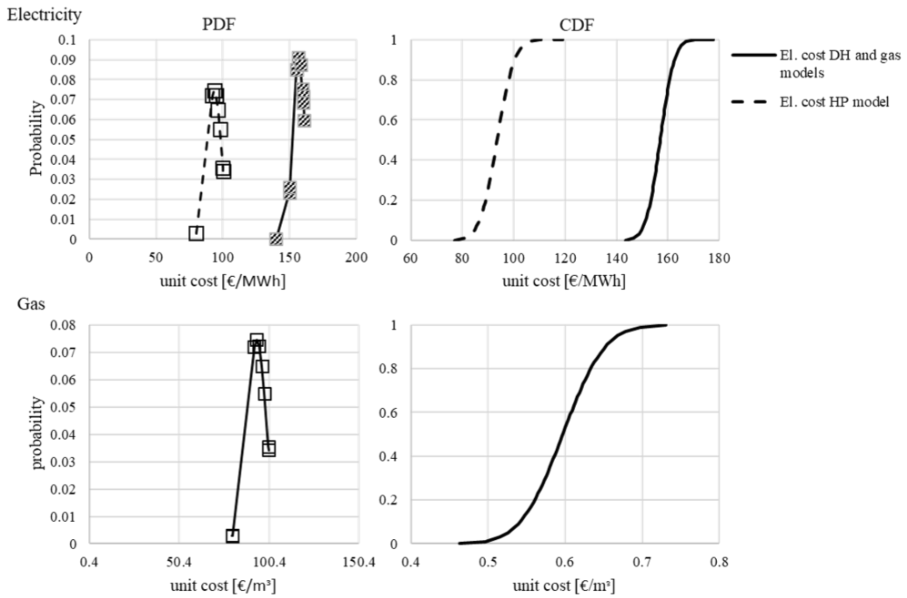


Figure 7 Probability density function (PDF - left) and cumulative distribution function (CDF – right) for electricity and gas, respectively

Unit cost for implementation of new windows is described by a normal distribution function. All remaining parameters identified in Table 2 are variated by means of uniform distributions with the ranges identified in Table 1. The applied variation range is based on the cost of windows with the same energy performance (class B) but differing in price due to opening mechanism and frame material. Data used for calculation of standard deviation and mean and resulting PDF are acquired from renovation cost analysis in [19], which are also the basis for selecting the renovation package forming the baseline model in this paper. Table 3 summarises the variated parameters, their respective distribution types, sources and limit values.

Table 3 Summary of variation parameters applied in Monte Carlo method.

Category	Parameter	Unit	PDF		Source
Operation	Electricity – DH and gas	€/MWh	Normal	μ=157; σ= 4.39	DEA [28] and [30]
	Electricity – HP	€/MWh	Normal	μ=93.5; σ= 5.35	DEA [28] and [30]
	Gas	€/m³	Normal	μ=0.6; σ= 0.04	DEA [28] and [30]
Implementation	Attic insulations	€/m²	Uniform	104-156	Assumed
	Roof mounted PV	€/system	Uniform	49.5 – 134.2K	TDC [26]
	New windows	€/m²	Normal	μ=147.1; σ= 50	Assumed
Lifespan	Heat pump	year	Uniform	15-25	TDC [25]
Amount	Attic insulation	m²	Uniform	1400-2400	Assumed

3.2.2. Sensitivity analysis

This section presents the results for all models variated with Monte Carlo (MC) method. To begin with, results for the three models representing different fixed levels of DH unit cost are analysed by histograms and calculated cumulative distribution functions. After that, results concerning parameter sensitivity and model linearity are presented.

The effect of the distinct, fixed unit costs of DH on the NPV output is shown in Figure 8. As it can be observed, the spread and range of variance of the results seem to be identical for the three cases. Clearly, the results differ due to the distinct unit cost of DH applied in each case (low = 34, medium = 68, high = 108 €/MWh), but as it can be observed, the distribution, spread and variance magnitude seem to be identical. This is confirmed, given that the resulting standard deviation of each of the three distributions is equal (σ = 117,220 €). The mean value of the results for the low, medium and high price of DH unit cost is -1.54, -1.93 and -2.31 million euro, respectively. This suggests DH unit cost also influence the result in a linear manner. This can be stated due to (1) the equal variance of the three distributions and (2) the exact regression coefficients and R2 values obtained from the regression analysis, shown further in the section.

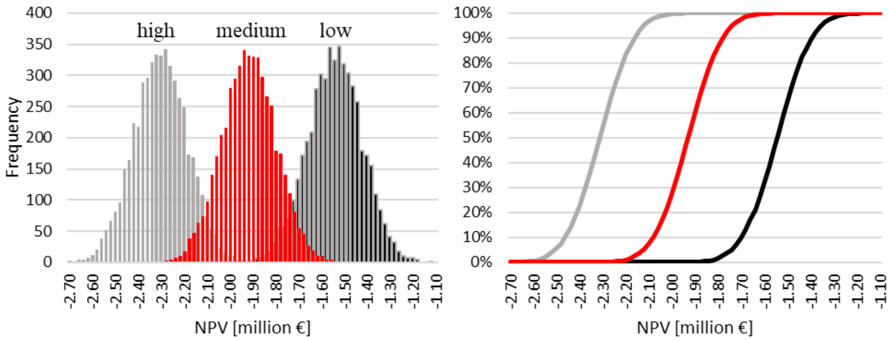
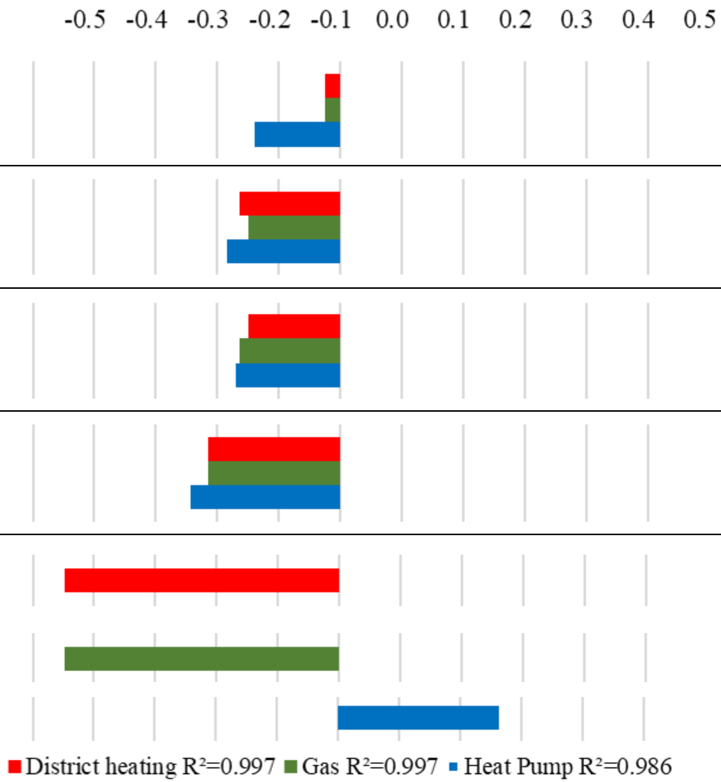


Figure 8 Probabilistic NPV for LCC calculation models incorporating district heating at three distinct costs of energy supply.

Table 4 provides a summary of multivariate regression results for each model. The first four parameters (unit cost of electricity, attic insulation and PV, and the amount for attic insulation) are common. All four are variated in every model. In contrast, parameters 5, 6, and 7 are specific for DH, gas, and HP models. Complete regression result for each model variation is available in Appendix A.

Table 4 Summary of linear regression results for the three investigated space and DHW heating systems. Source [4]

Nr.	Variable	Sensitivity	Standardised Regression Coefficient (SRC)		
			DH	GAS	HP
1	Electricity unit cost		-0.029	-0.067	-0.303
2	Attic insulation unit cost		-0.299	-0.447	-0.400
3	PV unit cost		-0.237	-0.408	-0.366
4	Attic insulation amount		-0.393	-0.588	-0.526
5	**Model DH:** New windows unit cost		-0.823		
6	**Model: Gas** Gas unit cost			-1.229	
7	**Model Gas:** Lifetime of HP				0.57



All sensitivity indexes, except the lifetime of HP, in Table 4 are negative. This means that an increase of a variated value would result in a decrease in the output. Since calculations consider only expenses (disregard positive cash flow/ income), the NPV output is negative, thereby decreasing the output asserts a more costly solution. The results of DH and gas models suggest close to equal importance for the four common parameters. The unit cost of electricity is the parameter with the most negligible influence on the output. For gas and DH, it is noticeably less impactful than the remaining variated inputs. The unit cost for attic insulation and implementation of PV is the next most influential parameter, where minor differences can be noted for gas and DH. In the case of DH, the unit cost for implementation of PV is more influential than the unit cost of attic insulation and vice versa for gas. The model-specific parameters in DH and gas scenarios (unit cost for new windows and gas, respectively) are the most influential in the respective cases.

Regarding the HP scenario, there are a couple of main differences compared to results for DH and gas. The first main difference is the positive sign of the regression coefficient of HP's lifetime. It is expected as a high value of the parameter (longer lifetime) results in decreased NPV. In this case, increasing the heat pump's lifetime with 1 σ (3 years) would change the output with 0.57 standard deviation in the positive direction. The second main difference for HP results is the difference in the relative importance of the five variated parameters.

Contrary to results for DH and gas, derived coefficients for the HP have smaller differences between them, and thus the importance is more evenly distributed. While the least influencing parameter is still electricity unit cost, its importance is much greater compared to scenarios of gas and DH. This is an interesting observation, as the electricity cost in the HP model is lower than DH and gas models (see Figure 7); however, the increased electrical consumption compensates for the price difference and increases the importance of the parameter. The order for the second, third and fourth parameters in the HP scenario are the amount of attic insulation, the unit cost of attic insulation and PV implementation.

3.3. Global cost robustness of the baseline

The secondary objective of this study is to test the robustness of the identified cost-effective package in [18], applied as a baseline for the sensitivity analyses studies in this paper. Robustness analyses are carried out by comparing the variations from the MC method to GC of renovation packages obtained in [18].

The comparison for the three energy supply systems is shown in Figure 9, where the grey markers depict packages from [18], while the marker types categorise the packages by achieved energy savings. Packages 1-6 with approximately 20%, Packages 7 and 8 with 40%, and 9 and 10 with 60% energy savings compared to the pre-renovated energy demand of the case study building. The variations attained by the MC method for the baseline (Package 7) are visualised by the box plots in Figure 9. The mid-line in the box plot marks the median of the output data, while "x" depicts the mean. The box bounds the first and third quartile (interquartile range, meaning 50% of the observations), whereas the whiskers bound the minimum and maximum data values excluding extremes.

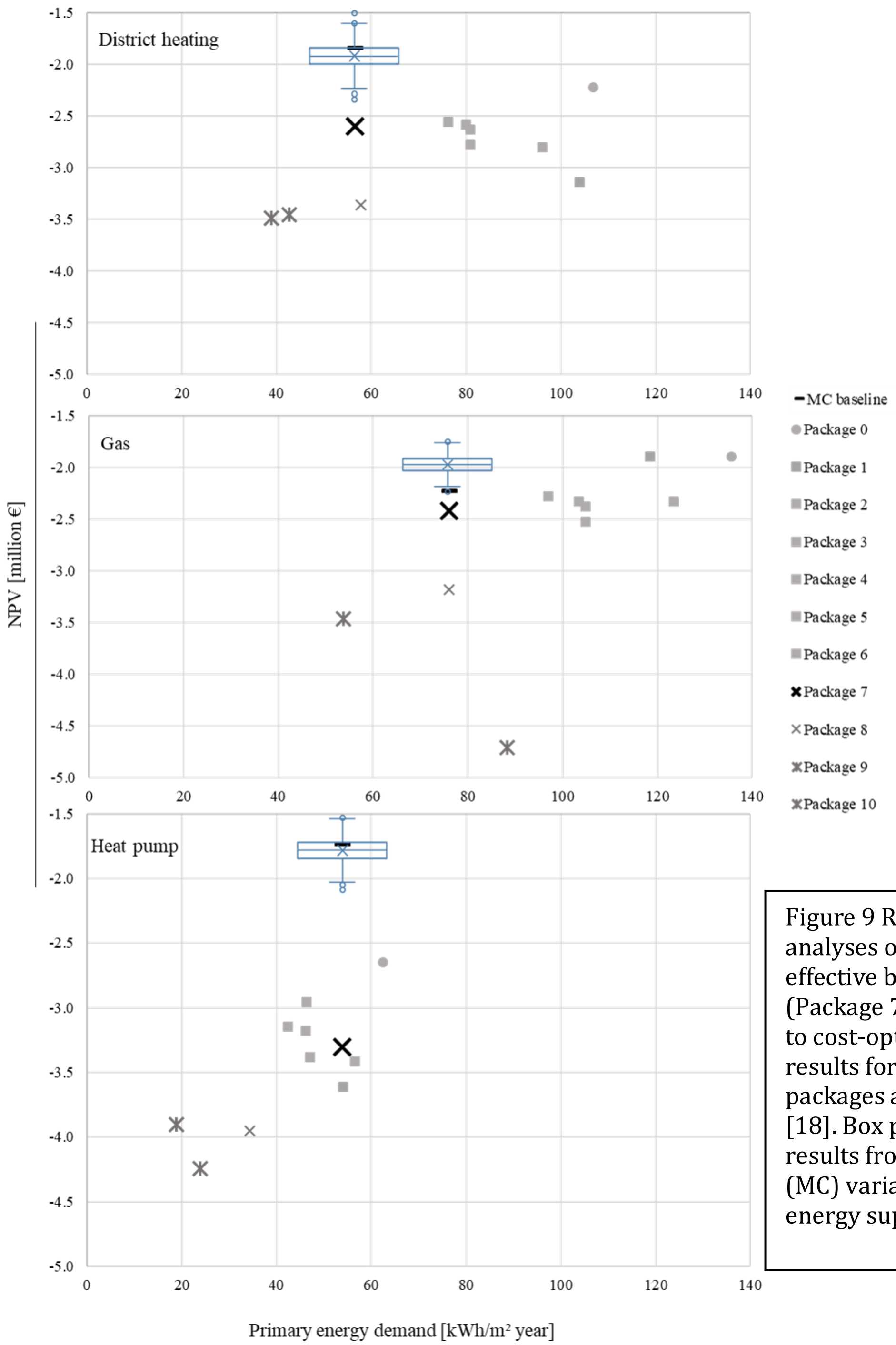


Figure 9 Robustness analyses of the cost-effective baseline (Package 7), compared to cost-optimality results for renovation packages adapted from [18]. Box plot depicts results from Monte Carlo (MC) variation for three energy supply systems.

A key observation in Figure 9 is a discrepancy in NPV values of Package 7 from [18] (marked with a black cross) and the baseline values for the studied systems (marked with horizontal line), despite that both models are identical. This is caused by updated DR from 2018 to 2021. As stated in section 2, the updated DRs are 0.5% points lower than the previously applied values from 2018. As expected and stated in [23], a lower discount factor would result in lower global cost (in this case NPV), consistent with the results in Figure 9. This leads to the conclusion that the NPV of different solutions is highly dependant on the DR, which is ultimately a policy decision.

In all three cases, the difference due to the updated DR values is larger than the obtained spread from variated parameters. In the case of the HP, the change of DR has a significant effect on the result (1.5 m.€), while for DH (0.7 m.€) and gas (0.18 m.€) the difference is still considerable although to a smaller extend, compared to HP. This shows that the DR significantly influences which technology will be singled out as cost-optimal. For example, with DR rates applied in the analysis in [18] (marked in grey in Figure 9), the HP is not competitive with DH or gas. In contrast, HP is comparable to the other technologies with the updated DR rate types, and in fact, HP is the solution with the lowest NPV.

Suppose the difference stemming from updated DR is corrected, so the NPV of Package 7 and this of the baseline for the represented variations are equal. Nearly all package solutions with lower energy reduction targets (Package 1-6) fall in the range of box plot whiskers for all three systems. This is logical as the NPV of most of these packages is within ±5-10% of that of the baseline. Comparing the box plots' IQR, the number of packages falling range is reduced to 4 for DH and gas and 2 for HP. This indicates that the selection of packages with close NPVs should be taken with caution as variation in the input may cause the re-arrangement of the packages.

On the contrary, the NPV of packages with similar or higher energy-saving targets than the baseline (Packages 8-10) falls outside the respective box plot's ranges. Higher energy savings in Packages 8-10 are achieved by additional or more expensive renovation actions than the baseline. For DH and gas, the NPV of Packages 8-10 is at least 30% more expensive than the baseline, whereas the NPV for the same packages combined with HP is in the range of 20-30%. This indicates that the cost comparison between solutions with a significant difference in NPVs can be taken with certainty, assuming that the LCC approach for all solutions has been consistent. On the other hand, solutions with similar NPV results are not as certain, and thus decision making in such situations should be made with caution.

Overall the results show that the global LCC is significantly sensitive to DR, which is ultimately a policy decision. The difference between the results is greatest for the HP and smallest in the case of gas. This is also consistent with the intentions of set out in [23]. Moreover, the greater difference for the HP is also compatible with findings presented in [14] for the greater effect of reduced discount factors for solutions with greater energy savings.

4. Discussion

The approach used in this paper provides findings that shed light on the importance of different parameters in an LCC calculation, their interaction and rank of importance. The findings are, however, limited to the scope of the analysis. In this paper, the analysis considers the perspective of a multi-family building owner, disregarding income. For such cases, income in LCC calculations can originate from rent, rent increase, selling electricity to the grid, savings of purchased energy from the grid, etc. If one or more of these profits are integrated into LCC analysis, the results for the influence and relative share of importance for each parameter could change significantly.

The applied combination of local (OAT) and global (MC) methods seemed appropriate as OAT approaches are good estimators of sensitivity for linear or nearly-linear mathematical models. The linearity of the investigated baseline model (and its variations) was proved by the very high R2 values of multivariate linear regression. It should be noted that the linearity of this model(s) is expected as boundary conditions and model inputs are investigated separately. Models where the variation of boundary conditions and inputs are variated simultaneously, may prove to be non-linear.

The MC and quasi-random sampling approach was selected due to its property of covering the solution space comprehensively. This, however, is true when the sample number is sufficient to represent the combinations of variated parameters. A "sufficient" number of samples is typically determined based on the number of variated parameters and investigated variations. The MC simulations at hand are limited to five variation parameters and 5,000 samples for each investigated energy system. While this is a relatively low amount of samples for MC simulation, even coverage of the solution space is perused by the use of Sobol quasi-random sample selection [8]. Moreover, given that the calculation models proved to be linear, a relatively small number of samples may be sufficient to provide even coverage of the solution space. To check if the 5000 samples are an adequate number of simulations for the investigated models, the DH baselines are simulated with a different number of samples. The spread in results is compared in Figure 10 by a histogram depicting the standardised frequency to the sample number. The figure shows that despite the different number of samples, the spread of the results is nearly equal in all cases. Considering the linearity of the model, this result was anticipated. A slight difference is evident for the cases with 100 and 500 input samples, where the distribution differs slightly, but the results range is similar to all other cases.

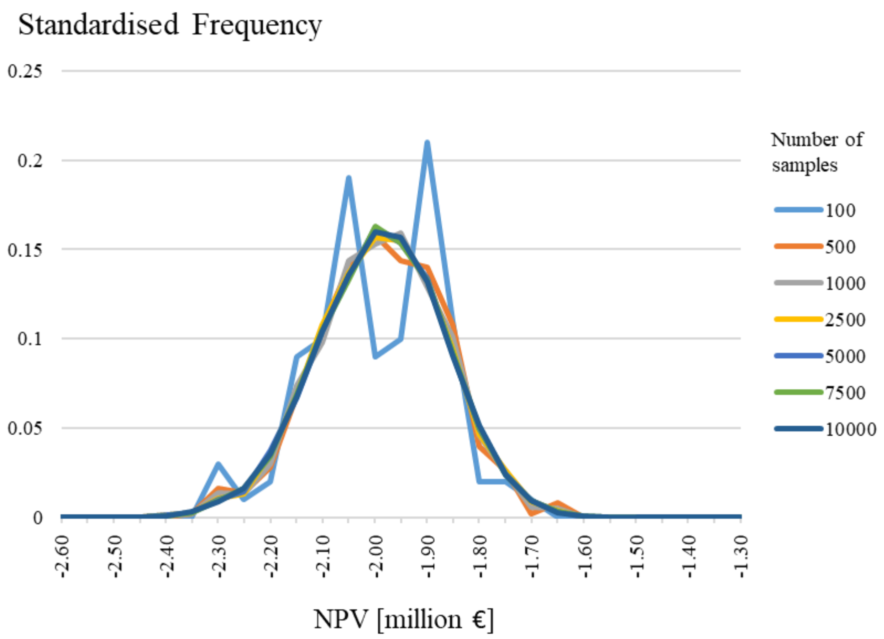


Figure 10 Comparison of the number of simulations.

A growing body of literature has explored the sensitivity of financial assumptions in LCC calculations, specifically DR and energy price development [4,10–12,14]. Despite the variety in the applied methods for assessing sensitivity and the scope (entities considered in the calculation) of the referenced papers, there is consensus that financial assumptions significantly impact LCC output. This corresponds well with the findings of this paper, considering the comparability between OAT-based sensitivity indexes for boundary conditions and those of most influencing energy efficiency measures. Even though the interactions of financial and building-related inputs and their effect on the output is not investigated in this paper, there is a need of further exploration on the matter. This is evident as results in [14] showed that financial input parameters alone have interactive effects on the LCC output, representing cost-optimal renovation cases. To the best knowledge of the others, only one study focuses on the sensitivity of both financial and building-related input [17]. The study applies MC and Sobol sampling methodology, based on sensitivity and uncertainty analysis for evaluation of economic performance for a range of energy efficiency levels. The findings in [17] for investment cost and lifetime of the most expensive solution being the most influential for the output are compatible with the results of this paper's HP scenario.

5. Conclusions

This study examined the relationship between input and output of LCC calculations for a pre-selected renovation case of a residential building in Denmark. The study also sheds light on currently available data and sources for the inputs required for LCC calculation, focused on renovation expenditures. The applied approach consists of one-at-a-time (OAT) and Monte Carlo (MC) methods for variation of the inputs. A simple first-order sensitivity index is calculated for all model inputs variated with OAT to compare the sensitivity of the parameters and select the most influential ones for further variation with the MC method. Investigation of the interactive effects of variated parameters on the output is quantified by the use of linear regression and analysis of standardised regression coefficients for the selected parameters.

Performing OAT variation on boundary conditions and building-related inputs allowed for comparing the individual effect of the three boundary conditions (discount rate (DR) type, price development and calculation period). Based on the results, it can be concluded that DR type and price development for electricity and district heat have approximately the same effect. At the same time, the variation of the calculation period showed greater sensitivity indexes for the studied scenarios. However, these results should be taken with caution as they represent the individual effect of each input on the output and not the interactive effects of all inputs. Nevertheless, the financial parameters and calculation period in Denmark can be considered deterministic, as their values are determined by legislation. Given that specific values are determined with respect to the investigated building type, the variation applied in this paper aimed at quantifying the expected variance when a different set of boundary condition assumptions are used in the selected baseline. The applied OAT approach to building-related model inputs showed that energy demand-related inputs are most influential.

The OAT results implied a linear relationship of the input and outputs, which was verified by the high R2 values resulting from regression analysis of the MC results for all studied models. Furthermore, the applied regression method (Sensitivity Ranked Regression Coefficients) ranked each of the five variated parameters in respect to how sensitive the output is to them. The analysis representing calculation models with District Heating (DH) and gas show that the most influential inputs are about twice as sensitive as the next most influential ones. In those cases, the relative importance of the parameters of DH and gas is nearly equal, with a slight variation between the ranking in the two cases. On the contrary, for a scenario with a Heat Pump (HP), the lifetime of the HP is determined as most sensitive. However, in this case, the difference in importance (value of regression coefficient) between the different parameters is much smaller than DH and gas cases.

This study adds to the understanding of the relationship of inputs and output for LCC calculation, considering a cost-effective renovation package combined with three energy supply systems for heating and DHW production.

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Conflict of interest
The authors declare that they do not have competing financial interests, personal relationships or any known conflict of interest that could have influenced the work reported in this article.

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Appendix A

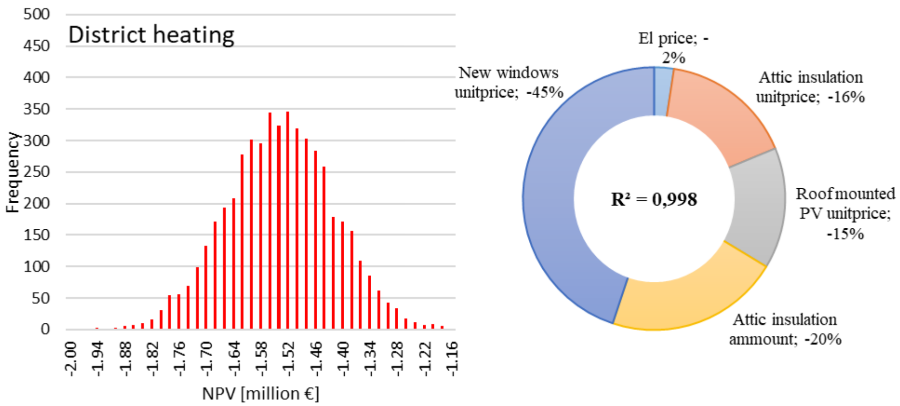

Figure A1 Left, histogram representation of resulting NPV for low district heating unit cost. Right, resulting share of regression coefficients and R2 value of the linear approximation.

Table A2 Regression parameters for calculation model with District Heating. Regressions for all three cost level of DH are identical.

Parameter x_i	New windows	Attic insulation	Roof mounted PV	Attic insulation	El price	ε
Attribute	unit price	Amount	Unit price	Unit price	Unit price	
coefficients	-0.822	-0.393	-0.273	-0.299	-0.044	-4.15E-16
standard error values of coefficients	0.000643	0.00064274	0.00064274	0.00064274	0.00064274	0.00064274
R^2	0.9979	0.0454	#N/A	#N/A	#N/A	#N/A
Regression - sum of squares	483126.4	4994	#N/A	#N/A	#N/A	#N/A
residual sum of squares	4989.684	10.3155142	#N/A	#N/A	#N/A	#N/A

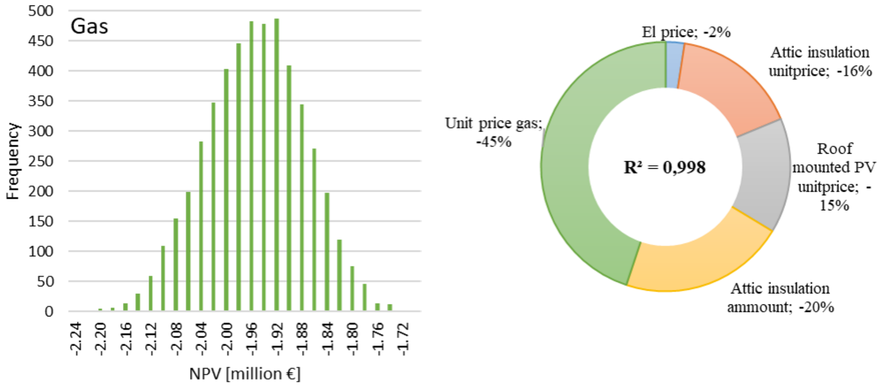

Figure 12 Left, histogram representation of resulting NPV for gas. Right, resulting share of regression coefficients and R2 value of the linear approximation.

Table 6 Regression parameters for calculation model with gas.

Parameter x_i	Gas	Attic insulation	Roof mounted PV	Attic insulation	El price	ε
Attribute	unit price	Amount	Unit price	Unit price	Unit price	
coefficients	-1.229	-0.587	-0.408	-0.446	-0.066	5.561
standard error values of coefficients	0.00096	0.0009604	0.0009604	0.0009604	0.0009604	0.000960
R^2	0.9979	0.067917329	#N/A	#N/A	#N/A	#N/A
Regression - sum of squares	483126.4	4994	#N/A	#N/A	#N/A	#N/A
residual sum of squares	11142.74	23.0361	#N/A	#N/A	#N/A	#N/A

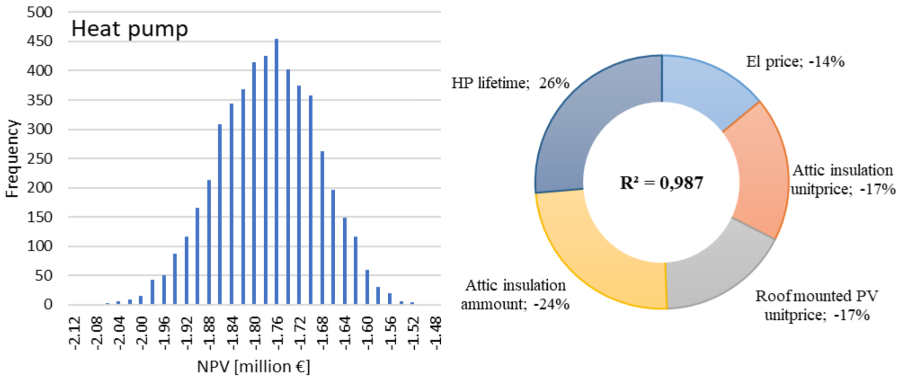

Figure 13 Left, histogram representation of resulting NPV for heat pump. Right, resulting share of regression coefficients and R2 value of the linear approximation.

Table 7 Regression parameters for calculation model with heat pump.

Parameter x_i	Heat pump	Attic insulation	Roof mounted PV	Attic insulation	El price	ε
Attribute	Lifetime	Amount	Unit price	Unit price	Unit price	
coefficients	0.5703	-0.5255	-0.3659	-0.3998	-0.3033	-1.12E-14
standard error values of coefficients	0.0016	0.001634	0.001634	0.0016348	0.0016348	0.0016348
R^2	0.9866	0.1150	#N/A	#N/A	#N/A	#N/A
Regression - sum of squares	73830.49	4994	#N/A	#N/A	#N/A	#N/A
residual sum of squares	4933.26	66.73	#N/A	#N/A	#N/A	#N/A

PAPER #5

Methodology and platform for NZEB renovation of residential buildings

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Methodology and platform for NZEB renovation of residential buildings

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Abstract

Renovation of the existing building stock is a vital part of reaching upcoming energy savings and CO2 emission targets. The European Union (EU) continuously publishes directives and guidance to support the transition of existing buildings to nearly-Zero Energy Buildings. A method for calculation of cost-optimal levels for minimum energy performance was introduced in 2012. Its aim is to compare and select different renovation alternatives, based on energy savings and global costs. It has been successfully applied on a package level; however, its complexity has restricted it from being used for comparing renovation alternatives between single components with the same and different functions. This paper presents a methodology for determination of a simplified value linking economical and efficiency parameters on a component level. The value allows for fast overview of cost-benefit of different renovation alternatives between components and systems. It serves a decision-making aid for compilation of renovation packages, which are further evaluated with the cost-optimal approach. The paper also introduces novel refurbishment assessment platform that can assist decision makers with fast compilation of refurbishment packages incorporating key aspects of the presented methodology. The current functionality of the platform is showcased at the end of the paper by a case study.

1. Introduction

Buildings are a major factor in the transition of clean energy as they account for 36% of the final energy use and 40% of carbon emissions globally [1]. To reduce building related energy use and emissions, the European Union (EU) has implemented number of directives as the recast of Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive (EED) to drive the improvement of EU buildings. Those two well-known directives have been amended by DIRECTIVE (EU) 2018/844 [2], requiring Member States to develop and implement long-term renovation strategies for cost-effective transformation of the existing building stock to nearly-Zero Energy Buildings (NZEB). Two of the mentioned obligations under the new Article 2a are approaches for cost-effective renovation and, transparent and assessable advisory tools for customers and designers.

In 2012 the EU established a comparative framework for calculation of cost-optimal levels for minimum energy performance requirements for buildings and building elements [3]. The methodology employs energy saving and Life Cycle Cost (LCC) calculations to evaluate efficiency measures, renewable energy sources and packages applied to reference buildings with the aim of identifying cost-optimal levels for minimum energy performance requirements. While the aim of this methodology was to set minimum requirements for cost-optimal levels, literature review in [4] showed that it has been applied for evaluation of single buildings. Even though the framework for the cost-optimal methodology can be applied on a single element, it is mostly applied on a package level. This could be due to the rather tiresome amount of parameters and complexity of LCC calculations when analysing a single element. Moreover, cost calculations and energy savings are typically estimated in different software and combined in spreadsheets like e.g. Excel, requiring great deal of bookkeeping.

The work presented in this paper is twofold. First, a presentation of novel renovation methodology for evaluation of single actions and their compilation in renovation packages. The method proposes simplified economic evaluation for single renovation actions as a pre-step to the well-established cost-optimal method, incorporating LCC. Secondly, a novel refurbishment assessment platform is introduced and showcased by a case study. The platform can collect results from energy saving and economic calculations performed in different software. In spite of its early stage of development, the platform allows for fast and easy compilation and comparison of renovation scenarios, based on data from energy audits, energy and cost analysis for each individual renovation action. The data can be either imported via common JSON file format, or typed in manually, making it independent and flexible.

2. Low cost renovation to NZEB

Overview of the complete process, included in the methodology is presented in Figure 1. The procedure considers a renovation project with an owner of a specific building(s) and associated renovation targets. The method does not include securing of financing schemes, however, when in place the specifics of such can be accounted for. The methodology is structured as a flowchart with three main sections – 1) project definition, 2) evaluation of the applicable single actions, 3) evaluation of selected renovation packages (scenarios). Detail design of the selected renovation package is beyond the scope of the proposed method. Each section and corresponding tasks and activities within are explained in the following subsections.

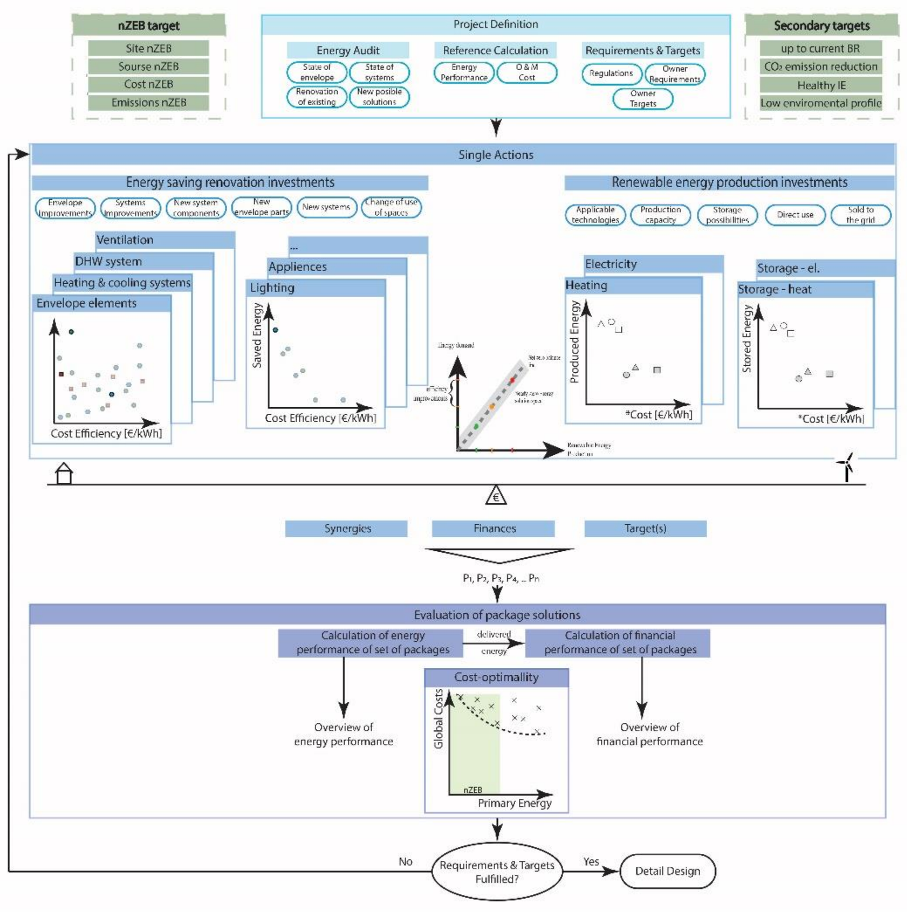

Figure 1 Overview of methodology for obtaining least-cost renovation scenarios for specific building projects.

2.1 Project definition

The project definition stage of the methodology is where the designer is aquatinted with the general project information as age, type, size, function of the building, etc. At the same time the owner's primary, secondary targets and motivations for renovation are set.

The method is focused on reaching NZEB, therefore, it is important to establish the specific NZEB definition. This plays an important role in the actions to be included and the focus of the optimization. According to the definition provided in the EPBD, an NZEB is a building with low amount of energy, covered mainly by 3enewable [5]. In most Member States, maximum limit of primary energy is used as main determining factor for reaching NZEB. The maximum limit value varies in magnitude and the way that it is determined from country to country. In few cases the indicator is determined via non-dimensional parameter, relative to a reference building [6]. Other Member States, apply carbon emissions as indicator, while in third, emissions are used in combination with primary energy [6]. Since the release of the EPBD, various interpretations and calculation methods for NZEB have been illustrated [7]. Some interpretations throughout literature have defined NZEB depending on the considered boundary (e.g. at the building – Site NZEB or at the supplier – source NZEB), the emissions or by the cost of the energy [8]. Due to the evolving nature of the NZEB definition the methodology presented on Figure 1 is not targeted to a specific NZEB definition or main indicator, rather designed in a way to assess the necessary building parameters in order to fulfil a given NZEB requirement.

The owner may also have secondary targets, besides reaching NZEB. Those can be of varying nature, for example, improvement of indoor comfort, addition of extra living space, low environmental profile, etc. Some of those may also be imposed by the local regulations, which are set by the location of the building. Depending on the country/region, requirements for renovation can be defined on a component or building level or combination of both. If the building is with historic or cultural value one or more elements may be protected and not allowed to be changed.

A reference calculation determining the existing energy demand is necessary in order to estimate the potential energy savings of a component or complete renovation package. This calculation can be performed either with steady-state or dynamic methods. The selection of the method is up to the designer, however, there may be specific regulatory framework and/or the project specific needs.

Reference calculation models provide theoretical estimate of the energy performance of a building, while an energy audit can provide knowledge for the actual energy use under real conditions. If available, the historical energy use of the building can be used to calibrate the reference energy models. Calibrated models can yield more realistic results for potential energy savings from different renovation interventions. While performing the audit, the designer can also assess the state of different building parts and systems, and if those are in need of replacement, renovation to a given extend or readjustment of set-points and operation parameters. Furthermore, ideas and considerations of the possible solutions for each building part can be initiated and discussed with the property manager and/or building users.

To obtain grounds for financial comparison between investigated renovation scenarios and state of the building before renovation, it is necessary to know the running, operation and maintenance cost of the building in its existing state. This information is valuable, yet rather hard to obtain. A good source for such information (if it is not recoded explicitly) is the property manager, as he/she is responsible for the daily operations or the building and performing day-to-day maintenance tasks.

2.2 Evaluation of single actions

It is proposed that after completion of the project definition stage, the applicable single renovation actions are evaluated independently. The goal is to obtain an overview and compare how the different actions, applicable to the specific building, perform both in terms of potential energy savings and costs. The methodology used to evaluate and rank energy efficiency actions is presented and tested in detail in [4] and briefly explained further.

Investments in energy efficiency are evaluated based on a value termed cost-effectiveness, linking implementation cost, primary energy savings and lifespan of the evaluated actions. The cost-effectiveness of each action is calculated using the equation (1) and represents the cost of saved kWh primary energy for the different actions. The lifespan of investigated improvements is taken into account by dividing the implementation cost by the expected lifespan of the action in question. The implementation cost at this stage of the method include all cost necessary to implement an action (removal and disposal of old materials, equipment, labor and investment for the new materials or components). In this way, a building owner obtains a direct overview of the required investment to implement a given action at the beginning of the renovation process.

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

It is proposed that the cost-effective parameter for investments in renewable energy production and storage is with the same unit as the cost-effectiveness of investments in energy efficiency measures. This is done with the aim of obtaining grounds for direct comparison of cost-effectiveness between energy producing systems and energy efficiency improvements. Improvements in energy efficiency and energy production are different by nature and thus cannot be evaluated in the same way and require different approach for estimating their benefits and level of costs.

The annual investment is obtained in the same way as for the energy efficiency actions - by dividing the total costs by the expected lifetime of the system. The considered costs for cost-effectiveness of production systems are the investment, installation, operation, maintenance, variable and fuel costs.

The total fuel costs can be estimated based on the energy demand of the building, total amount of fuel needed to cover the demand (estimated with calorific value for the fuel in question), the cost of the fuel and technological specifications of the system.

The investment cost of a system is dependent on its production capacity. In the present methodology, the required capacity is determined during the project definition via the reference calculation. In principle, the capacity of a system, dimensioned according to the existing heating demand would be able to cover the demand of the building prior renovation. It is possible to reduce that when applying energy efficiency measures to the building. However, for cases where the energy producing system is outdated, while other building parts are not, the energy demand of the existing building would be the appropriate for dimensioning of the new system. The idea is that the comparison of all applicable systems is based on the same demand in order to obtain a relative comparison between the options. The correct system parameters, dimensioning and its costs are taken into consideration in the next stage when all efficiency actions are selected.

While the value of cost-effectiveness considers the total costs throughout the lifetime of the considered systems, it does not take into account the price increase of fuel with time and inflation, as it is done in LCC calculations. This simplification however, provides grounds for comparison between multiple systems, and energy production systems energy efficiency actions. Moreover, the process acquires solid background of all parameters necessary for LCC calculations, performed in the next step of the method on package level.

2.3 Balancing energy efficiency and energy production

Achieving balance of investments in energy efficiency and renewable production in accordance with the budget of the project is sought by using the schematic chart represented in Figure 2. Knowing what is the demand of the building prior renovation, the cost-effectiveness of produced and/or saved energy by each action; one can use the chart to assess the different ways to reach the NZEB standard, while considering their cost.

The chart shows the Net zero balance line, where the energy use and renewable production are equal for a given period. However, as discussed above, Member states have imposed different NZEB standards. In countries where the only requirement is primary energy the limit value is above zero, thereby there would be solutions satisfying NZEB requirements, which are not exactly on the net zero balance line. Higher limit values for energy demand would increase the solution space for NZEB (indicated in grey in Figure 2).

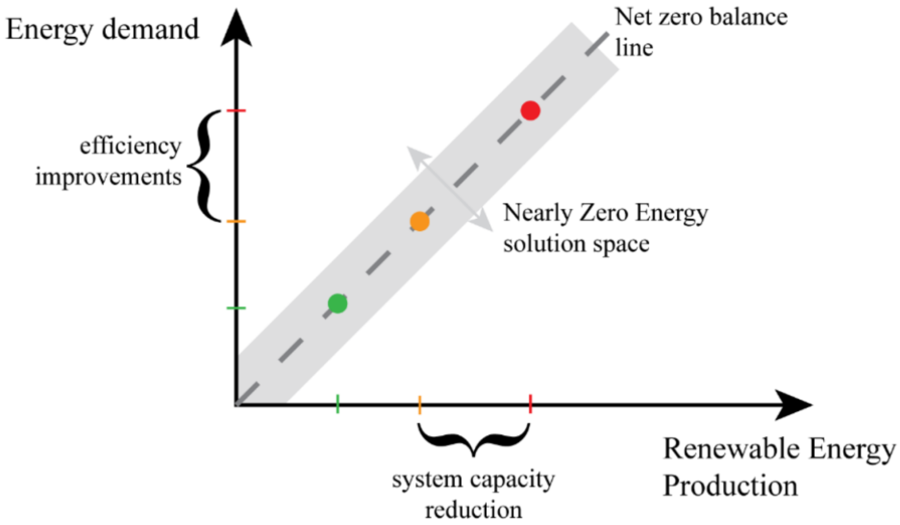

Figure 2 Schematic representation for balancing energy efficiency improvements and renewable energy production, adapted from [9].

Depending on criteria and targets set in the project definition stage, one can estimate the required amount of efficiency actions and the resulting required renewable energy production, necessity to reach NZEB. In principle if the complete demand is covered by own renewable production, a building may be zero energy for. However, the definition in EPBD and local regulatory requirements set comfort and efficiency requirements as well. This means that if those are covered the NZEB may be reached by simply suppling the demand by renewable production. Otherwise, some actions have to be taken to satisfy comfort and efficiency requirements, besides providing renewable production. Overall, there are many different ways to reach NZEB and their cost can differ considerably. Thereby, this should be checked on the package level by applying the well-established LCC approach, where number of various packages, compliant with the specific project at hand are compared.

This is the pivotal point of the methodology as all information acquired in project definition and single action stages is segregated in making viable package solutions. Besides obtaining NZEB standard, the designer has to take into account synergy of actions, the targets and finances of the project, dependence of actions on the result as well as other unforeseeable factors as rebound effect of the packages, implementation complexity, time, etc.

2.4 Evaluation of renovation packages

The last stage of the method consists of comparing the “balanced” renovation packages using LCC

calculations. For consistency and comparability reasons throughout the EU, those are to be done in accordance to the cost-optimal methodology, introduced in the EPBD [5]. While the method was imposed by the EPBD for regulation of national building standards it has been shown throughout literature that it can be successfully applied to single buildings with various functions (cf. Literature review provided in [4]).

The method consists of obtaining an overview of energy and financial performance of each selected package and plotting the resulting global cost as a function of the energy performance of each package as indicated in the bottom part in Figure 1. This visualization allows the designer to compare different packages in terms of global costs and if they satisfy the NZEB demands or not. Figure 1 provides an example where NZEB requirements are defined by maximum limit for primary energy, however, that can be replaced with the parameter valid for the country or region, if that is not primary energy.

When and if the satisfactory package is found, the last step of the methodology is to check if the selected package fulfils all primary and secondary targets of the project. If that is true, the process can continue with detail design of the selected package. If some of the requirements and targets are not fulfilled, the designer can loop back to either selecting a different package, or creating new set of packages from the single actions, defined in the previous step.

3. Refurbishment assessment platform

The refurbishment assessment platform (for simplicity referred to as the platform) is an online tool created to segregate information for a project and empower the building owner or designer in taking decisions. The platform is capable of combining results from different types of software by either directly importing their results via JSON file or manually entering data to the platform. The goal is that the platform and Least-Cost Method (LCM) complement each other in a way that the LCM provides overview of the tasks and calculation methodology for renovation assessment, while the platform provides bookkeeping of all gathered information and external software results. Furthermore, the platform allows for combination and re-calculation of the imported data into key performance indicators, used for decision support and comparison of renovation scenarios. In time of writing of this paper, the platform is still under development. It currently integrates activities from the first two stages of the LCM: project definition and to some extend the evaluation of single actions. The third part of the method – evaluation of packages using LCC calculation is not part of the platform yet. To understand how the platform, in conjunction with the LCM, support designers and building owners its principles and functionality is explained below.

Similarly, to the method, the platform is also disconnected from country specific regulation or NZEB definition. Its user-friendliness allows direct import from the EPIQR+ [10] and ECOSOLUTION [11] calculation tools; however, it is not limited to those, as the user may also enter data manually. The software EPIQR+ is a tool for assessing the state of the building and evaluating the cost and energy performance of different refurbishment scenarios. This is possible after an audit of the building, which is the basis for obtaining most of the information in the project definition stage and the cost necessary for economic evaluation of single actions. The tool ECOSOLUTION complements EPIQR+ with specific energy saving calculations for HVAC and renewable energy producing systems. It also requires energy audit in order to find the specific energy use of a component and/or system and compare it to a new proposed alternative. In that way ECOSOLUTION also covers tasks from project definition and calculation of single actions stages of the LCM. If a designer plans to use the LCM and platform from the beginning of a project, a great deal of double work can be avoided. For example, single audit can serve both tools and cost and energy savings can be shared by both tools via the platform. The project targets and regulatory framework are currently not an explicit part of neither the two tools nor the platform. Therefore, the designer must be conscious of the project targets and regulatory requirements.

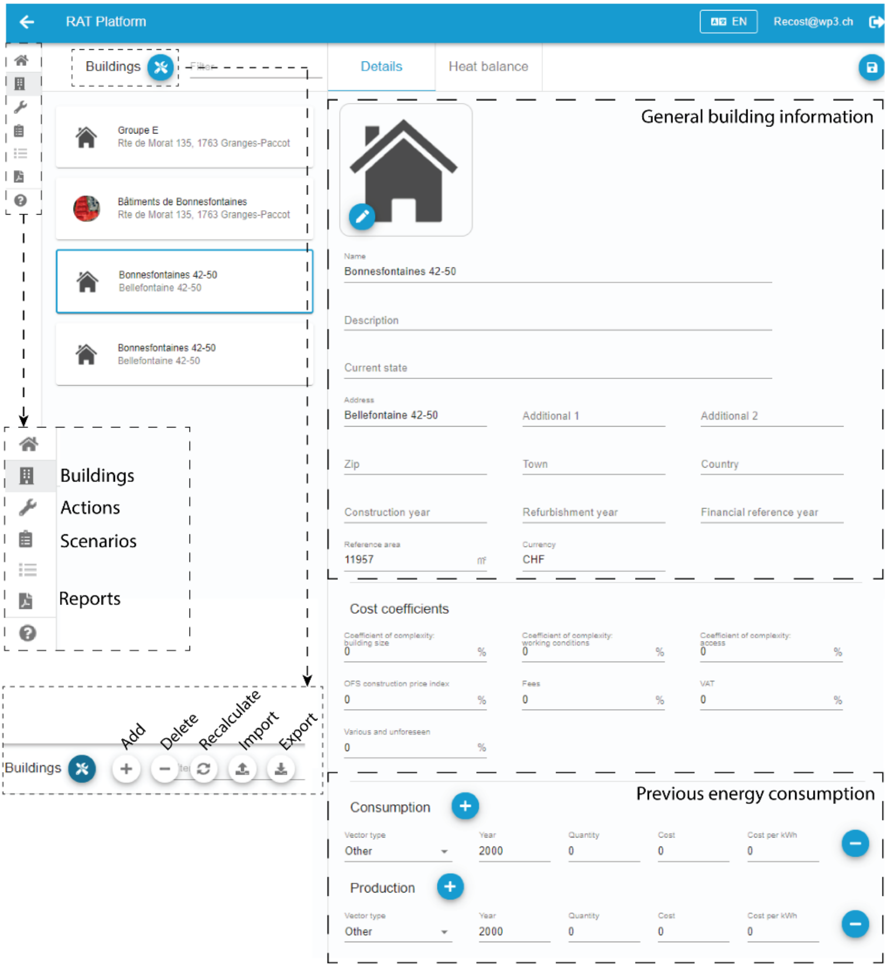

Figure 3 Home screen of the online refurbishment assessment platform.

Figure 3 shows a screen print of the first page of the platform, including the functionality behind some of the main buttons. A building can be added manually or imported through a JSON file. Currently the functionality of EPIQR+ and ECOSOLUTION tools allows direct export of JSON files which are compatible with the platform. The user can perform basic operations as import, export of JSON files, add or delete a building data. The "Recalculate" button performs calculations from the cost and savings (energy or CO2) data to indicators of cost- or CO2-effectiveness, similar to those described in the LCM.

When a building is selected, on the right-hand side, a user can enter general information for the building as name, address, description, age etc. Below, there is a possibility to enter cost coefficients related to complexity, fees, VAT, price indexes and unknown costs. At the bottom of the page, one can enter the historical energy consumption, type of fuel and energy produced at the site, if that is available.

The ribbon on the left-hand side is the backbone of the platform. The buttons for Actions, Scenarios and Report link respective pages. Actions and Scenarios pages are shown in Figure 4 and Figure 5, respectively.

Figure 4 shows the actions page of the platform. On the right-hand side, the user can see a list with all imported and/or created actions. Each action contains a part with general information, a part with techno-economic parameters and a part with the total energy and CO2 savings, achieved by the action. The general information contains name, description, as well as some categorization and grouping parameters as which building part, element and group the action belongs to. Technology parameters are the investment cost, payback time, share of energy relation of the action, priority, planned date and type of works - maintenance, refurbishment, improvement, etc. If using the EPIQR+ software, values for Global warming potential, primary (embodied) energy and Abiotic Depletion Potential (ADP fossil) are calculated automatically. A main technology parameter that is not yet implemented in the platform is the lifetime of an action. Due to that, when recalculating the effectiveness parameters, the lifetime is not included and the cost- and CO2-effectiveness are simply the cost divided by the achieved savings or CO2 savings.

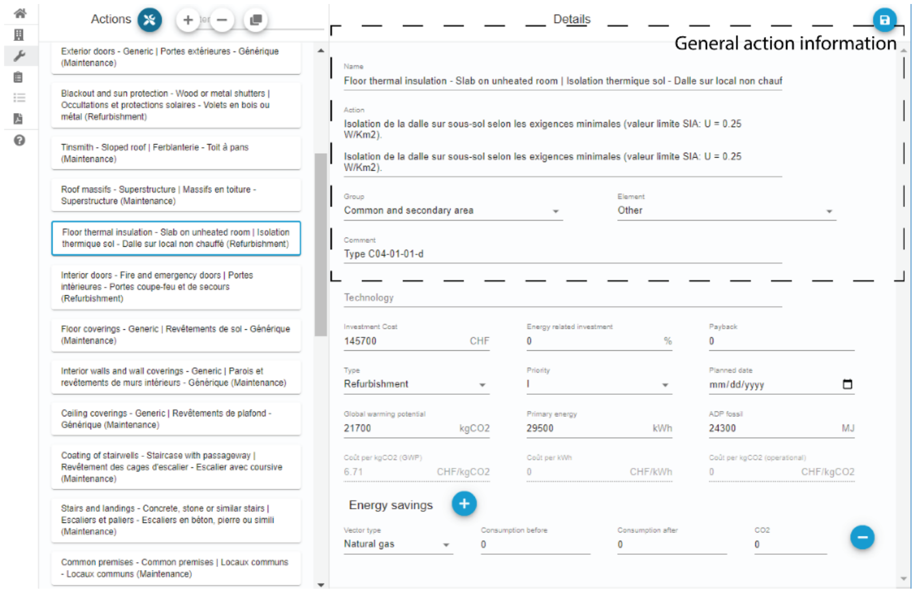

Figure 4 Actions page in the online refurbishment assessment platform.

The page where different scenarios can be created, evaluated and compared is shown in Figure 5. On the left-hand side, the user can see all scenarios that have been created, as well as a quick overview of the total cost, energy savings and global warming potential (GWP) of each one.

A scenario is constructed by adding a new or selecting existing one and editing its content. When a scenario is selected, on the right-hand side on top of the page, the user can see the three parameters shown in the list of scenarios - cost, energy savings and GWP. Additionally, the cost- and GWP-effectiveness for the whole scenario are shown. In the middle section of the page the user can add the name of the scenario and a comment of own choice.

On the bottom right-hand side of the page, the user can select the actions, which make up the scenario in question. The list of actions, defined in the previous page, is interactive and can be re-arranged depending on the preferences of the user. It is possible to filter and sort the actions according to building type or group, ascending or descending cost or energy savings, cost- and CO2-effectiveness. This provides great flexibility and excellent bookkeeping when comprising and comparing different scenarios.

It must be noted that the total amount of cost, energy savings and GWP is a result of the addition of the separate values. This should be used only as guiding value, especially when considering energy savings and cost. This is imperative, as addition of energy savings calculated on element level does not provide correct global energy performance of their addition. This is due to synergies and contradictions (interactive effects) between the different actions. In relation to cost, those could also differ when considering global scenario. The global cost may be smaller if a certain cost can be avoided or reduced if several actions are combined (quantity discounts, exclusion of tasks due to nature/location of works). On the contrary, global cost of a scenario may be larger than the addition of separate single actions if complexity, timeframe is extended due to technological sequences of the tasks being applied to the building. Therefore, the selected scenario must be re-evaluated using a global method to obtain more accurate estimate of the predicted performance of the building after renovation.

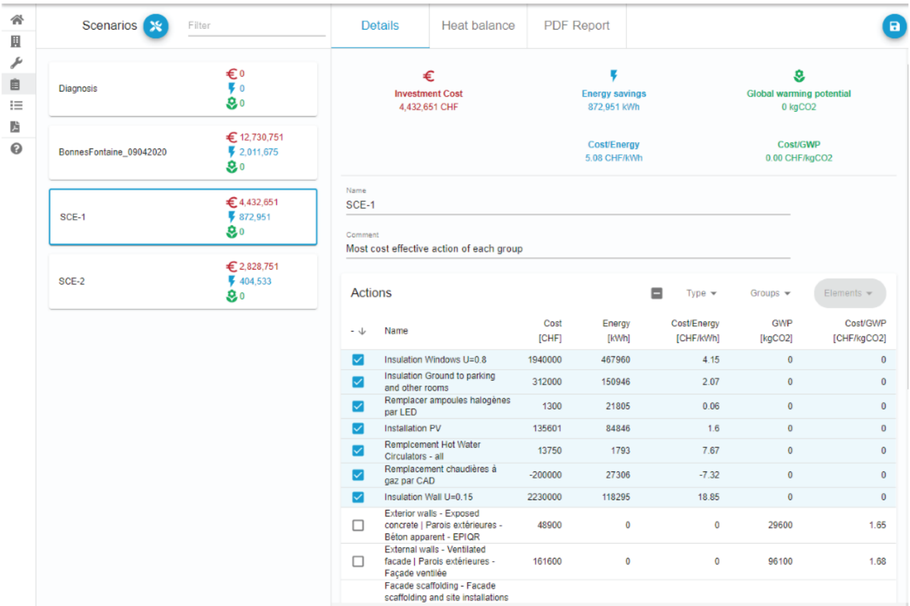

Figure 5 Scenario page in the refurbishment assessment platform.

The LCM surpasses the platform in many of described activities. The specific methodology for comparing energy producing technologies, balancing the renovation packages as well as the final stage of package evaluation is not yet available in the platform. However, for its 'young age' the platform proves to be a great tool for decision support by providing opportunity for comprising, comparing, and reporting on expected performance of renovation scenarios. The platform can be used in the early stages of a renovation process in an iterative way by providing both initial quick overview of possibilities and performance.

Moreover, the possibility for manual entry allows the user to apply preferred calculation methods for cost and energy savings and thus use the platform in the latter stages of the renovation process or in cases where greater accuracy is required. The functionality, advantages and drawbacks of the platform are discussed via a case study, described in the next section.

4. Case study

The selected case sturdy is a public building complex located in Fribourg, Switzerland, and shown in Figure 6. It consist of 10 buildings constructed in 1993 – a round tower and nine rectangular buildings. There are 125 dwellings distributed over five floors with total heated floor area of 13,144 m^2. The complex houses studios, single, double room apartments as well as such on two and three levels with total capacity for 370 inhabitants. The housing complex is equipped with unheated parking in the basement and common laundry facilities.

Figure 6 Site plan of the case study building complex.

Calculation model using the compliance tool CECB classifies the complex in energy class E, with primary energy demand of 133,4 kWh/m^2 year. The buildings are naturally ventilated through windows; the kitchens are equipped with independent extraction hoods, while the bathroom ventilation occurs via centralized chimneys employing stack effect. The heating of the building is done via water based heating system with radiators and floor heating (supplied from radiator return). The heating system consist of a common gas boiler located in the basement and individual substation with heat exchanger for each individual building. Domestic hot water production and supply are done in the same way as for space heating.

The building envelope elements vary in regards to typology. There are two different roof types; seven different external wall types; three different floors and two different window types. Three of the seven wall types constitute about 90% of all building external wall, those are the ones considered in the analysis below. The most represented external wall type is bricks with rigid external insulation and plaster on both sides. It constitutes for 34% of the total external walls and has U-value equal to 0.3 W/m^2 K. The other two wall types comprise of brick, insulation and concrete (28% of all external walls, U-value of 0.29), and brick insulation and ventilation gap (27% of all external walls, U-value of 0.28). The biggest share of the floor is this over the unheated parking, constituting of about 95% of all floors part of the thermal envelope. It is with the highest U-value (0.77 W/m^2 K) and the only type where no relocation of tenants is necessary; thus, this is the only floor type considered in the analysis. Both roof types have undergone improvements in recent years and are therefore not part of the analysis. In regards to the window, replacement with two different types is investigated. While none of the building envelope elements complies with the current regulation, they are in good condition. Therefore, economic feasibility evaluation is necessary in order to determine the most appropriate actions in order to reach the owner's target and NZEB standard.

Table 1 presents the evaluated refurbishment actions selected for the initial test of the platform. The actions are selected to test the capabilities and drawbacks of the platform rather than perform in-depth renovation analysis for the building complex. That is why a precise description of obtaining of each indicator as cost, energy savings, GWP and CO2 savings are not part of this publication. The actions were determined after energy audit, cost and energy analysis of the buildings. Energy saving analysis are done using the ECOSOLUTION and Lesosai tools, while cost analysis were performed using EPIQR+. Due to recent upgrade and integration of EPIQR+ with an LCA database developed for the RECO2ST project, actions analysed with EPIQR+ automatically provide environmental indicators as embodied energy, GWP and ADP.

Envelope	Distribution systems	Producing technologies
- Insulation of slab over unheated parking - Insulation of external wall - 2 types - Replacing windows - 2 types	- Circulation pump for heating - Circulation pump for DHW - LED lights for parking, laundry room and hallways	- MVHR - Renewing existing gas boilers - Switching to district heating - DHW boilers (PAC)

Table 1 Single refurbishment actions included in the analysis.

Using the scenario creation page, presented in Figure 5, four scenarios were created. Using the sort function, a scenario with the three top ranking actions for the following criteria were compiled: lowest cost, highest energy savings, lowest cost-effectiveness and lowest CO2-effectiveness. The resulting actions for each of the four scenarios, their total cost, energy and CO2 savings are presented in Table 2.

Despite the limited number of investigated actions, the results from the different selected optimisation parameters show the capability of the platform of creating various scenarios and obtaining an overall idea of their performance. For example, the cost-effectiveness scenario is 30% less in energy savings but 85% cheaper, compared to the scenario with highest energy savings. This indicates that with greater number of investigated actions the optimization options would be greater variation of the content of scenarios.

Scenario	**Lowest cost**	**Highest energy savings**	**Cost-effectiveness**	**CO_2-effectiveness**
Actions	-LED Hallway -LED Parking -LED laundry	-MVHR -3 layer windows -PAC boiler for DHW	-LED Hallway -DHW boilers (PAC) -MVHR	-MVHR -Floor insulation -Wall insulation
Cost [CHF]	11 100	2 296 700	324 200	3 533 581
Energy savings [kWh]	26 129	2 217 012	1 770 857	1 755 360
CO_2 savings [$kgCO_2$]	300	510 300	263 100	721 440

Table 2 Actions and respective cost, energy and kgCO2 savings.

Further work for the platform should include integration of the lifespan of building parts, and treat renewable energy producing systems as described in the LCM. It would also provide even greater value to the renovation process if LLC calculation on a package level is integrated. However, the presented variability in the scenarios with limited number of renovation actions, the user friendliness and the ease of creating and comparing scenarios are encouraging factors that the platform could be a great tool for decision support for a renovation process.

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