LIFE CYCLE SUSTAINABILITY ASSESSMENT OF ENERGY RENOVATIONS

A case-study of a multi-family building in Sweden

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Master thesis in Energy-efficient and Environmental Buildings
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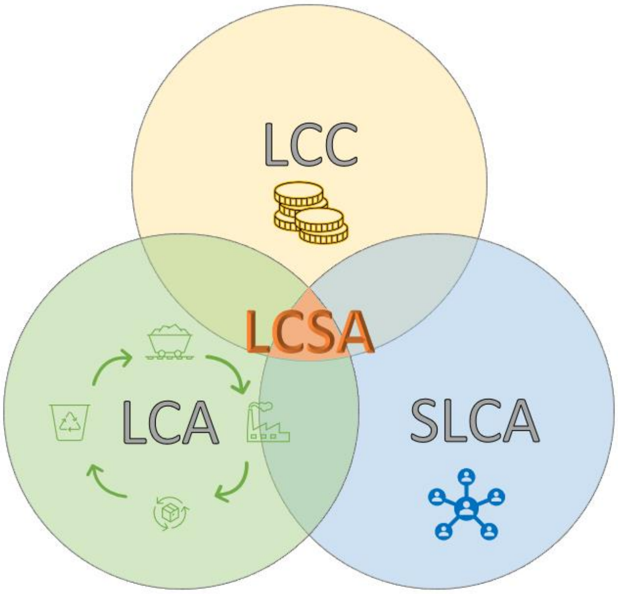

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Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280-degree programs and 2 300 subject courses offered by 63 departments.

Master Program in Energy-efficient and Environmental Building Design

This international program provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Summary

In Sweden, during the 1964 and 1975 period, almost one million residences were built during the so called “Swedish Million Program”. Approximately 20% of those buildings were successfully renovated but still the rest of them remain in need of large-scale renovations. Those buildings have a high energy demand compared to the new building standards and designs and therefore they have a high energy consumption and environmental impact. Most European countries need large-scale building renovations, due to the upcoming climatic changes but also since most buildings will remain habitable by 2050. However, only 0.4% to 1.2% is the annual rate of large-scale renovation in EU countries including Sweden. Consequently, there is a great need of large-scale renovations and due to the building’s high energy demand, the EU policies are driving the legislations and regulations towards a more sustainable and environmentally friendly framework, by following the climate neutralization goal by 2050 and for Sweden by 2045.

The purpose of the project is to combine the costs with the environmental impact of the selected renovations solutions and draw conclusions. The study was a continuation from a previous project where renovations were applied on a multi-family building towards passive house. The same building in South Sweden, from the Swedish Million Program was used as a case-study building, to apply several renovation solutions but also to weight the environmental impact of them. The several renovations were analysed from the economic, from the environmental perspective, but also from their combination of both. The examination was on the most important key-parameters and their interconnections between them, thus, to continue to the decision making-process. Three renovation packages were applied: The envelope renovation, i.e. thicker wall insulation, adding roof insulation, new passive house windows, the heat recovery, i.e. adding only heat recovery to the existing HVAC system and keeping the base case envelope construction, and the deep renovation, i.e. which was the combination of the envelope plus the heat recovery renovation.

Regarding the Life Cycle Cost analysis, the investment and the operational costs were calculated by using the Net Present Value and Life Cycle Profit. Then the Life Cycle Assessment was conducted, by using the Dutch approach, i.e. shadow cost, and by assigning a monetization value to the potential environmental impacts caused by the building, that the government or the society should pay to mitigate those damages. The economic and the environmental assessment was conducted considering a life cycle of 60 years. In the end, the economic and environmental results were combined into one result into the Life Cycle Sustainability Assessment and to draw conclusions from the results.

From the energy simulations applying the selected renovations, it was found that they had a better energy performance, by decreasing the energy need of the base case building. The best renovation was the deep renovation, followed by the envelope renovation and last was the heat recovery renovation. From the economic perspective, the heat recovery renovation, was resulted economic profitable, having a positive Life Cycle Profit, during the studied life cycle. The cases with economic loss were the deep renovation and the envelope renovation, resulting in negative Life Cycle Profits and high Net Present Values. On the other hand, from the environmental perspective, it was beneficial to conduct energy renovations, due to the lower environmental impact compared to the base case building. All the applied renovations resulted in lower shadow costs compared to the base case. The last part was the

Life Cycle Sustainability Assessment, where both the economic and the environmental aspects were combined, and it was found that the heat recovery case resulted in having the lowest Life Cycle Sustainability Assessment result compared to the base case and to the other renovation cases.

Currently, there is a need for such studies and further research should be done assessing the key-parameters that play a critical role to those large-scale renovations. Economic, environmental but also social aspects should be considered and be balanced to reach to decision-making process and indeed take practical actions towards a more sustainable and environmentally friendly future.

Abstract

Various renovations were applied to the existing post-war building stock of the so called "Swedish Million Program", that were built during the 1965 and 1974 period. Only 20% of those buildings were renovated and still the rest of them remains in need of vast renovations, to mitigate the climatic impact of the existing building stock. Nowadays, the annual rate of large-scale renovation in EU countries including Sweden is only 0.4% to 1.2% per year. Consequently, there is a great need for large-scale renovations and due to the building's high energy demand, the EU policies are driving the legislations and regulations towards decreasing the environmental impact towards climate neutrality by 2050 for EU and 2045 for Sweden.

A building in South Sweden, from the Swedish Million Program was used as a case-study building, to apply several renovation solutions. The renovations were analysed from the economic but also from the environmental perspective. Three renovation packages were applied: envelope renovation, ventilation with heat recovery, and deep renovation. With Life Cycle Cost analysis, the investment and the operational costs were calculated using the Net Present Value and Life Cycle Profit. Then the Life Cycle Assessment was conducted, by using the shadow cost, i.e. a monetization value associated to the potential environmental impacts caused by the building. In the end the economic and environmental results were combined into one accumulated result into the Life Cycle Sustainability Assessment (LCSA) and to draw conclusions from the results.

It was found that the energy renovations were, in most cases, not profitable from the economic point of view. The heat recovery case resulted in a positive Life Cycle Profit and the cases with a negative Life Cycle Profit were the envelope renovation and the deep renovation. On the other hand, from the environmental perspective, all energy renovations were beneficial, due to the lower environmental impact, i.e. shadow cost, compared to the base case building. So, from the Life Cycle Sustainability Assessment, from the combination and the contribution of both the economic and environmental results, it was found that the heat recovery case was a profitable investment from both aspects. The LCSA results of the other cases, were resulted having higher values compared to the base case, since the LCC results dominated the LCA results, due to their high investments. Consequently, the LCC in the present study is determinant in the decision process. This kind of Life Cycle Sustainability Assessment would benefit the countries to the decision-making process on applying sustainable renovations to the existing building stock.

Preface

This study was part of the two-year master program in Energy-efficient and Environmental Building Design at Lund University, campus Helsingborg in Sweden. This study is a continuation of a thesis work that investigated energy renovations towards the passive house, but in this study it was considered the climate impact of the materials used during the renovations.

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Georgia Betsi

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Terminology

ACH: Air Change per Hour
AHU: Air Handling Unit
ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers
A_{tempt}: Heated floor area
BBR: Boverket’s Building Regulations
BREEAM: Building Research Establishment Environmental Assessment Method
BC: Base Case
CAV: Controlled Air Volume
DHW: Domestic Hot Water
DR: Deep Renovation
ER: Envelope Renovation
EPD: Environmental Product Declaration catalogues
HR: Heat recovery
HVAC: Heating Ventilation and Air-Conditioning system
IDA ICE: IDA Indoor Climate and Energy
kWh: Kilowatt hour
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCP: Life Cycle Profitability
LCSA: Life Cycle Sustainability Assessment
LEED: Leadership in Energy and Environmental Design
MFB: Multi Family Building
NPV: Net Present Value
TNO: The Netherlands Organization of applied research
SEK: Swedish Krona
SLCA: Social Life Cycle Assessment
SVEBY: Standardisera och verifiera energiprestanda för byggnader/ Standardize and verify energyperformance for Buildings
VAT: Value Added Tax
WS: Wikells Sektionsfakta NYB

Environmental Impact Categories:
ADPE: Abiotic Depletion Potential for non-fossils resources, expressed in kg Sb equivalent.
ADPF: Abiotic Depletion Potential for fossils resources, expressed in kg Sb equivalent.
AP: Acidification Potential, expressed in kg SO_2 equivalent.
EP: Eutrophication Potential, expressed in kg PO_4 equivalent.
GFA: Gross Floor Area in m^2
GWP100: Global Warming Potential for time horizon 100 years, expressed in kg CO_2 equivalent.
ODP: Ozone Depletion Potential expressed in kg CFC-11 equivalent.
POP: Photochemical Oxidation Potential, expressed in kg C_2H_4 equivalent.

Terms and definitions

Shadow cost: Monetary relating value that represents the price that society and or government has to pay in order to compensate for the environmental damages caused by the construction, demolition or renovation of a building. In this study, the shadow cost (in Euros) represents the cost that society is willing to pay to ensure environmental quality and mitigate one unit of emissions (Toon van Harmelen et al., 2007).

LCA: The assessment of quantifying the environmental impact/damage caused by a product/procedure over its lifetime.

LCSA: *"Life cycle sustainability assessment (LCSA) refers to the evaluation of the economic, environmental and social impacts or and benefits and plays a critical role in the decision-making processes towards a more sustainable result or product throughout their life cycle"*(UNEP, 2012).

Environmental Impact: Environmental polluting effects caused by a product or substance or procedure. There are different environmental categories, that describe and quantify specific environmental impacts. The categories defined below and used to this study are derived from the Handbook of Life Cycle Assessment (Guinée, 2002), that followed the ISO 14042 and the work of the SETAC-Europe Working Group on Impact Assessment ("SETAC Journals - Society of Environmental Toxicology and Chemistry," 1994).

Abiotic Depletion: *"Abiotic resources are natural resources (including energy resources) such as iron ore, crude oil and wind energy, which are regarded as non-living. Abiotic resource depletion is one of the most frequently discussed impact categories and there is consequently a wide variety of methods available for characterising contributions to this category"* (Guinée, 2002).

Acidification: *"Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). Examples include fish mortality in Scandinavian lakes, forest decline and the crumbling of building materials. The major acidifying pollutants are SO_2, NOx and NHx"* (Guinée, 2002).

Eutrophication: *"Eutrophication covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In addition, high nutrient concentrations may also render surface waters unacceptable as a source of drinking water"* (Guinée, 2002).

Global Warming: *"Climate change is defined as the impact of human emissions on the radiative forcing (i.e. heat radiation absorption) of the atmosphere. This may in turn have adverse impacts on ecosystem health, human health and material welfare. Most of these emissions enhance radiative forcing, causing the temperature at the earth's surface to rise. This is popularly referred to as the greenhouse effect"* (Guinée, 2002).

Ozone Depletion: *"Stratospheric ozone depletion refers to the thinning of the stratospheric ozone layer as a result of anthropogenic emissions. This causes a greater fraction of solar UV-B radiation to reach the earth's surface, with potentially harmful impacts on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials"* (Guinée, 2002)

Photochemical Oxidant Creation: *"Photo-oxidant formation is the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants. These reactive compounds may be injurious to human health and ecosystems and may also damage crops. Photo-oxidants may be formed in the troposphere under the influence of ultraviolet light, through photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx). Ozone is considered the most important of these oxidising compounds, along with peroxyacetylnitrate (PAN). Photo-oxidant formation, also known as summer smog, Los Angeles smog or secondary air pollution, contrasts with winter smog, or London smog, which is characterised by high levels of inorganic compounds, mainly particles, carbon monoxide and sulphur compounds. This latter type of smog causes bronchial irritation, coughing, etc. Winter smog, as far as considered in this Guide, is part of human toxicity"* (Guinée, 2002).

1 Introduction

1.1 Background

The building sector is one of the sectors with greatest energy demand and efforts have been made to reduce this energy demand during the operational phase (use phase). There is also an urgent need for reducing the environmental impact of a building during its whole lifespan, i.e. including the embodied energy of a building. An estimated 80% of the existing buildings will still exist and be used by 2050 (Vilches et al., 2017) and that means that Sweden and many other European countries are in demand of large-scale renovations of the post-war existing building stock (BBR, 2015).

New buildings and renovations of the existing building stock should be oriented towards more environmentally friendly and net-zero carbon dioxide strategies and satisfy human needs, they should adapt to the forthcoming environmental changes and should also provide high indoor air quality and comfort to the occupants. So far there is a lack of standardized actions that should take place in order to achieve efficient and profitable renovations for those building stocks and simultaneously regulations are pushing towards the reduction on the energy demand, which requires high investments and results into higher rental prices (Mangold et al., 2016).

To drive those renovations, the target of the European Commission on climate neutrality by 2050 (European Commission, 2020) should be followed. This commitment is driving all the EU policies towards this direction and especially Sweden has set a target with a new environmental policy framework which contains legislations that should be followed by businesses and the society reaching this Climate act by 2045 (UNFCCC, 2017). To meet those goals, the existing stock of multi-family houses needs to undergo renovations.

1.2 Motivation

Sustainable building design has the potential to improve the existing building stock towards more environmental friendly solutions in the context of climate neutrality (Mjörnell et al., 2019). According to the European Commission’s Estimations, large-scale renovations in most of the European countries are still lagging behind, having an annual rate of 0.4 to 1.2% (European Commission, 2019) compared to the dominant number of the small-scale and individual renovations, which result in minor energy reductions (BPIE, 2014).

More knowledge is needed regarding the most effective key-parameters that should be considered to succeed renovating a building in a way of balancing the environmental impact, costs and low energy use (European Commission, 2016). The main motivation of this study is to examine several renovation solutions on one case study of a multi-family building in south Sweden balancing the operational and embodied impact of a building, for lower energy demand, lower environmental impact and costs.

1.3 Objectives

The present study is a part of a continuation of a previous thesis work that investigated energy renovations towards passive house in a multi-family building (Albin Lithvall, Jovan Panić, 2020), but did not consider climate impact of the materials used for the renovations. The objective of this study is to investigate for the same building selected renovation solutions considering three relevant technical aspects: the low energy demand, economical perspective (Life Cycle Costing-LCC) and the environmental impact (Life Cycle Assessment-LCA), into one aggregated result (Life Cycle Sustainability Assessment-LCSA). The focus will be on searching if and at which scale the selected renovation solutions would be suitable and economical feasible and which other parameters should be considered and affect indeed the decision-making process.

The study will attempt to answer the following questions:

- Which energy renovation "packages" (solutions) could be most suitable for the case-study?
- Which materials could be used and what is the environmental impact of the renovation cases (operational and embodied climate impact)?
- What are the resulting values for the parameters for the renovation case-studies?
- How could the environmental impact, economic impact and low energy demand of the renovations be balanced?

1.4 Overall approach

The overall approach of the study was divided into the following six parts:

- **Literature review part**
  This was the first step, to realize the current status quo of the subject and to orientate better the project's workflow. A literature review was carried out to present the Swedish building regulations and standards and the LCA context, method, database and tools that were used in the present study. Moreover, information was found on previous energy renovation cases until now and on LCA, LCC and the energy use of those cases.
- **Energy simulations using computer software**
  An important step was to apply the energy renovation solutions, on the selected building typology, based on the literature review. Simulations on the energy need of the building were conducted using building simulation software.
- **Life Cycle Cost analysis**
  Using a construction catalogue data base, all the investment costs i.e. construction, demolition and transportation costs were considered to calculate the selected renovation solutions. The Net Present Value (NPV) and the Life Cycle Profit (LCP) were calculated for the selected lifespan.
- **Life Cycle Assessment and environmental impact**
  Following a specific methodology an LCA analysis was conducted by using Environmental Product Declaration (EPD) catalogues, from construction companies, and an LCA software.
- **Life Cycle Sustainability Assessment**

This was the last step of combining the LCC and LCA results into one factor (result).

- **Analysis**
  Finally, this is the last step of interpreting the results.

1.5 Limitations

This study focuses mainly on the assessment of the environmental impact of the materials, the cost, and the energy demand of the selected renovation solutions of a real case multi-family building in Sweden, as well as on the interdependence between them. For this study, one typology building was chosen, i.e. a multi-family building in Helsingborg city, from the Million Program, which was continuation of a thesis work that looked into energy renovations towards passive house for the same building (Albin Lithvall, Jovan Panić, 2020), but the difference is that the present study considers the climate impact of the materials for the selected renovation solutions. The renovation “packages” (solutions) were chosen based on an earlier literature review study and were already applied in multi-family buildings in the Nordic climate (Ramirez Villegas et al., 2019). Regarding the selected renovation cases and especially for the envelope renovation solutions, structural but also moisture safety analysis was not part of the scope of this study.

Regarding the energy simulations, the selected renovation cases were performed with the climate data of Helsingborg, in southern Sweden. The orientation was towards south, with the half of the roof surface towards the south and half of the roof towards the north. Based on the geographical location and building orientation, the results could be considered comparable with other similar building typologies and with similar on-site prerequisites and location.

The LCC analysis results might be higher in reality given the fact that unexpected costs might appear in real-time-projects and conditions, e.g. construction damages, supplementary material, weather conditions, extra hours for workmanship, etc. Moreover, one of the selected renovation solution’s costs used in this study, i.e. mechanical exhaust and supply air with heat recovery ventilation system also named as “FTX”, was not calculated in detail for this study, but instead an approximation based on the building’s dimensions was used (reference cost), based on a previous study, where it was calculated in detail (Hadzimuratovic and Swedmark, 2016). Furthermore, the lifespan of different building materials and its need for replacement during the analysed period was not considered. Renewable energy production was not considered neither.

The last part of the LCSA analysis was limited to a combination of the LCC and LCA analysis only. A complete LCSA analysis is comprised also from the Social Life Cycle Assessment (SLCA), which is a very complex part, and it was exempted in this study. The SLCA analysis is mainly a combination of psychology and social science and it is difficult for the engineering fields to take it into account. The difficulty lied in the lack of knowledge over the SLCA methodology and availability of resources and data. A literature review for the LCSA gives an overview and an insight to the reader and guide him over the methodologies and further information towards this field. Other aspects that were outside of the scope of this study were the fire safety investigation, the thermal comfort, and the daylighting analysis.

2 Literature review

In this chapter is included the LCSA context and overview, various energy renovation cases in Sweden, LCC and LCA literature review paragraphs.

2.1 Life Cycle Sustainability Assessment – context and overview

“Life cycle sustainability assessment (LCSA) refers to the evaluation of the economic, environmental and social impacts and plays a critical role in the decision-making processes towards a more sustainable result or product throughout their life cycle”(UNEP, 2012). LCSA methodological framework follows the ISO 26000: Social Responsibility Guidance Standard and the ISO 14040 series (Environmental management – Life cycle assessment – Principles and framework), and several other international LCSA initiatives and tools (UNEP/SETAC Life Cycle Initiative et al., 2011). Figure 1, illustrates the definition described above.

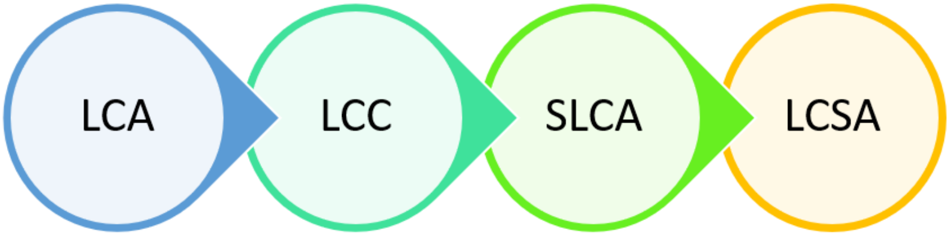


Figure 1: LCSA definition. Adapted from reference (UNEP, 2012).

The LCA is transformed over the years into LCSA method, which has integrated from various models, describing various fields and parameters, into one accumulated model. In the beginning of the 21st century the LCA has been applied more than ever and continues to draw the attention (Guinée, 2002). In 2002 the Life Cycle Initiative, by applying the Life Cycle Thinking (LCT), was born by the contribution of the United Nations Environment Program (UNEP) and the Environmental Toxicology and Chemistry (SETAC) (Life Cycle Initiative, n.d.; Zira et al., 2021). The LCT also referred as Life Cycle Perspective (LCP) is a way of thinking more sustainably, consolidating environmentally friendly transition into the decision-making process (UNEP/SETAC Life Cycle Initiative et al., 2011). Over the years the European Commission, other organisations and involved stakeholders promoted more the LCA and the need of moving towards a more sustainable and environmental low-carbon footprint direction and policies (European Commission, 2003). Consequently many carbon-footprint standards and LCA certifications have been established (ACLCA, 2021). In the second half of the 21st century increased attention is thought to be drawn over the LCSA method, which is a future framework of the LCA. It will contain a broader scope of plethora of results related to the economic, social and ISO’s regulations of the environmental impact aspects (Guinée, 2002).

The LCA methodology assesses the environmental impact of a product or process over its life cycle and follows the ISO 14040 and 14044 standards and in practice is a combination of four phases: 1. Goal and scope, 2. Inventory analysis, 3. Impact assessment and 4.

Interpretation of results (UNEP/SETAC Life Cycle Initiative et al., 2011). In the present study the LCA refers to the different materials used for the renovation solutions analysed in the present study, the life cycle is 60 years and the method followed is the CML baseline. The impact of the energy use during operation was also considered. The detail analysis and results will be presented in the following chapters.

The LCC analysis comes from the accumulated costs of a product or a process over its studied life cycle. It is also carried out in four steps: 1. Definition of the goal, scope, and functional unit, 2. Inventory analysis, 3. Aggregate costs by cost category, 4. Interpretation of results (UNEP/SETAC Life Cycle Initiative et al., 2011). In the present study the accumulated LCC is expressed with the Net Present Value (NPV), the life cycle is 60 years and the accumulated costs refer to the investment, the operational and maintenance costs of the different renovation solutions analysed in the present study. The detail analysis and results will be described in the following chapters.

The SLCA analysis is described as a *"potential social impact method and the goal is to analyse the social and socioeconomic aspects of products and their positive or negative impacts along their studied life cycle"*(UNEP/SETAC Life Cycle Initiative, 2009) and follows the ISO 14040 framework (Rainer Grießhammer et al., 2006). It is also carried out in four phases: 1. Goal and scope of the study, 2. The inventory, 3. Impact assessment and 4. Interpretation of result (UNEP/SETAC Life Cycle Initiative et al., 2011). The aspects and data assessed and analysed in the SLCA method affect directly or indirectly the stakeholders e.g., government, society, company, etc. The potential negative or positive impacts might be connected to the initiatives behaviours to social, socioeconomic and to social capital (UNEP/SETAC Life Cycle Initiative et al., 2011). In the present study the SLCA analysis was not included since it was not in the study's scope. The study focused on combining the LCC and LCA analysis and their interconnections between them, so it could be referred more as an Integrated Life Cycle Assessment (ILCA) (Hájek and International Federation for Structural Concrete, 2013), but the context and the goal was around the LCSA as an early-stage study and attempt to approach the LCSA analysis.

But indeed, what are the advantages of such a complex method in practice? The decision-makers, e.g. government, companies and other stakeholders could assess the LCSA results to organise their data and have a wide spectrum of the whole picture from the interconnections of those parameters i.e., LCC, LCA and SLCA. By prioritizing the impacts and the interactions of the studied parameters, the interpretation of the results could help them take more responsible, sustainable, and eco-friendly decisions that will contribute to the society (UNEP, 2012).

2.2 Life cycle assessment – context, method, definitions, database, and tools

Life cycle assessment definition

According to the ISO 14040:2006, the definition of life cycle assessment is *"The assortment and assessment of the inputs, outputs and the potential environmental aspects and impacts of a product system throughout a product's different life cycle stages"* (ISO 14040, 2006). The following LCA specify the procedure:

- ISO 14040:2006 Environmental management – Life cycle assessment – Requirements and guidelines
- EN15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method

There are different life cycle stages such as the “raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)”(ISO 14040, 2006). To assess a product from the life cycle point of view and analyse its life cycle assessment and environmental impact it is important to find both the “Embodied” and the “Operational” impact. Following and completing all the stages and by considering both impacts the LCA analysis is complete.

Life cycle assessment phases

According to ISO, the LCA analysis can be carried out in four phases. The graphical presentation is shown in Figure 2 below.

1) Goal and scope definition
2) Inventory analysis
3) Impact assessment
4) Interpretation of results

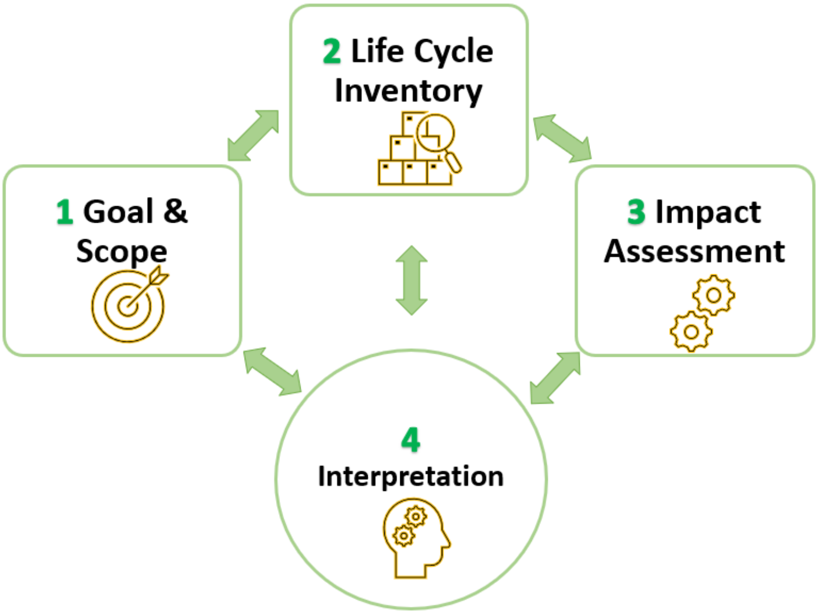


Figure 2: LCA graphical presentation process. Adapted from reference (Ecochain, 2019).

1) *Goal and scope definition phase*

The first part is called “The goal and scope definition phase”, where the LCA´s purpose, the functional unit of the analysed product, the system’s boundaries, the life cycle geography, and other further assumptions are presented.

- Based on the LCA handbook, it should be clearly stated the LCA’s purpose, for its life cycle product assessment (what?), it’s method (why? and how?) and its performance (how well?) and its duration (for how long?) (Joint Research Centre, 2010).

- The system boundaries, where it is defined which stages of the life cycle are included in the assessment. Based on the EN standard the LCA analysis comprises of different lifespans, as it is shown in the Figure 3, from A1 to D stage. The life cycle stage "cradle-to-grave" is when a product starts as a raw material and ends with waste treatment, re-used or re-cycled. For the life stage "cradle-to-gate", the product starts as a raw material and ends when the product is produced. The stage "gate-to-grave" starts after the products production and ends with waste treatment. The last stage is "cradle-to-cradle" and it is the stage where the product starts from raw material and ends with being reused in different processes (EN 15978, 2018; ISO 14040, 2006). An EPD is from cradle-to-grave, and some do not present the End-of-life cycle stages (D), as it is shown in Figure 3. In the system's boundaries it is included the geographical place of the studied material or process.

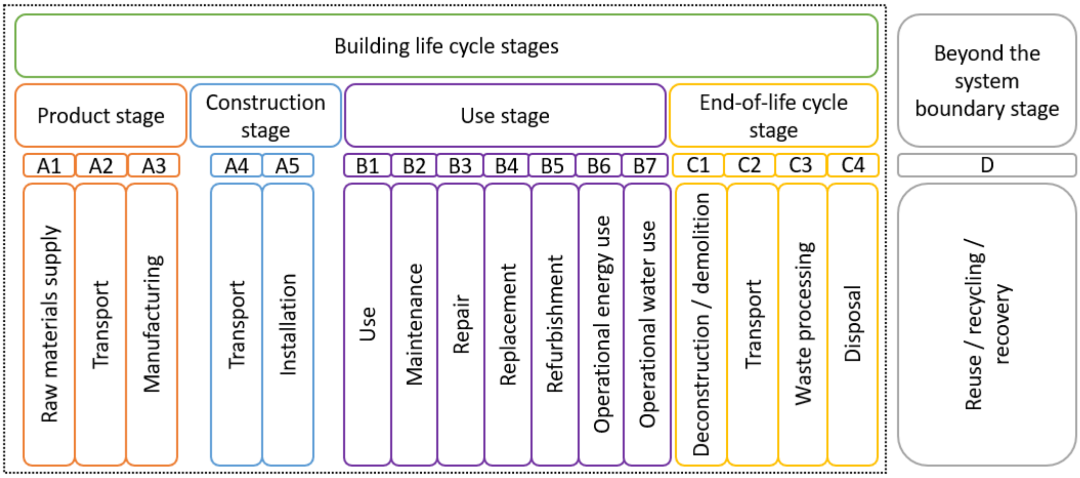


Figure 3: EN 15978 building life cycle stages. Adapted from reference (EN 15978, 2018).

- Further assumptions and limitations correspond to several processes that are given a standard value related to a specific selected approach to avoid unjustified differences in the calculations and refer to the same value due to the assumptions.

2) *The inventory analysis*

The second phase is "The inventory analysis phase", where the needed data based on the defined goal and scope are collected, flows of materials and energy into one product system are connected and allocation problems are defined. The life cycle inventory is a list of quantified incoming and outgoing flows.

3) *Impact assessment*

"The Impact assessment" step of the environmental impact categories, it has the meaning of the different compounds of a material, or a material itself from the inventory analysis into environmental impact categories using specific value indicator.

4) *Interpretation of results*

The last phase is the "Interpretation of the results", where all the stages have been completed and the results should be evaluated based on the predefined goal and scope of the study. In this stage, the results are used to make decisions (government, company etc.), by comparing cases.

Although these steps could be seen as a step-by-step predefined linear procedure, the interconnection, and interrelations between the steps, could make the LCA process iterate between each phase. Similarly, this interaction on multiple changes could be followed to the data from the inventory analysis. Finally, when interpreting the results, not only the impact assessment should be considered, but also the decisions made in each step.

Operational impact

The “Use stage” from B1 to B7, as it is shown in Figure 3, is called “Operational impact”. In essence, it is the building’s climate impact of its energy consumption. The operational impact is different for each building, and this is the reason why it cannot be put into EPD catalogues. To quantify this impact, the analysis should be done through a building simulation software and then input the energy need of the building into an LCA software.

The operational phase is the main focus of energy saving measures, since the energy need of a building is far higher than the energy need during the other life cycle phases together (Aden, 2010). The reduction of the operational energy could be succeeded with renovations on the building’s envelope, energy efficient design strategies, efficient lighting and building services renovation strategies (Bournas et al., 2016). To apply those renovations many building legislations and regulations exist and could be followed, e.g. Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), based on the customer, the company, and the geographical location of the building.

Environmental Product Declaration catalogues (EPD) and Embodied impact

The development and the analysis of the EPD catalogues, created by the construction companies, follow the European Standard EN 15804. Below the LCA standards for the European Standard EN 15804 are presented.

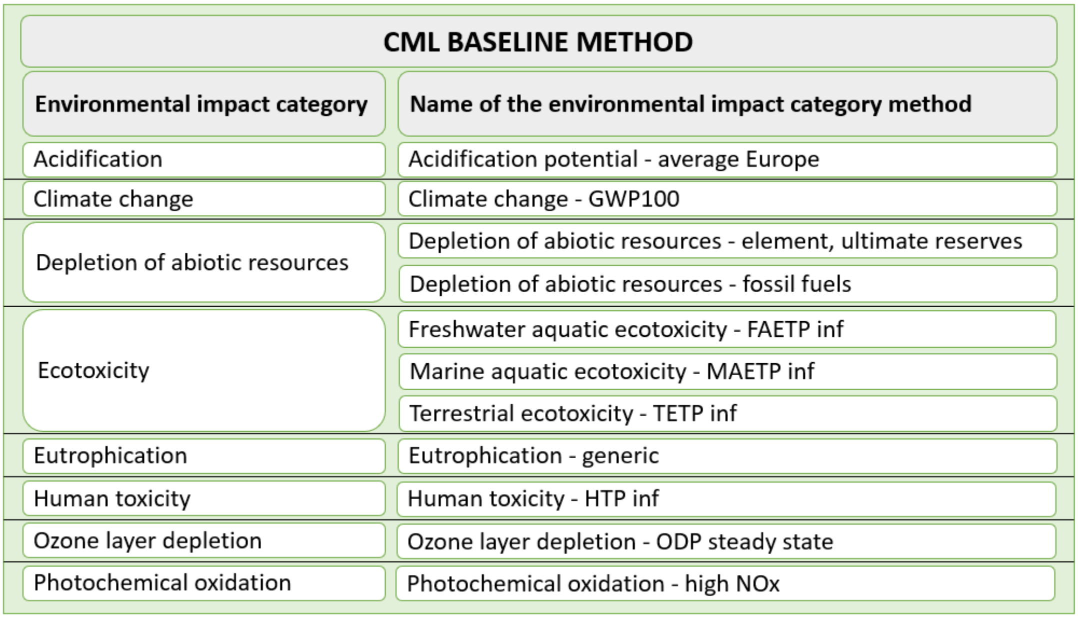
- ISO 14025:2010: “Environmental labels and declarations – Type III environmental declarations – principles and procedures”
- ISO 14044:2006: “Environmental management – Life cycle assessment – requirements and guidelines”
- EN 15978:2011: “Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method”

In an LCA analysis it is important first to define the life cycle stage which is analysed, to find the relevant inputs and outputs. The stages “Product”, “Construction” and “End-of-life”, from A1 to A5 and from C1 to C4, as it is shown in the Figure 3, are described as “Embodied impact” and they could be found from the EPDs. The results of the embodied impact, essentially the impact that comes from the production, construction and end-of-life cycle stages is written in every EPD catalogue and it is the LCA study conducted by the companies for the production of the specific product. It is a way to “mark”, to declare their product’s environmental impact footprint. In low-energy buildings the embodied energy and the environmental impacts from an LCA ends up being higher than in conventional buildings (Asdrubali and Grazieschi, 2020).

Regarding the embodied, impact too little attention has been drawn to the energy used during the rest of the life cycle stages expect from the operational phase of a building (de Klijn-Chevalerias and Javed, 2017). For conventional buildings, the embodied energy comprises of a small amount of a building's life cycle compared to the operational energy (Sartori and Hestnes, 2007). The impact of this energy has been exempted in the past and not many studies have been included the environmental impacts during all the phases of a building's life cycle (Dixit et al., 2012; Lenzen, 2000). Based on various studies, it has been indicated that low-energy buildings appear to have higher or comparable embodied energy compared to conventional-energy buildings (Sartori and Hestnes, 2007), due to more and high-energy intensive materials that were used during the construction phase, which greatly compensate the decline in operational energy (Nationale Milieudatabase, 2014). The embodied impact of a building is a complex combination of many aspects i.e. energy sources, material's construction process, technology, location and it fluctuates over time (Ding, 2004). Consequently, the results of the embodied impact might vary significantly, due to different methodologies used, system's boundaries, energy sources, availability of data etc. (Praseeda et al., 2015).

Environmental impact categories

The environmental impacts are many and they are described through different methods. The one which is the most common and significant is the "CML". This method was created by the University of Leiden in the Netherlands in 2001. This type of method is divided into two other subcategories, the "baseline" which is the most commonly used and the "non-baseline". (Acero, Rodríguez, et al., 2016). The following Figure 4 shows the environmental categories of the "CML baseline" method.



CML BASELINE METHOD

Environmental impact category	Name of the environmental impact category method
Acidification	Acidification potential - average Europe
Climate change	Climate change - GWP100
Depletion of abiotic resources	Depletion of abiotic resources - element, ultimate reserves
	Depletion of abiotic resources - fossil fuels
Ecotoxicity	Freshwater aquatic ecotoxicity - FAETP inf
	Marine aquatic ecotoxicity - MAETP inf
	Terrestrial ecotoxicity - TETP inf
Eutrophication	Eutrophication - generic
Human toxicity	Human toxicity - HTP inf
Ozone layer depletion	Ozone layer depletion - ODP steady state
Photochemical oxidation	Photochemical oxidation - high NOx

Figure 4: Impact categories contained in the method "CML baseline". Adapted from reference (Acero, Rodríguez, et al., 2016).

Normalization

To compare the different units of the different environmental impacts, first a normalization should be done. Normalization is the combination and conversion of different environmental impact units to a single-point unit. It is the conversion of different units to normalized units (Tommie Ponsioen, 2014). The normalization could be “internal” or “external”. The selection is based on the reference system which could depend on or be independent from the analysis.

The internal normalization of the environmental impacts could be done by dividing it by an internal reference system, i.e. division by sum, average or baseline for each environmental impact. The external normalization could be done by dividing the environmental impact by an independent reference system connected with the corresponding LCA method. For instance, the CML-baseline method has the following packages of normalization factors, for each environmental impact category: West Europe 1995, World 1990, EU25+3 2000, EU25, World 2000, World 1995, the Netherlands 1997.

Weighting

Weighting is a procedure that follows the normalization of the environmental impacts. It is a process of multiplying the normalized results of each impact category, by assigning a weighting factor with a relative importance to each impact category. The determination of the weighting factors depends mostly on the geographical impact, i.e. global, regional or local impact and on the distance to policy target, distance to scientific target, monetization and people’s opinions on weighting (Ellen Meijer, 2014).

For the present study the Dutch approach, with the shadow cost was selected, to create comparable results. It was important to choose one method, to add a monetization value to the results. It is a virtual highest acceptable monetization value, which the society and/or the government should pay in order to compensate for the environmental damages caused by the building during the construction and operation processes (Toon van Harmelen et al., 2007). The weighting factors of shadow cost were determined from The Netherlands Organization (TNO) of Applied Research (Toon van Harmelen et al., 2007). These weighting factors are updated regularly to determine the latest changes and society’s legislations (de Klijn-Chevalerias and Javed, 2017). The shadow cost is the total of the building sections/parts and/or of the environmental impact categories. (Toon van Harmelen et al., 2007). By using such an approach, the environmental impact categories are both normalized and weighted. The shadow cost normalizes and weights the different environmental impact categories, and the results could be comparable with each other, because they have been assigned with a different weight of a monetization value, depending on the environmental impact category.

2.3 Previous energy renovation cases until now

The Swedish parliament had decided to renovate the almost one million past-war apartments that were built in 1965-1974 (Byman, K. & Jernelius, S., 2013) and almost half of them were located in Stockholm, Gothenburg and Malmoe (Industrifakta, 2008). Almost 20% of those buildings have been renovated and only a small percent could cover the future energy sustainable needs and regulations requirements (Industrifakta, 2008). The renovation plans were targeting the reduction of the architectural aesthetical impact and to use less concrete-based buildings (Byman, K. & Jernelius, S., 2013). Those buildings used 80% concrete as a construction material, for the façade 33% bricks and the rest were other material i.e., panels, metal sheet, combination of brick etc. (Industrifakta, 2008). The program included an analysis of glazed parts, which made the renovations even more sustainable. The renovation costs accounted for 50 billion SEK (SABO, 2009).

Another example from smaller-scale renovations were the properties build in ’70, in Brogården in Alingsås, close to Gothenburg (Naturskyddsföreningen, 2016). The 300 apartments were renovated under the energy efficient scope, succeeding an energy reduction of 60%. The renovation cost per apartment was one million SEK and included wall and roof insulation, replacement of the free-standing balconies, replacement of the old windows with new triple glazed ones and controlled air and preheated air when is need, supplied to the apartments (Naturskyddsföreningen, 2016).

The SigtunaHem company in Northern Stockholm (SigtunaHem, 2016) proposed small-scale renovations, the so-called “Mini” renovation packages, targeting affordable renting prices with profitable energy results over the years. The company did not target environmental requirements, only focused on the tenants’ preferences. Specifically they offered three options of renovation packages, the “Mini, Midi and Maxi”, which were available to the tenants based on their income (Lind et al., 2016). The renovations consisted mainly of interior modifications and replacement of the heat exchangers of the district heating system, forecast control, adding heat recovery from ventilation system and new weather stripping on the doors and windows or painted and replaced with new ones (SigtunaHem, 2016). By choosing the “Mini, Midi or Maxi” renovation, the rental cost would be increased by 82 €, 179 € or 190 € per month respectively (Lind et al., 2016).

2.4 Life cycle assessment, life cycle costing and energy use of energy renovation cases until now

Buildings have been identified as one of the major sectors that demand urgent measures to reduce the energy demand and the carbon dioxide emissions to the environment (IEA, 2017).

It is essential to underline that to choose a renovation package, first the type of energy refurbishment should be chosen. There are two types of energy renovations: top-down or bottom-up, which means either following the regulation systems or considering the operational costs of the building respectively (Ekström et al., 2017).

Before presenting the studied cases in more detail, it is important to describe the various “renovation packages” based on the literature. The following cases describe typical renovations in Sweden (Ramirez Villegas et al., 2019). Some refurbishment scenarios that have already been tested and described in a study (Ramirez Villegas et al., 2019) were: the deep energy refurbishment (DEERS) (Zinko, 2011), the upgrade of the ventilation system by adding heat recovery and decreasing the indoor temperature (HRV21) or without decreasing the indoor temperature (HRV22.7) and the building envelope renovation case

(BEnS). The analytical characteristics of the renovations packages from the study are presented with the following Table 1.

Table 1: The characteristics of the renovation packages described on the case-study (Ramirez Villegas et al., 2019). Not changed means that the referring parameter remained the same as in the base case building before renovations.

Renovation part	**DEERS**	**HRV21**	**HRV22.7**	**BEnS**
External walls	480 mm insulation	Not changed: 120 mm insulation	Not changed: 120 mm insulation	480 mm insulation
Attic	New insulation	Not changed: insulation	Not changed: insulation	New insulation
Windows	3 low emissivity pane windows, filled with argon	Not changed: 2 pane windows	Not changed: 2 pane windows	3 low emissivity pane windows, filled with argon
Ventilation system	Heat recovery	Heat recovery	Heat recovery	Not changed: Mechanical
Indoor temperature	21.7ºC	21.7ºC	Not changed: 22.7ºC	Not changed: 22.7ºC

The case-study building was a three-story residential building of a total heated floor area of 2822 m^2, in the Northwest side of Stockholm, in the Borlänge municipality and the studied lifespan was 50 years. The renovations examined the energy use and the LCA impact of the building. More specifically the simulations were conducted using IDA-ICE tool. In the base case building some maintenance on the replacement of the exhaust ventilation components was conducted. The DEERS energy reduction was 43% compared to the base case building. In the BEnS and HRV21 cases the energy reduction was approximately 27% and for the HRV22.7 case was only 15%, compared to the base case (Ramirez Villegas et al., 2019).

Regarding the LCA analysis, the studied stages were from “cradle to grave”, the method used was the CML from the University of Leiden and the studied environmental impact categories were the GWP, AP, EP and ADP for fossil and non-fossil elements. From the environmental impact categories tested, the GWP was reduced the most and the highest environmental impact was caused from the operational energy in all renovation cases. Specifically, the DEERS case had the highest GWP reduction and a total emission saving of 19%, HRV21 with 16% saving, the HRV22.7 and BEnS with 10%. Comparing the LCA results, an interesting finding was that the HRV21 had higher emission reduction compared to the BEnS the, even thought it had a slightly worse energy performance. This could be explained by the higher environmental impacts from the more and extra materials used during the construction process of the BEnS renovation case (Ramirez Villegas et al., 2019).

Another renovation project was the *"Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation” (Annex 56)* of International Energy Agency (IEA), from the program “Energy in Buildings and Communities (EBC)” (IEA, 2017), intended to reduce the embodied impact from the manufacturing, replacement and end-of-life processes, and embodied primary energy. The methodology that was followed was based on an Integrated Life Cycle Assessment (ILCA), together with the Life Cycle Costing (LCC), so as to create future measures and standards for the building sector (IEA, 2017). One of the refurbishment cases was in Sweden, in Gothenburg, in 2009. The type of the building was a multi-family house, and the renovation packages were three and all of them were based on the regulations of BBR 2012 (BBR, 2012). Most of the proposed renovations that were examined were characterized as not efficient for an economical, but also an environmental perspective, i.e. the total primary energy and carbon reduction was not significant, compared to other renovation packages to other countries examined. The explanation is that the Swedish building in the case-study was using efficient heating systems i.e., district heating that favours the analysis compared with other energy alternatives of gas, oil etc. (IEA, 2017).

A single-family house in Dalarna, in Sweden, was assessed for the environmental impact of the building materials and an LCA analysis was conducted for a 100 year lifespan (Petrovic et al., 2019). The outcome came after the analysis on a software combined with the Environmental Product Declaration catalogues (EPDs). This study covers the LCA of the building materials and not the energy use, or the cost of the building's materials. It was found that the insulation and wooden parts of the building's construction had the lowest environmental impact compared with the concrete slab which had the highest impact (Petrovic et al., 2019). Based on the study, the full renovation of the building's envelope with new materials, will cover almost half of the whole environmental impact over one century, with the use of wooden parts having the lowest CO_2 emissions (Petrovic et al., 2019).

Examining the existing work so far on this field, in this project, there is the need to go one step further. The examination of the renovation packages in the context of minimizing climate impact and by assessing the energy use, LCA and LCC of building materials is important, in order to come up with feasible renovations that are a good compromise of the LCC and LCA.

3 Methodology

The study is based on quantitative methods. The study includes energy simulations for the selected energy renovation packages (energy renovation solutions) of a MFB, LCC analysis, LCA analysis of the materials used in the renovations, and LCSA analysis combining both LCC and LCA results, into one accumulated result. Figure 5 illustrates the workflow of this project.

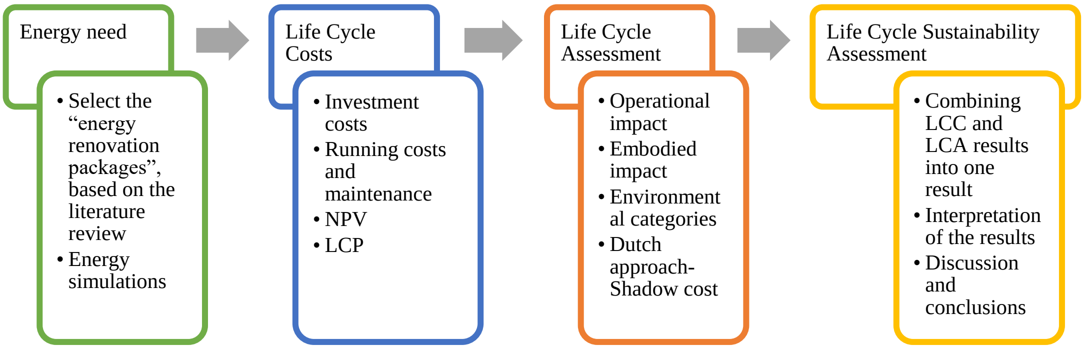


Figure 5: The workflow of the project, created by the author.

3.1 Energy modelling and inputs

The software used to conduct the energy simulations was IDA ICE 4.8 by EQUA company. The software IDA ICE produced by a Swedish company EQUA Simulation AB and it is used worldwide from many companies to conduct building performance simulations ("Building Performance - Simulation Software | EQUA," 2021).

A MFB was modelled, which was one of the representative types of buildings built during the Swedish Million program. The modelling of the MFB is a real building in Helsingborg in Sweden. To bring the project as closer as it could be to the reality, BBR, SVEBY, FEBY and other Swedish building regulations were followed.

In the software, the available climate file used for the energy simulations was from Ängelholm/Barkåkra, provided by ASHRAE 2013, representing similar climate conditions compared to Helsingborg in southern Sweden. The location of the building was in Helsingborg city, in Dalhem.

3.2 Base case energy simulation and inputs

The simulated building used to this project was intended to represent a fairly common MFB from the million program.

The chosen MFB was a three-story building which was based on the model created on a previous study (Albin Lithvall, Jovan Panić, 2020). In this study, energy renovation towards Net-Zero energy Buildings, using photovoltaic systems and batteries, was studied. Or similar inputs as in the previous studies were used (Albin Lithvall, Jovan Panić, 2020; Ramirez Villegas et al., 2019; Warfvinge, 2008). All the base case simulation inputs are presented in the following Table 2.

Table 2: Base case inputs for the simulation of MFB.

Input	Multi-family building	Method / Source
Heated floor area Atemp / m^2	1095	Based on simulation program
Envelope area / m^2	1532.5	Based on simulation program
Heating setpoint / °C	21 in apartments, 16 in staircases, auxiliary spaces	Sveby
Air leakage rate / $l/(s/m^2)$ envelope area at 50 Pa pressure difference	1.4	Based on previous studies
Thermal bridges / % of UA	20	BBR
Ventilation system	Mechanical exhaust air without heat recovery	Based on previous studies
Exhaust ventilation air flow / $l/(s{\cdot}m^2)$, heated floor area	0.35	BBR
Heating system	District heating	Based on previous studies
Domestic hot water (DHW) use / $(kWh/(m^2{\cdot}y))$	25	Sveby
Construction part	***U*-value / $(W/(m^2K))$**	**Source/Source**
External roof	0.23	Approximated based on previous studies
External wall	0.26	Based on previous studies
All glazing parts	2.4	Based on previous studies

The base case building was simulated with mechanical exhaust only-return-air ventilation system, without heat exchanger, with an exhaust ventilation air flow of 0.35 $l/(s{\cdot}m^2)$, based on BBR (BBR, 2020). The SFP for the return air ventilation was assumed 2.0 $kW/(m^3{\cdot}s)$ and the air leakage rate is 1.4 $l/(s{\cdot}m^2)$ enclosing envelope area at 50 Pa pressure difference, based on previous case studies (Ekström et al., 2017). The building was using district heating and DHW, which is 25 $kWh/(m^2{\cdot}yr)$ for multi-residential buildings (Sveby, 2012)

The lifespan for the simulation of the BC building was assumed to be 60 years and during this period maintenance costs were assumed, i.e. roof and façade renovation, but the energy demand of the building, i.e. heating, electricity and DHW demand, was assumed not to be affected. The addition of maintenance in the BC was to have a fair comparison between all cases and avoid favouring this case, since some maintenance of the building would be needed due to wear and tear. Regarding the LCC analysis, the maintenance affected the investment costs and not the running costs, while regarding the LCA analysis, it affected the embodied climate impact.

3.3 Energy renovation packages and inputs

For this project one MFB was modelled using different renovation packages. In other words, different groups of energy modifications were chosen, by changing different parts of the building, in order to achieve a reduction of the energy demand. These were based on the literature review.

presented in the chapter 2.4 (Ramirez Villegas et al., 2019). The first package of renovations was based on the building's envelope (1. ER) and contains a renovation of external wall and attic with added insulation and new 3-pane low emissivity windows. The ventilation system and the indoor temperature remained the same as the base case (BC). For the second renovation package, a mechanical exhaust and supply air ventilation system with heat recovery was added (2. HR), while the building's envelope did not change. The third renovation package was called deep renovation (3. DR) and it was a combination of the ER and HR. It was an addition of a mechanical exhaust and supply air ventilation system with heat recovery system. All the inputs of the energy renovation packages are presented in the following Table 3.

Table 3: Inputs of energy renovation packages for the MFB.

Input	1. Envelope renovation	2. Heat recovery	3. Deep renovation	Method / Source
Heated floor area Atemp / m^2	1095	1095	1095	Based on simulation program
Envelope area / m^2	1532.5	1532.5	1532.5	Based on simulation program
Heating setpoint / °C	21 in apartments, 16 in staircases, auxiliary spaces	21 in apartments, 16 in staircases, auxiliary spaces	21 in apartments, 16 in staircases, auxiliary spaces	Sveby
Air leakage rate / l/(s/m^2) envelope area at 50 Pa pressure difference	0.3	1.4	0.3	FEBY
Thermal bridges / % of UA envelope	20	20	20	BBR
Ventilation system	Mechanical exhaust air	Mechanical exhaust and supply air with HR = 80%	Mechanical exhaust and supply air with HR = 80%	Based on previous studies, Passive house institute
Exhaust/ supply ventilation air flow / l/(s·m^2), heated floor area	0.35	0.38/0.35	0.38/0.35	BBR
Heating system	District heating	District heating	District heating	Based on previous studies
Domestic hot water (DHW) use / kWh/m^2, annually	25	25	25	Sveby
Construction part	***U*-value / (W/(m²K))**			**Method / Source**
External roof	0.12	0.23	0.12	BBR, previous studies
External wall	0.15	0.26	0.15	BBR, previous studies
All glazing parts	0.8	2.4	0.8	BBR, previous studies

The ER and the DR packages have the same envelope renovations with the difference that in the DR case, an additional heat recovery system to the mechanical ventilation was added. By improving the building envelope, an improvement in airtightness was assumed, based on the Passive house principles by applying lower *U*-values on the thermal envelope, compared to the base case (Passivhaus Institut, 2015). In terms of the selected value of airtightness, a

0.3 l/(s/m²) at 50 Pa pressure difference, is assumed after renovating the building envelope i.e. ER and DR, following the requirements of the Passive House standard (FEBY, 2018), with no leakage airflow through the foundations (Ekström et al., 2017). The thermal bridges were considered as 20% of the building's average heat loss coefficient, that will affect the building after the renovations (BBR, 2020).

To apply the energy renovation packages DR and HR, previous studies were used (Hadzimuratovic and Swedmark, 2016; Ramirez Villegas et al., 2019), to extract technical information and installation costs of the exhaust and supply air ventilation with heat recovery system (FTX-Swedish abbreviation), to conduct the simulation and the LCC analysis. An additional requirement for this type of system is that in the current building extra ductwork and extra building construction activities should be done, which would cost more and were considered in the LCC analysis. The ductwork and placement were based on supplying fresh air to living room and bedrooms, where tenants spent most of the time. Regarding the ventilation air flow per heated floor area, the extraction should be higher than the supply, based on Swedish building regulations (BBR, 2020)

In the study *"Study of active technologies for prefabricated multi-active facade elements for energy renovation of multi-family buildings"* of *Hadzimuratovic and Swedmark* (Hadzimuratovic and Swedmark, 2016), the detail installation of an FTX system in a MFB was examined. A detailed dimensioning of the ventilation system work was conducted, where calculations of required air flows, ductwork dimensioning, calculation of pressure drops and data for SFP calculations were made (Hadzimuratovic and Swedmark, 2016).

The Heating Ventilation and Air-Conditioning (HVAC) system was a continuous air volume system (CAV) The heat exchanger efficiency was 80%, based on previous studies and on the Passive house institute (Ramirez Villegas et al., 2019; Wolfgang Feist, 1998) and a heating coil was included to ensure a constant supply air temperature of 17.5 °C from the AHU.

3.4 Material properties

The materials that were considered for the maintenance of the BC and during the new renovations that were examined in the LCA analysis, were conventional materials and information were found from EPD catalogues. The use of the selected materials was affected by the availability of EPD catalogues data. The used EPD catalogues for the material were gathered from Norwegian EPD website (EPD-Norge, 2021). The properties of the material used for the energy renovation packages are presented in the following Table 4 and Table 5.

Table 4: Materials used during the maintenance of the BC.

Construction part	Material name	Thickness / m	Density / (kg/m^3)	Service life / years
Façade	Façade plaster-coating	0.0001	900	60
Roof	Steel sheet	0.0012	7850	60
Roof	Water-tight membrane	0.0039	100	60

Table 5: Material used in the renovation packages.

Construction part	Material name	Thickness / m or Dimension / m	Density / (kg/m^3)	Thermal conductivity, λ / (W/(m·K))	Service life / years	Country
Wall	Glass wool-Isover	0.22	49	0.030	60	Denmark
Roof	Glass wool-Isover	0.18	49	0.030	60	Denmark
Construction part	**Material name**	**Thickness / m or Dimension / m**	**Density / (kg/m^3)**	***U*-value / (W/(m^2·K))**	**Service life / years**	**Country**
3 pane windows (133 items)	NorDan-3panes, aluminium cladding	Window dimension: 1.23 m x 1.48 m Triple glazed: 44mm alu. frame with timber: 105	Glazing part: 223.02 aluminium Frame with timber: 323.74	0.81	60	Norway

3.5 Life cycle costing

To investigate the economical aspect of the proposed energy renovation packages, it was important to carry out an LCC analysis, in order to reach balanced decisions between the environmental and the economic impact of the selected renovations.

All the initial costs were found and quantified in Wikells Sektionsfakta NYB[1] (WS). The selected source is an online data base (book), that includes costs for buying new materials, construction process, demolition process, transportation of the demolished material process, workmanship and it is used by investigators in the construction industry during the construction process. It is a data base that contains different kind of chapters i.e. Building

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[1] Contribution for creating personal account license on Wikells Sektionsfakta from Alexander Askblom, Wikells Byggberäkningar AB.

process (construction and demolition process), electricity work, plumbing work and HVAC work, for the different parts of a building e.g. shafts, ground, basic construction, wall, windows, plumbing material, fans and diffusers etc. (“Wikells Sektionsfakta,” 2021).

Initially, an LCC analysis of the base case was conducted. It was assumed that the base case building was in need of renovation due to era and tear of the façade and roof. Therefore, maintenance costs of these construction parts were assumed. The maintenance costs that were considered as investment costs were the renovation of the roof with a watertight membrane and a steel sheet on top and renovation of the wall façade with an outdoor façade plaster. Those costs affected only the LCC analysis and not the energy performance of the building, so no changes were assumed during the running costs.

The LCC analysis quantified the Net Present Value (NPV) and Life Cycle Profit (LCP) for the various energy renovations. The LCP shows how much the NPV is reduced after applying a renovation compared to the base case, thus a positive LCP shows that the investment is profitable. The LCC analysis comprised of initial investment costs of the various renovation cases, the running costs of the district heating and electricity system as well as maintenance costs. The goal was to quantify the costs for the various energy renovation packages during an entire lifespan of 60 years. The selected lifespan for the LCC analysis was based on the material’s endurance, given by the construction companies. All the initial breakdown costs, for each renovation, are shown in the following Table 6.

Table 6: Initial breakdown costs of the BC and the new energy renovation packages, including VAT.

Construction part	**Construction process**	**Base case**	**1. Envelope renovation**	**2. Heat recovery**	**3. Deep renovation**
Wall façade	Existing masonry brick, refurbished	1 518 kr / m²			
External wall	Construction: existing masonry lightweight concrete + 220 mm mineral wool outside + facade plaster	-	1 869 kr / m²	-	1 869 kr / m²
Roof	Replacement of strip-covered sheet metal roof (sheet metal roof and water-tight membrane)	1 103 kr / m²	-	-	-
	Construction: existing lightweight concrete roof is insulated with 180 mm mineral wool	-	773 kr / m²	-	773 kr / m²

Windows	Demolition: small windows torn	-	405 kr / st	-	405 kr / st
	Demolition: large/wide windows torn	-	486 kr/st	-	486 kr / st
	Construction: small window of aluminium clad wood, fixed	-	5 059 kr / st	-	5 059 kr / st
	Construction: large/wide window of aluminium clad wood, fixed	-	7 35 kr / st	-	7 35 kr / st
	Transport of demolition materials		258 kr / m^3		258 kr / m^3
Filter for HR	Air handling unit of type supply and return air with HR: Maintenance cost: filter change	-	-	3 000 kr / year	3 000 kr / year
Exhaust & supply air ventilation with HR (FTX)	Ductwork (ducts, silencers, fire dampers and supply diffusers), core drilling in present for diffusers, AHU of type supply and return air with HR	-	-	1 331 kr / m^2	1 331 kr / m^2
Investment cost / SEK	-	1 468 835	2 572 514	1 457 840	4 030 354
Investment cost / (SEK/m²)	-	1 341	2 349	1 331	3 681

Transportation costs for the demolished windows were added to the LCC and data regarding the produced debris mass were retrieved from a respective study (Llatas, 2010). For the ER and DR the wall was insulated from the exterior side with 220 mm insulation and extra cost was added for an exterior façade plaster. In this way, money would be saved from demolishing the existing exterior façade and then applying the renovations. Regarding the roof renovation, an idea was to renovate the whole roof by demolishing the existing aluminium siding, wood and studs and placing the new insulation and then restoring again the demolished layers. By applying such a renovation, the costs were much higher since extra money were needed for the demolishing of those material. So, it was assumed that it was possible to create a cold roof instead, by adding insulation to the exterior side of the ceiling, i.e. interior side of the roof.

For the implementation of the exhaust and supply air ventilation with heat recovery system (FTX) to the present HVAC unit, data regarding the LCC and information were found from previous study of *Hadzimuratovic and Swedmark.* The cost of the FTX system for the present study was calculated based on the present building's dimensions and stemmed from one of the energy renovation alternatives presented explicitly in the reference study (Hadzimuratovic and Swedmark, 2016). Additionally, based on this study, extra maintenance cost was added due to the annual filter replacement, which was 3 000 SEK in their present money value (Hadzimuratovic and Swedmark, 2016).

Other costs such as district heating prices were taken from the Öresundskraft company, for the present year from 1st of January to 31st of December, based on seasonal fluctuation consumption öre/kWh including VAT (Öresundskraft 2021), as it is shown in Figure 6.

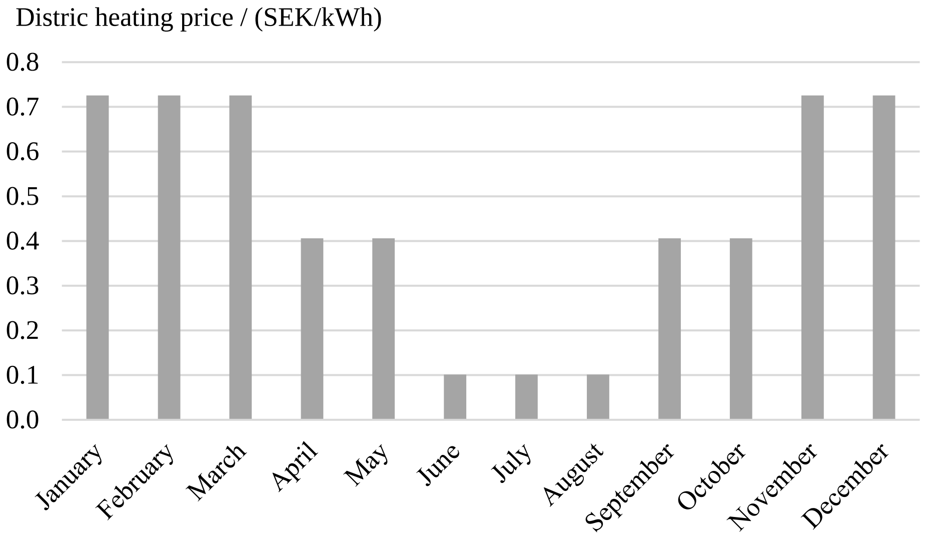


Figure 6: District heating prices per month. Source (Öresundskraft, 2021)

For the electricity price, the value 1.8 SEK/kWh, was retrieved from International Energy Agency (IEA) and Swedish energy agency, a national survey report of PV power applications in Sweden, for 2019 (Lindahl et al., 2020).

For the LCC analysis the following Eq.1 and 2 were used to find the NPV. The total NPV were found from the Eq.3

$$A_1 = C_0(1 + i)^n \text{ [SEK] (1)}$$

$$NPV = A_1 \left(\frac{1 - \frac{(1+g)^n}{(1+i)}}{1-g} \right) \text{[SEK] (2)}$$

$$NPV_{total} = I_c + NPV_{heating} + NPV_{electricity} + NPV_{maintainance} \text{ [SEK] (3)}$$

A_1: *Accumulated costs in year one, for heating, electricity and maintenance in SEK*
C_0: *Represents the running cost in year zero, for heating or electricity in the current money value in SEK*
i: *Rate of return of the investment in %*
n: *Lifespan of the life cycle in years*
g: *Constant electricity price growth rate or constant district heating price increase in %*
I_c: *Initial cost the actual investment in SEK*
NPV_{total}: *Net Present Value of the life cycle cost of the initial cost and running costs in SEK*

All the rates were changed from nominal to real rates using the following the Eq.4.

$$i_n \approx i_r + k \text{ (4)}$$

I_n: *Nominal rate*
I_r: *Real rate*
k: Inflation

The lifespan used for the LCC analysis for the energy renovations tested was 60 years and based on the material's lifetime. The rate of return was set to 2.3% (Statens-Fastighetsverk, 2020) with inflation excluded 1% ("Historic inflation Sweden – historic CPI inflation Sweden," 2021). The average electricity price increase rate was assumed to be 2%, using the Eq. 4 excluding the inflation (Statens-Fastighetsverk, 2020). The constant district heating price growth rate was assumed to be 1.5% annual with inflation excluded (Statens-Fastighetsverk, 2020). The LCP of each alternative was calculated by applying Eq.5 and describes the new energy renovations applied to the MFB and it shows how much is the NPV be reduced after applying the renovation package, thus showing whether the examined investment is profitable.

$$LCP = NPV_{base\ case} - NPV_{renovation\ package} \text{ (5)}$$

3.6 Life cycle assessment and environmental impact in the present study

For the LCA analysis the following methodology was used, to analyse the renovation packages that were presented in the chapter 3.3. In order for the reader to be able to follow this methodology, it is important to mention all the specific parts and definitions which are considered in the present study.

Based on the literature review in paragraph 2.2, this chapter includes the specific inputs and parameters used for the present LCA study. The software used for the LCA analysis was openLCA, version 1.10.3 (GreenDelta, 2007) It is an open-source software, which provides sustainable assessment in various projects all over Europe and in the US. This software could be used in industry and in consultancy, for educational persused and research. The company created the software is the GreenDelta, a sustainability consulting and software company located in Germany and founded in 2004 (GreenDelta, 2004).

LCA phases and environmental impact categories

For each LCA analysis all the LCA phases mentioned in the paragraph 2.2 should be followed. The same was applied for this study. In the present LCA they were investigated the environmental impacts of different materials during a life cycle of 60 years of a MFB per an envelope area (Gross Floor Area-GFA) of 1095 m^2.

This project considers the “cradle to grave” life cycle stage, phases A1 to C4, as it was mentioned in the paragraph 2.2, when the products start as raw materials and end with the disposal of the materials. The building was in Dalhem, Helsingborg and for each material, transportation process were considered, depending each time of the product’s location based on the information of the EPD representative catalogues.

For this project, seven environmental impact categories of the Life Cycle Sustainable Assessment (LCSA) method were assessed. The method used for this project is the CML baseline from University of Leiden in the Netherlands (Acero, Rodríguez, et al., 2016). Based on the available resources from the EPD catalogues, it was possible to assess only seven of the impact categories. The available impact categories were: Global warming (GWP100), Acidification potential (AP), Eutrophication potential (EP), Ozone layer depletion potential (ODP), Photochemical oxidation (POP), Abiotic Depletion Potential for Non-Fossils resources (ADPE) and Abiotic Depletion Potential for Fossils resources (ADPF). Human Toxicity Potential (HTP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Marine Aquatic Ecotoxicity Potential (MAETP) and Terrestrial Ecotoxicity Potential (TETP) were not able to be assessed due to the lack of available data.

Operational impact

For the operational impact of the building, energy simulation with IDA ICE software was firstly conducted and then the results for the energy use of the building, i.e. kWh/year, were used to the openLCA software to conduct the LCA analysis.

In this software, the first step was to create the flows, which were the cases examined to this study, i.e. BC building, 1. ER building, 2. HR building, 3. DR building. In this step it was selected the location of the building, i.e. Sweden and the reference unit, i.e. building’s GFA of 1095 m^2. Then the flows were created and connected with the processes (cases). A process contains the inputs and transforms them into an output (Dr A. Ciroth et al., 2020). In the processes the location, the life cycle of 60 years and the energy source were selected. The type of energy source for heating together with DHW and separately for the electricity of the building were selected, as it is shown in the Table 7 (Dr A. Ciroth et al., 2020).

Table 7: Inputs for the processes in the openLCA software

Inputs: Energy carriers category	Unit	Provider	LCA emission factor / (kg CO_2 eq./kWh)	Life cycle / years
Flow Electricity mix	kWh	Electricity Mix, consumption mix, at consumer, AC, 230V - SE	0.11	60
Flow Heat and steam: Process steam from waste incineration	kWh	Municipal solid waste (MSW), average European waste-to-energy plant, -EU-27	0.38	60

Regarding the energy flow, the selected energy source for heating and electricity of the building, i.e. the kWh/year of energy selected each time, was based on the results during the simulations of the BC and the applied renovation packages. Each renovation package based on the different parameters and had a different energy need for the building in kWh/year, as it is presented in the results chapter 4.1 below.

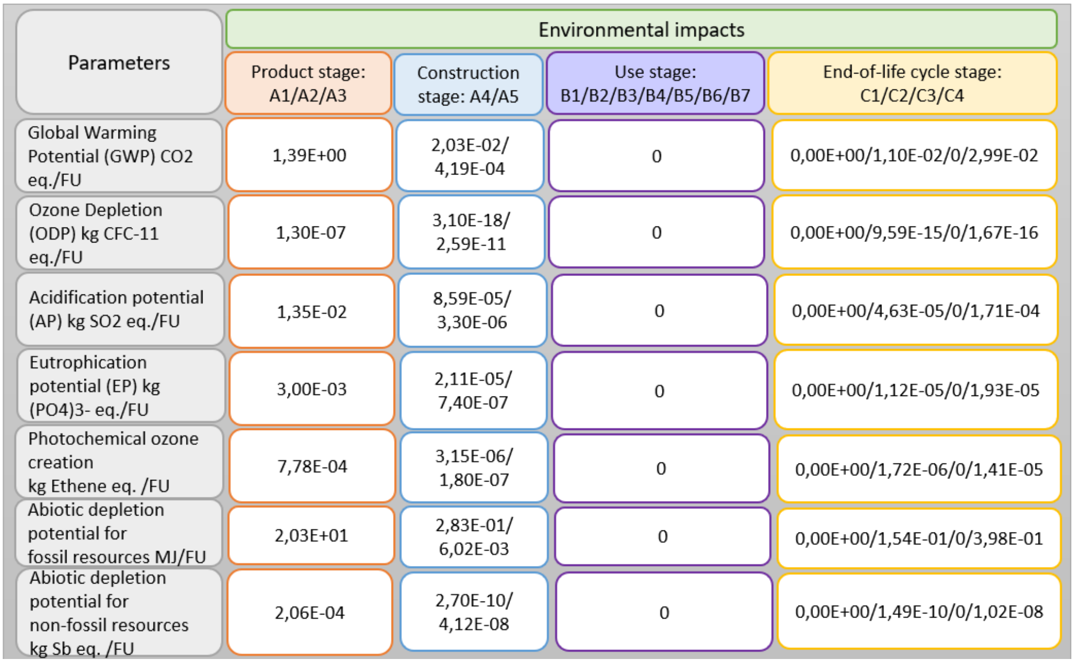
The LCA emission factors were selected based on the available choices of the LCA software's, i.e. openLCA, specifications. The specific providers were selected, presented in Table 7. In order to estimate the value of the factors a simple calculation was done based on the program's results.

By looking at the European Commission's Guidebook on *"How to develop a sustainable energy action plan (SEAP)*(European Commission, 2014), it can be observed that values that the software uses do not deviate much from the values in the guidebook, which are 0.08 kg CO2 eq./kWh for the consumed electricity in Sweden and 0.33 kg CO_2 eq./kWh for the MSW in EU-27.

Embodied impact

For the LCA analysis, EPD catalogues were used to calculates the impact of the specific materials used to the BC and to the energy renovation packages. All the information were provided by those catalogues and the main source for those catalogues was the Norwegian EPD Foundation (EPD-Norge, 2021).

The stages described as "Embodied impact" are presented in the EPD catalogues from A1 to A5 and from C1 to C4, as it is shown in one of the EPD example catalogue, used to this study in Figure 7 below, excluding the D stage, i.e. reuse, recovery and recycling. The transport cost for the products was taken into consideration and a multiplication factor was used as it was referred in the EPD catalogue (for the stage A4) for transporting the materials from their produced location to Sweden.



Parameters	Environmental impacts			
	Product stage: A1/A2/A3	Construction stage: A4/A5	Use stage: B1/B2/B3/B4/B5/B6/B7	End-of-life cycle stage: C1/C2/C3/C4
Global Warming Potential (GWP) CO2 eq./FU	1,39E+00	2,03E-02/ 4,19E-04	0	0,00E+00/1,10E-02/0/2,99E-02
Ozone Depletion (ODP) kg CFC-11 eq./FU	1,30E-07	3,10E-18/ 2,59E-11	0	0,00E+00/9,59E-15/0/1,67E-16
Acidification potential (AP) kg SO2 eq./FU	1,35E-02	8,59E-05/ 3,30E-06	0	0,00E+00/4,63E-05/0/1,71E-04
Eutrophication potential (EP) kg (PO4)3- eq./FU	3,00E-03	2,11E-05/ 7,40E-07	0	0,00E+00/1,12E-05/0/1,93E-05
Photochemical ozone creation kg Ethene eq. /FU	7,78E-04	3,15E-06/ 1,80E-07	0	0,00E+00/1,72E-06/0/1,41E-05
Abiotic depletion potential for fossil resources MJ/FU	2,03E+01	2,83E-01/ 6,02E-03	0	0,00E+00/1,54E-01/0/3,98E-01
Abiotic depletion potential for non-fossil resources kg Sb eq. /FU	2,06E-04	2,70E-10/ 4,12E-08	0	0,00E+00/1,49E-10/0/1,02E-08

Figure 7: Example from an EPD insulation catalogue: "ISOVER glass wool" used in the study, excluding the D: reuse, recovery, and recycling stage. Adapted from reference (EPD-Norge, 2021).

In this study six different EPD catalogues were used to calculate in detail the embodied impact of the materials. For the base case maintenance renovations three catalogues were used to calculate the environmental impact of the roof watertight membrane, roof metal sheet and for the plaster façade. For the new renovation cases three catalogues were used for the wall and roof insulation, the new windows and the rectangular ducts added to the FTX system. For the calculations of each of the materials, different functional units (FU) were considered as it was presented in the EPD respective catalogues. The output/ unit of each of the calculated embodied impacts was in kg equivalent of each of the environmental categories. The parameters that were considered during the embodied impact calculations of the materials are presented in the following Table 8 and Table 9.

Table 8: Embodied impact parameters based on the building dimensions and EPD catalogues for the base case.

Parameters	**Roof: watertight membrane**	**Roof: steel sheet**	**Façade plaster-coating**
FU from EPD catalogue	1 m^2	1 kg	1 kg
Density / kg/m^3	100	7 850	900
Area / m^2	368.6	368.6	506.2
Thickness / m	0.0039	0.0012	0.0001
Weight / FU	4.85	1.03	1
Transport multiplication factor / %	38.8	38.8	55
EPD: A1 to A5 and C1 to C4 stages for GWP100, AP, EP, POP, ADPE, ADPF	kg eq. based on EPD catalogue	kg eq. based on EPD catalogue	kg eq. based on EPD catalogue

Table 9: Embodied impact parameters based on the building dimensions and EPD catalogues for the different renovation cases: 1. ER: Envelope renovation, 2. HR: Heat recovery, 3. DR: Deep renovation.

Parameters	**1. Envelope renovation and 3. Deep renovation**			**2. Heat recovery**
EPD catalogue	Roof: glass wool insulation	Wall: glass wool insulation	Windows: 3pane with aluminium and timber frame, *U*-value = 0.81 (W/(m^2·K))	Rectangular ventilation duct
FU from EPD catalogue	1 m^2 with thermal resistance 1 m^2·K/W	1 m^2 with thermal resistance 1 m^2·K/W	1 window measuring 1.23 m x 1.48 m	1 kg with a thickness of 0.7 mm
Thermal conductivity / W/(m·K)	0.03	0.03	-	-
Thickness / m	0.18	0.22	-	0.0007
Area / m	368.6	368.6	242.1	-
Weight / kg per item	-	-	67.23	1.02
Thermal resistance / (m^2·K/W)	6	7.3	1.23	-
Transport multiplication factor / %	6.11	6.11	53	7
EPD: A1 to A5 and C1 to C4 stages for GWP100, AP, EP, POP, ADPE, ADPF	kg eq. based on EPD catalogue	kg eq. based on EPD catalogue	kg eq. based on EPD catalogue	kg eq. based on EPD catalogue

In order to find the total amount of the ducts needed for the HR case, a reference study was used, where the dimensioning and the sizing of the ducts was conducted in detail to renovate the existing HVAC system with an FTX system (Hadzimuratovic and Swedmark, 2016). In this study it was found that the needed ducts corresponded to 2819 kg for a building with a

GFA of 9235 m^2. To use this amount in the present study the found weight of ducts used for the corresponding GFA of 1095 m^2 instead.

Normalization and weighting

After the operational results were retrieved from the software and the embodied impacts were calculated from the EPD catalogues, they should be normalized and weighted, based on their potential environmental impact. The results from openLCA software come either normalized or not (Dr A. Ciroth et al., 2020). In this case it was chosen to retrieve the results without normalization, since the normalization was performed through the Dutch Assessment Method, by using the shadow cost. The environmental impact categories from the operational and embodied impact were weighted using a monetization methodology with a unit cost, i.e. Euros, representing each category, as it is shown in the Table 10 below (Stichting Bouwkwaliteit, 2014).

Table 10: Weighting factors of the environmental impact categories (Stichting Bouwkwaliteit, 2014).

Environmental impact category	Unit	Shadow cost / (€/kg eq.)
Abiotic Depletion Potential for Non-Fossils resources (ADPE)	Sb eq.	0.16
Abiotic Depletion Potential for Fossils resources (ADPF)	Sb eq.	0.16
Global Warming Potential for 100 years (GWP100)	CO_2 eq.	0.05
Ozone Depletion Potential (ODP)	CFC_{-11} eq.	30.00
Photochemical Oxidant Creation Potential (POCP)	C_2H_2 eq.	2.00
Acidification Potential (AP)	SO_2 eq.	4.00
Eutrophication Potential (EP)	PO_4 eq.	9.00

Then, the embodied weighted results and the operational weighted results were added together. This means that the output was the overall environmental performance of the selected building materials for the different renovation cases, expressed with the shadow cost, i.e. Euros per year, per square meter of the GFA (€/year/m^2 GFA). In essence, this was the stage where the LCA results were calculated. The formula for the calculation of the LCA of every case is described below in the Eq.6.

$$LCA = \sum(OI_j \cdot WF_j + EI_j \cdot WF_j) \quad (6)$$

j: Environmental impact category, e.g. GWP, AP etc.
OI: Operational impact, unit: kg eq. (from openLCA software)
EI: Embodied impact, unit: kg eq. (from EPD catalogues)
WF: Shadow cost weighting factors, unit: €/kg eq. (from Table 10)

3.7 Life Cycle Sustainability Analysis: Combining the Life Cycle Costing and Life Cycle Assessment

Three aspects should be considered before renovating a building, to reach the decision-making process. The energy need of a building, the LCC analysis, i.e. investment, maintenance and running costs, and environmental impact must be considered. For sustainable solutions, those three aspects need to be combined and follow the methodology of the Life Cycle Sustainability Assessment (LCSA). Following the LCSA method, the LCC and LCA analysis could be combined into one accumulated result to reach an Integrated Life Cycle Assessment (ILCA) plan and decisions (IEA, 2017).

The methodology consists of first an LCC, then an LCA analysis and the last part is a combination of them into an LCSA analysis. The LCSA value of every case is shown in the Eq.7.

$$LCSA = LCC + LCA \quad (7)$$

LCA: The shadow cost result from the LCA analysis, unit: €/year/m^2 *GFA*
LCC: The NPV result from the LCC analysis, unit: €/year/m^2 *GFA*

4 Results and analysis

In this chapter all the obtained results described in the methodology chapter are presented. First, the energy results obtained from the simulations on the MFB of the base case and the different renovation cases are described. Then, the results of the LCC of the various cases and the results of the LCA analysis are presented. Finally, the results from LCC together with the LCA are presented, comprising and completing the LCSA analysis.

4.1 Energy results analysis

By applying the three different energy renovation packages, the annual delivered energy was reduced, as it is presented in Figure 8, compared to the 122 kWh/m^2/y in the base case. The specific annual delivered energy need per month for each of the cases, is presented in the Appendix A .

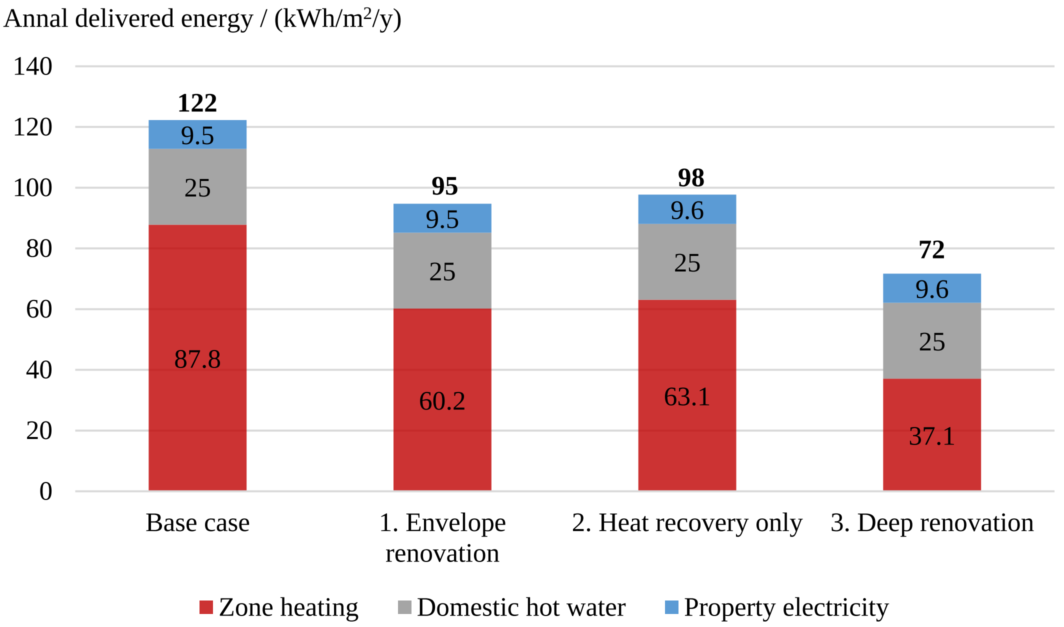


Figure 8: Annual delivered primary energy to MFB before and after the renovations. The total energy is allocated to its respective uses: Property electricity, domestic hot water, and zone heating.

For the renovation HR and DR, heat recovery was added to the exhaust and supply air ventilation system and a very small amount to zone cooling was originated. This happened because occasionally cooled air was needed to keep the supply air at a certain temperature. However, this amount was very small, and it was assumed that the cooling need would disappear if window opening was taken into account, so it was omitted from Figure 8.

From the results, it can be noticed that the zone heating demand at all the renovations was lower than the heating demand of the base case, with the best renovation solution being the DR case, with a 41% of a total energy decline. The total energy demand reduction for the ER and HR cases compared to the base case was 23% and 20% respectively.

4.2 Life cycle costing analysis

In this chapter, the results from the LCC analysis of the MFB are presented, by calculating the Net Present Value (NPV) and the life cycle profitability (LCP) of the energy renovation packages. The results from the LCC analysis of the base case and the renovation packages are presented below in Figure 9. In Figure 10, the LCP, and the investment cost (initial costs) analysis and in Figure 11 the LCP together with the NPV are presented.

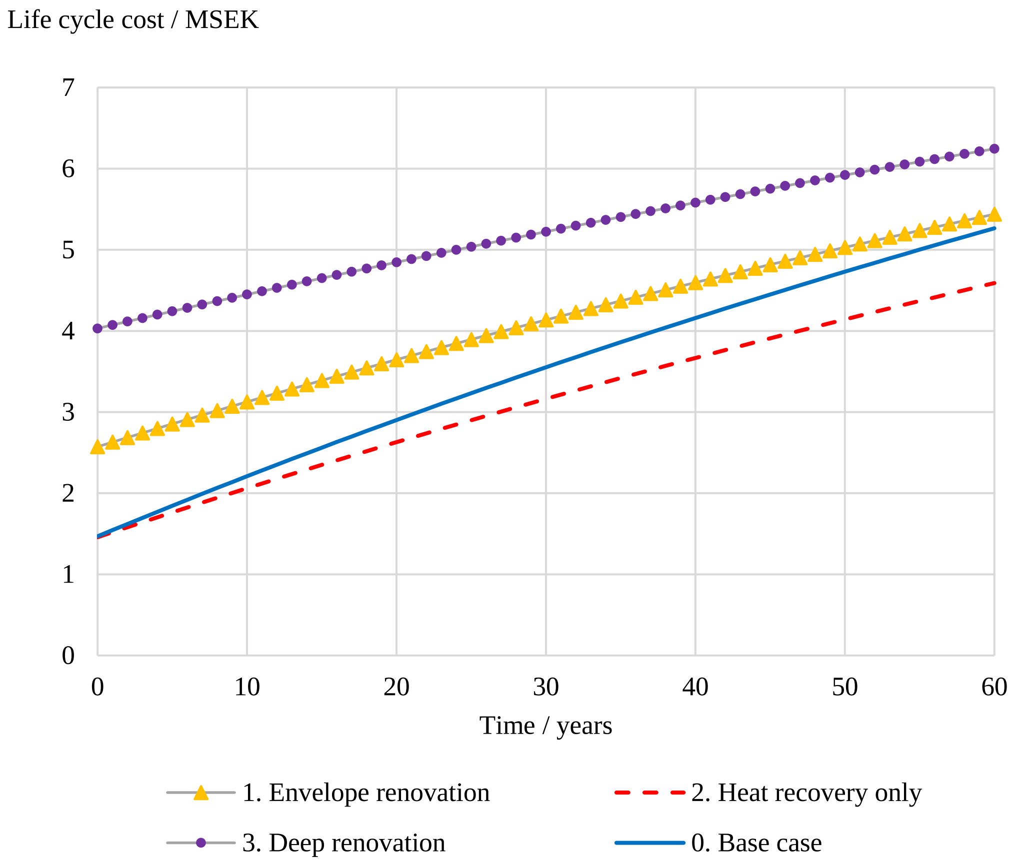


Figure 9: Accumulated LCC of the base case, envelope, heat recovery, and deep renovations.

From the LCC analysis in Figure 9 it can be observed that the second renovation package, the HR case reaches the economical breakeven point from the first year and the other cases do not reach an economical breakeven point during the studied life cycle of 60 years. The ER case could have reached that point if the economical parameters and the market would be different, since it seems to be closer to the BC compared with the DR case.

Therefore, if one renovation case could be selected by a stakeholder as profitable, that should be the HR case, compared with the other renovation case s which are is not considered cost effective.

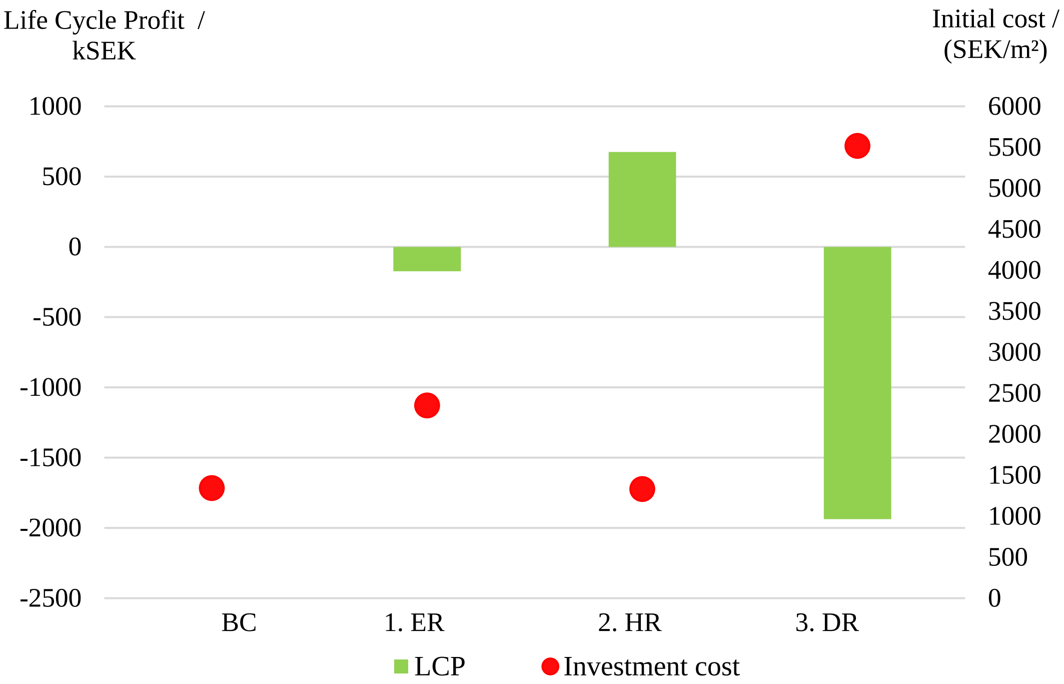


Figure 10: LCP on the left axis and investment costs on the right axis, for the Base case, 1. Envelope renovation, 2. Heat recovery only, and 3. Deep renovation.

From the LCP analysis in Figure 10 it can be observed that only the HR case was found to be a profitable case because of its positive LCP. resulted as economical feasible, having a positive LCP. The DR and ER cases presented a negative LCP, meaning that they are not profitable investments. This can be explained by the fact that the HR had a 20% energy reduction compared to the BC, while the investment, and the running costs, i.e. for heating, electricity, and maintenance, were not that high compared to the DR and ER cases.

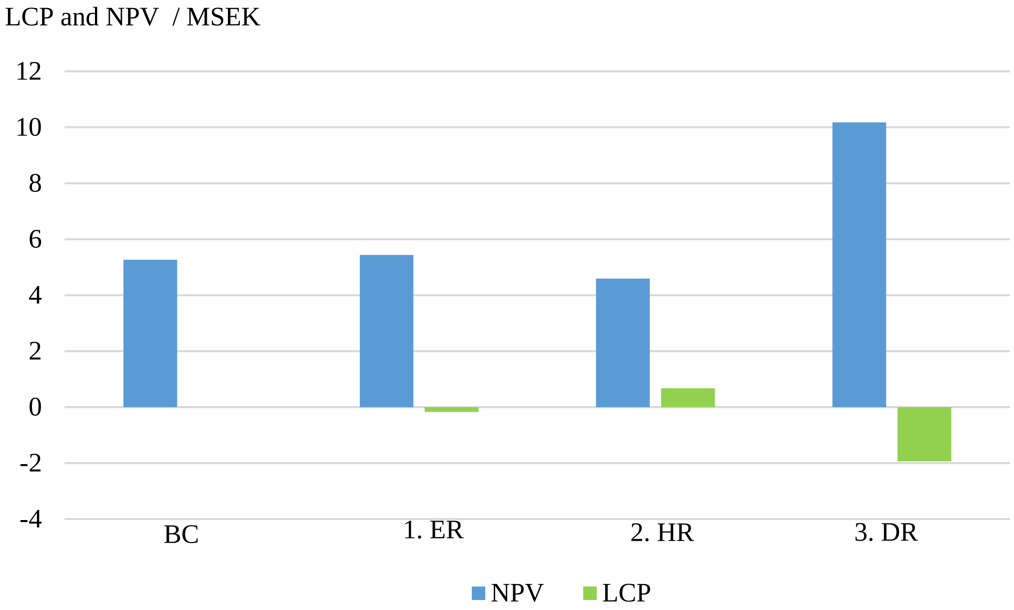


Figure 11: Life Cycle Profit and Net Present Value of the Base Case, the Envelope Renovation, the Heat Recovery, and the Deep Renovation cases.

From the LCP and NPV graph shown in the Figure 11, the same conclusions can be drawn as they were analysed in the Figure 10.

4.3 Life cycle assessment and environmental impact analysis

In this section the results from the LCA of the studied renovations are presented. To be able to compare the environmental impact categories, the Dutch approach was used, expressed in shadow cost (€/year/m^2 GFA). First, the results from the LCA analysis, i.e. the operational, embodied impact and the sum of them two are presented in Figure 12. In Figure 13 it is presented the shadow cost breakdown per environmental impact category and last, a comparison between weighted and not weighted data is presented in Figure 14.

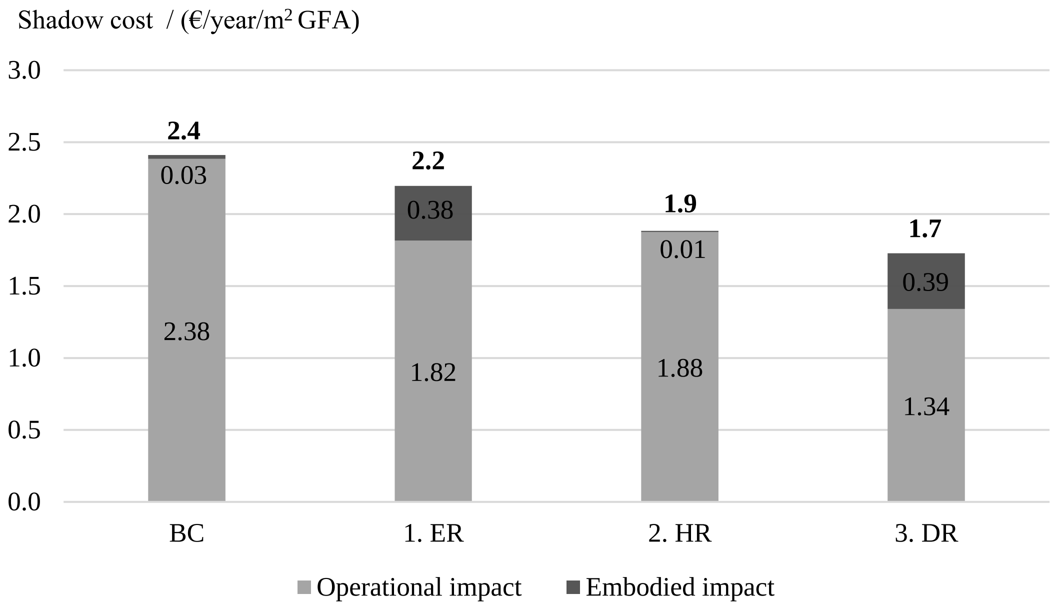


Figure 12: The total shadow cost results are comprised from the operational and embodied impacts of the Base Case and the other renovation solutions: 1. ER: Envelope renovation, 2. HR: Heat recovery and 3. DR: Deep renovation.

From Figure 12, it can be noticed that the shadow cost of embodied impact, based on the calculations from the EPD catalogues, is lower in the HR case compared to the other cases. This is because the weight of the ventilation ducts used to the FTX system was not so much or that the construction of this material did not have that impact to the environment compared to the other materials used in the other cases. Therefore, the environmental impact from the embodied impact of the HR case was lower. For the ER and DR cases the amount of the calculated embodied impact is the highest, since for those renovations more materials were used. The BC calculated embodied impact corresponded to the maintenance material that were used, i.e. for the roof and the wall.

On the other hand, the operational impact is higher in the BC compared to the other renovation solutions. The lowest operational impact was from the DR case, since the energy need for the building was lower compared to the base case. The ER and the HR cases appeared to have almost the same amount of operational impact. The raw data of the operational impact results of the different environmental categories and cases, retrieved from the openLCA software, are presented in the Appendix B.

Comparing the different shadow cost results shown in the graph, it can be noticed that the highest shadow cost corresponds to the BC, compared with the other renovation solutions. That could be explained by the fact that by implementing renovations to the building, the energy need decreased, and so did the environmental impacts. In other words, the shadow cost corresponds to the money that the government or the society should pay to compensate for the damages caused by the building during the selected life cycle. In the BC the shadow cost was 2.4 €/year/m^2 GFA, which is higher compared to the other renovation cases, with the lowest shadow cost found in the DR case, with 1.7 €/year/m^2 GFA. The DR case had the best energy performance, thus resulted in lower shadow cost, which means lower environmental impact.

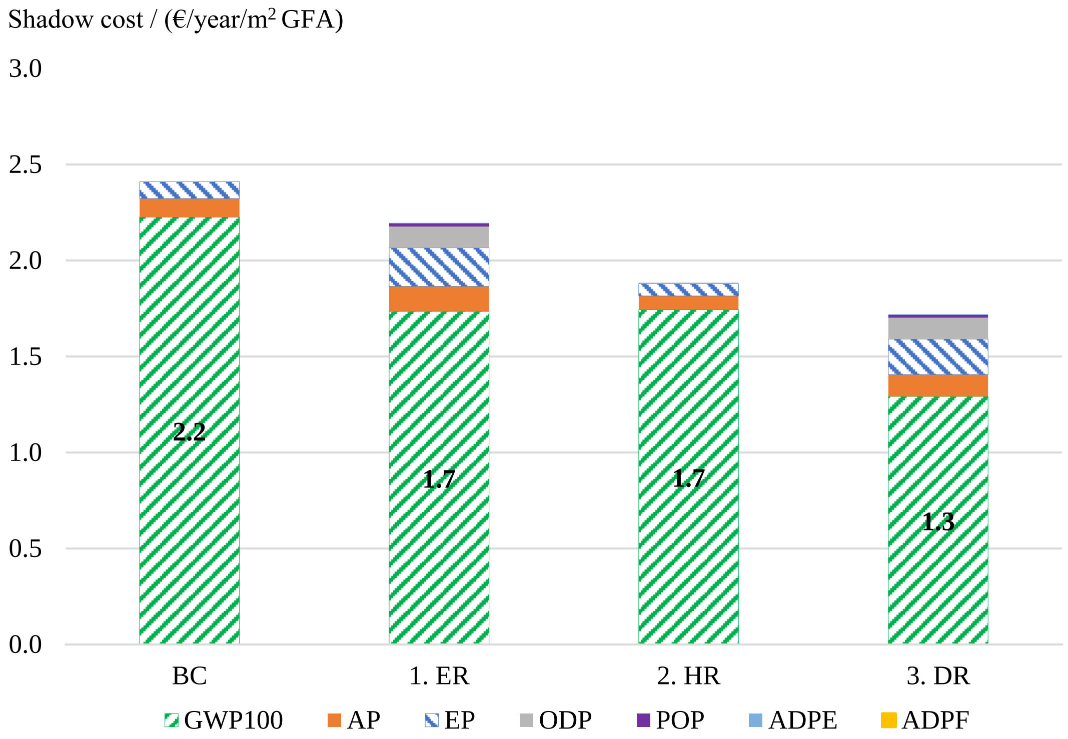


Figure 13: Shadow cost breakdown results per environmental impact for the Base Case and the different renovation cases: 1. Envelope Renovation, 2. Heat recovery only and 3. Deep renovation.

This graph, in Figure 13, presents the shadow cost breakdown results for each environmental category and for each renovation case. It can be observed that the GWP, the AP and the EP have the highest environmental impact compared to the other environmental impact categories, for each of the renovation cases. So, regardless of which renovation case would be chosen to implement to the building, it would mostly affect more the GWP, for the studied location compared to the other impacts.

It is worth mentioning that the POP, the ADPE and ADPF corresponds to zero shadow cost, which means that the products/materials tested, did not have a negative environmental impact from their creation/construction/use to the local/regional geographical impact tested in Sweden. Based on the GreenDelta, zero result could mean that there is no emission or resource depletion for those categories (GreenDelta, 2018).

After the comparison of the weighted LCA data, using the shadow cost, it would be interesting to compare the data's readability before and after using weighting. To do so, the raw data were compared for one of the renovation cases, i.e. envelope renovation. The environmental impact values without weighting are expressed in different units of kg eq. and the weighted values in thousands of euros are presented in Figure 14 below.

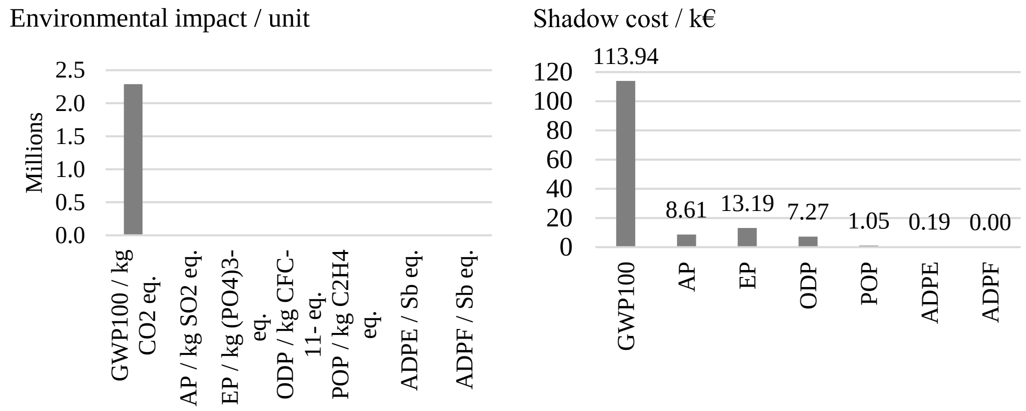


Figure 14: Environmental impact data before (on the left side) and after shadow cost weighting (right side), of one of the renovation cases: envelope renovation case.

In Figure 14, on the left-hand side, the environmental impact values are expressed in different units, e.g. kg per CO_2 eq., kg per SO_2 eq., etc., thus they cannot be compared to each other. In this case, the GWP has so high value, that the other environmental impact categories are not zero, but they cannot be read in the graph. Although the environmental impact categories cannot be read, they are accessible to the user and with the appropriate weighting method they could be processed and compared.

On the right-hand side of Figure 14, by assigning the weighting in euros, expressed as shadow cost, the environmental impacts could be compared to each other, since they have the same units. In this graph it could be noticed that the other environmental impact categories could be read in the graph. These graphs corresponded to a specific renovation case, but the same trend in the results appeared in all of the renovation cases. In conclusion the shadow cost both normalizes and weights the data, since the data are expressed in the same unit and thus, they could be compared to each other, but also gives an overview of what these impacts depict.

4.4 Life cycle sustainability assessment analysis (LCSA)

The LCSA is comprised of the LCC, LCA results. The combination of the LCC and LCA results into one result of the LCSA analysis is presented in Figure 15.

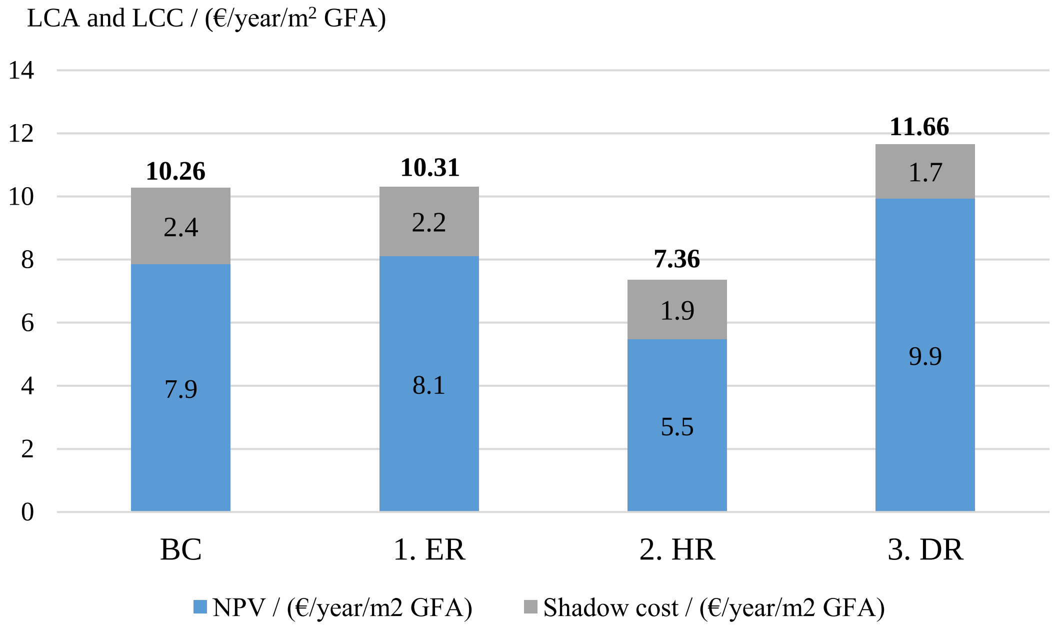


Figure 15: The total LCSA results are comprised of the LCC and LCA results of the Base Case and the renovation cases: 1. ER: Envelope Renovation, 2. HR: Heat recovery and 3. DR: Deep Renovation.

From the comparison of the LCC and LCA results in the Figure 15, regarding the LCA results, it can be observed that the BC has the highest shadow cost, which means the highest environmental impact, compared to the other renovation cases. The lowest shadow cost appeared for the DR, followed by the HR and the ER case. On the other hand, the results of the NPVs appeared to be higher in the ER, DR and BC cases, while the HR case had lower NPV. This is explained by the fact that the HR case had lower investements costs compared to the other cases.

Adding together the LCC and the LCA into one LCSA result, in Figure 15, the €/year/m^2 GFA of the various renovation packages were appeared to be lower only in the HR case compared to the BC. The other cases were resulted having higher LCSA results compared to the BC, thus they could be assessed as not profitable investments from the combination of the environmental and the economic perspective. Even though the shadow cost in the LCA analysis of the DR was the lowest, the LCC dominated the LCSA result. Thus, the DR resulted not being a beneficial renovation from their combination.

For the HR case, the LCP was positive, making this option a profitable investment from the economic point of view, having the smallest NPV compared to the other cases. On the other hand, the DR case, resulted in the lowest shadow cost, better building energy performance, but the highest NPV compared with the HR case. When the LCC and LCA results were added together into one LCSA result, the HR case appeared to be lower than the DR case. So, different impacts of the LCC and LCA results made this case the best renovation solution.

5 Discussion

This chapter contains an interpretation of the results from the energy simulations, LCC, LCA and LCSA analysis. Discussion points for each chapter are based on the results. The final conclusions are presented in a separate chapter.

5.1 Energy use

From the energy simulations conducted in the present study, all the renovation solutions reduced the building's primary energy need, compared to the base case. The renovation package with the best energy performance was the deep renovation. This renovation combines the envelope but also the HVAC renovation, by adding a heat recovery system. The second-best option was the envelope renovation and the last was the heat recovery case. From the applied renovation solutions, the main energy saving was the heating need, which decreased accordingly to the applied energy renovation packages.

Comparing the results of this project to those of *Ricardo Ramírez-Villegas et al.* study, described in the literature review part, the results of the renovation cases match with small deviations. The building of the case-study was 2822 m^2 GFA in northwest Stockholm and the present studied building was 1095m^2 in southern Sweden in Helsingborg, and both were built during the Swedish Million Program. The deep renovation in the study of *Ricardo Ramírez-Villegas et al.* and of this project had the highest energy reduction compared to the base case with 43% and 41% respectively. The energy reduction of the envelope renovation of the study and of this project, was 27% and 23% respectively. And finally, the heat recovery case of the study and of this project, was a bit lower than 27% and 20% respectively.

None of the renovation measures of the present study was considered "comprehensive" and therefore it was considered that new building rules does not apply, e.g. BBR etc. Therefore, only recommended *U*-values for different building elements were considered, based on the BBR regulation system (BBR, 2020). Results from simulations were compared with an Excel static calculation based on degree-hour method and found to be in fairly good agreement.

5.2 Life Cycle Cost analysis

Combining the energy simulations and conducting the LCC analysis, using selected values for economic parameters (annual interest rate, annual district heating price increase, annual average electricity price increase), for the different renovation solutions, the heat recovery renovation resulted into a profitable investment. By adding a heat recovery system, an economical breakeven point was reached after the first year compared to the base case. However, such solution might not be realistic in practice since improvement of the building envelope might be required which was not considered.

On the other hand, even though the deep renovation and the envelope renovation decreased in the building's energy need, they had high NPVs and negative LCPs, due to their hight investment cost and it seems that it cannot reach the economical breakeven point in a period of 60 years. Even though the LCP of the envelope renovation case was not positive, the NPV of it is still not very far away from the base case. That means that possibly under slightly different assumptions, e.g. different energy price, different material price or different economical parameters, i.e. interest rate, inflation, etc., this renovation could be profitable from the economic point of view.

A similar renovation project of a multi-family building was carried out by the real estate concern Alingsåshem, by Odegren and Jorlöv, and to achieve a 20% to 25% fraction of the total investment cost for the energy improvement measures, 3 000 to 3 750 SEK/m^2 would be needed. To achieve a higher fraction, i.e. 40%, 6 000 SEK/m^2 would be needed. Comparing this case-study with the present study's LCC results, by applying the envelope renovation the energy reduction that was achieved was 23% and 2 349 SEK/m^2 were needed, which is lower amount compared to the real estate project. The same trend appeared for the other renovation cases. For the heat recovery case, i.e. by only renovating the existing HVAC system with an FTX, the energy reduction was 20% and the investment cost was 1 331 SEK/m^2, but in reality this amount should be higher, since in practice improvement of the building envelope might be required which was not considered. And finally for the deep renovation the achieved energy reduction was 41% and the investment cost was 3 681 SEK/m^2, much lower than the real estate project.

The deviations of the present study LCC results with the real estate's project results could be due to the alternative applied renovation solutions and since in reality extra costs for more materials, workmanship, etc., would be needed. The idea of the present study was to find cost effective renovations and ideas, in order to avoid extra costs. For example, an investigation of the external wall and roof was done, and the first attempt was to renovate them by demolishing the external layers to add the insulation. This attempt resulted in higher investment costs, due to the extra demolition and transportation of the demolished material costs. Therefore, the external wall was renovated from the outside by adding extra insulation and exterior plaster façade, without demolishing the bricks. For the roof, instead of demolishing the roof layers, a cold roof was created by adding insulation to the exterior side of the ceiling, i.e. inside the roof.

The investment breakdown costs (including VAT) of the selected renovations were calculated using a data base (book) named Wikells Sektionsfakta, which corresponds to real-time and on-site costs e.g., including construction, demolition, workmanship, construction time, shipping, transportation for the demolished materials costs, etc. and it is used in Sweden by investigators in the construction industry during the construction phase. All the parameters used in the analyses (prices, rates, inflation etc.) were chosen based on assumptions. That means that the results could change and especially at cases such as the LCC of the deep renovation vs., the base case, the conclusion could change. In order for companies or the government to reach a decision-making process, a risk investment analysis should be conducted, by doing a sensitivity analysis on combining the various economical parameters. This will better forecast the impact of potential upcoming market changes, to decide into a more responsible direction and take serious decisions e.g., if some of the material or constructions costs will change in the future then the specific renovation solutions could be considered as feasible investments.

The goal of those large-scale renovations is to apply them while the building is habitable and in the scope of trying to cause the least disturbance to the tenants. So, most of the renovations, if that would be possible, should be conducted on the exterior surface. For the envelope renovation case all the costs were calculated considering demolishing the exterior brick wall and then adding insulation and an exterior plaster façade, which made the renovation more economically feasible than adding again the brick wall. The same principle applied for the renovation of the roof. On the contrary, renovating the windows would be beneficial from the energy perspective, decreasing the energy demand of the building, but it will cause disruption to the tenants. This could be solved if the construction company makes an agreement with the window supplier to make sure that the windows will be delivered on time, thus, to be installed at least to the apartments on the same day. In the rest of the spaces i.e., staircases and auxiliary spaces they could be installed the upcoming days. The only concern and problem could be the installation of the heat recovery system, where extra ducts should be placed inside the apartments. So, this renovation will probably disrupt the tenants more than the other renovation solutions.

5.3 Life Cycle Assessment and environmental impact analysis

Regarding the LCA of the present study, the operational impact of all cases was higher than the embodied impact, due to the energy consumed during the operational phase. In reality the climate impact from the operational energy would be lower, because the energy sources are becoming cleaner and cleaner every year. In the present study an assumption was made and for the whole life cycle of 60 years the energy need did not fluctuate, having the same kWh/year for the studied building per year and the same factors for electricity and heating providers per year. On the contrary, the embodied impact of the base case was lower compared to the renovation cases, since new and more materials were added during the renovation cases, e.g. deep renovation case. For the heat recovery case the embodied impact in reality might differ, since the ductwork dimensioning was out of the present's study scope and this impact was extrapolated from a similar case-study.

Comparing the present study's LCA results with the LCA results of *Ricardo Ramírez-Villegas et al.*, described in the literature review part, the studied stages and method were the same for both studies, i.e. from "cradle to grave" and the method was the CML baseline from the University of Leiden, the results match and do not deviate much. From the environmental impact categories tested, the GWP was reduced the most and the highest environmental impact was caused from the operational energy in all renovation cases and for both studies. Specifically in the study of *Ricardo Ramírez-Villegas et al.*, the deep renovation case had the highest GWP reduction and a total emission saving of 19%, the heat recovery case a 16% saving, and the envelope renovation case a 10%. The LCA results of this project were resulted following the same trend with the study. The deep renovation case had a 29% emission saving, the heat recovery case a 22% saving and the envelope renovation a 9% saving, compared to the base case. Both case-studies appeared to have an interesting finding that was that heat recovery case had higher emission reduction compared to envelope renovation case, even though it had a slightly worse energy performance. This could be explained by the higher environmental impacts from extra materials used during the construction process of the envelope renovation case.

Also, regarding the LCA emission factors, they were selected based on the available providers from the LCA software's choices. According to the European Commission's Guidebook on *"How to develop a sustainable energy action plan (SEAP)*, the factor for electricity mix in Sweden was lower compared with the estimated LCA program's factor. If the guidebook's electricity mix factor was selected, the operational result would decrease. However, it would decrease by the same amount for all cases because the electricity demand was almost the same for all cases. For the municipal solid waste provider, the LCA software's factor matches to one in the guidebook. Nevertheless, this factor corresponded to the municipal solid waste-to-energy in Europe and not specifically in Sweden. If a specific factor for municipal solid waste in Sweden was used, possibly it would be lower than the one used in the present study. Therefore, the operational impact would decrease by a different amount for every case because the heating demand was different in every case.

In the present study, if alternative materials were chosen and analysed, i.e. with more friendly upstream processes, thus lower their embodied impact, then the result would be different, and it would depend also on the operational impact e.g., those materials might not have the same strength, durability, and performance, thus higher the operational impact or vice versa. Being able to determine a building's embodied impact, which is greatly influenced by the chosen material at an early design stage of a project, will result in the environmental impact of the building, thus will help even from the early design stage for the decision-making process.

From the LCA results, it can be noticed that the shadow costs appeared higher in the base case and lower for the renovation cases. The lowest shadow cost appeared from the deep renovation, followed by the heat recovery renovation, and last the envelope renovation. Examining the environmental categories, the highest shadow cost appeared for the Global Warming Potential in all cases. The rest of the environmental categories resulted in lower or zero shadow costs.

5.4 Life Cycle Sustainability Assessment analysis

From the comparison LCC (NPV) and LCA (shadow cost) results it can be noticed that the lowest NPV appeared to the heat recovery case, since the initial costs were lower compared to the other cases and the energy performance was better compared to the base case. On the other hand, the LCP of the other two cases was negative. However, the LCP of the envelope renovation case was rather low compared to the deep renovation, denoting that the NPV of this case is much closer to the base case's. Regarding the shadow costs, the lowest appeared from the deep renovation, followed by the heat recovery renovation and last was the envelope renovation. The highest shadow cost appeared in the base case, since the operational cost appeared to be higher due to the higher energy need for the building. That means that the government should pay more to mitigate those damages caused by the building.

To reach to the decision-making process, those two aspects were combined into one LCSA result by adding the LCC and LCA value. From their combination the lowest value appeared to be the heat recovery case, compared to the other cases. Assessing those results, the conclusion that could be drawn is that the LCC dominated the results, thus it would be beneficial only for the heat recovery renovation case since the other cases had higher investment costs. But before the decision-making process, all the aspects and benefits of each renovation solution should be examined, since small variations in the data could make some of the renovations very sensitive and subject to changes, thus making them indeed not profitable or questionable.

The LCSA also consists of the SLCA, which would be greatly affected by the renovations, since the renovated apartments would greatly affect the psychology and upgrade the quality of living of the tenants. The buildings would be able to adjust and to withstand to the forthcoming climatic changes, but also, they would provide an upgraded indoor air quality and environment to the occupants. It is not easy and able to estimate SLCA aspect, and it was outside of the present study scope, but the renovations will most probably have a positive impact to the tenants.

6 Conclusions

From the energy simulations it was found that the best renovation was the deep renovation case, where a 41% in the building’s energy need was achieved, followed by the envelope renovation with a 23% energy reduction and last was the heat recovery case with a 20% energy reduction, compared to the base case building. Combining the energy simulations together with the LCC results it would be impossible to succeed renovating only the building envelope and achieving a very low energy demand. Consequently, the running costs would not be so much lower than in the base case, and thus the renovations would not result into feasible investments. So, in the present case-study more renovation changes would be needed to achieve better building energy performance, since the base case building was not performing so bad from the energy need perspective Buildings from the Million Swedish program need renovation due to wear and tear. Once it is time to carry out maintenance, e.g. like in the base case, the option to carry out a more extensive renovation arises. One can then choose from the analysed LCC analysis options and proceed into the decision-making process.

The LCC analysis of the studied MFB, could be applicable to similar multi-family buildings, by applying the same type of energy renovations. The economic analysis could result in deviations due to the extra and unexpected costs, but it could be possible for the same type of building, i.e. having the same dimensions and location. In order for companies or the government to reach to a decision-making process, a risk investment analysis should be conducted, a sensitivity analysis would be a useful next step.

The interpretation of the LCA results is based on the combination of the operational and the embodied impact of a building. It should be mentioned that, in the present study, the ductwork placement, paths and ductwork dimensioning for the FTX system it was out of the present’s study scope, in reality the heat recovery case should have higher embodied impacts, since extra material, i.e. ducts needed to be added to the apartments to extract the air and to supply it again and possibly envelope improvements to improve the air-tightness. Adding a monetization value to those environmental impacts, caused by the building is a way of indicating the price that the government or the society should pay to mitigate those emissions. By following the LCA results it could be possible for the decision-makers to drive the early-stage designs into a more sustainable and environmentally friendly designs.

By applying, the LCA, for this specific case-study a renovation can be beneficial from the environmental perspective, but not always from the economic perspective. To implement such large-scale renovations by having such high investment costs, a strong motivation will be needed, and this could be achieved by following the environment impact goal towards climate neutrality by 2050 and in Sweden by 2045.

The last part of the LCSA analysis was a combination of the LCC and LCA analysis, so it was basically and ILCA analysis, rather than an LCSA. From those results the lowest shadow cost appeared from the heat recovery case with 7.36 €/y/m^2 GFA, followed by the base case with 10.26 €/y/m^2 GFA, next was the envelope renovation case with 10.31 €/y/m^2 GFA and last was the deep renovation case with the highest shadow cost with 11.66 €/y/m^2 GFA. The LCSA is a useful methodology and tool of assessing together LCC and LCA and taking one combined result. Then it would be easier to draw conclusions, take decisions and actions considering the most feasible direction. In the present study, the conclusion that could be drawn is that the LCC dominated the results. The LCSA is a useful methodology and tool of assessing together LCC and LCA and taking one combined result. Then it would be easier to draw conclusions, take decisions and actions considering the most feasible direction. Regarding the last part that has an impact to the LCSA method, the SLCA, because it is a combination of phycology and social science, it is difficult for the engineering fields to take it into account. It is a whole different study field, which needs special independent assessment, knowledge, and data. Exterior partners should exist that will contribute greatly with their work and direct the SLCA with their perspective and results. An idea to assess the SLCA from a more practical way would be by conducting a research using questionnaires, asking the tenants what they think about the present situation of their building, what do they like and dislike and what do they want to change, if they could etc.

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Appendix A

Table A11: Specific annual energy need per month for the base case with total 122 kWh/m²/y.

Month	Property electricity		Zone heating / kWh	Domestic hot water / kWh
	Electricity need for lighting and facility / kWh	Electricity need for HVAC aux/ kWh		
January	372.1	514.0	15292.0	2281.3
February	347.4	480.8	13026.0	2281.3
March	371.6	514.0	11543.0	2281.3
April	359.6	497.4	7071.0	2281.3
May	371.3	514.0	3348.0	2281.3
June	359.5	497.4	2557.0	2281.3
July	371.6	514.0	2629.0	2281.3
August	371.6	514.0	2717.0	2281.3
September	359.5	497.4	3929.0	2281.3
October	371.3	514.0	7039.0	2281.3
November	360.6	497.4	12132.0	2281.3
December	372.5	514.0	14804.0	2281.3
Total kWh/y	4388.6	6068.4	96087.0	27375.0
Total kWh/m²/y	4.0	5.5	87.8	25.0

Table A12: Specific annual energy need per month for the envelope renovation with total 95 kWh/m²/y.

Month	Property electricity		Zone heating / kWh	Domestic hot water / kWh
	Electricity need for lighting and facility / kWh	Electricity need for HVAC aux/ kWh		
January	371.6	514	10228	2281.3
February	347.8	480.8	8647	2281.3
March	371.9	514	7386	2281.3
April	359.6	497.4	4221	2281.3
May	371.2	514	2800	2281.3
June	359.5	497.4	2556	2281.3
July	371.2	514	2629	2281.3
August	371.5	514	2717	2281.3
September	359.5	497.4	2586	2281.3
October	371	514	4252	2281.3

November	360	497.4	7947	2281.3
December	372	514	9918	2281.3
Total kWh/y	4386.8	6068.4	65887.0	27375.0
Total kWh/m^2/y	4.0	5.5	60.2	25.0

Table A13: Specific annual energy need per month for the heat recovery case with total 92 kWh/m^2/y.

Month	Property electricity		Zone heating / kWh	Domestic hot water / kWh
	Electricity need for lighting and facility / kWh	Electricity need for HVAC aux/ kWh		
January	371.8	510.1	10733	2281.3
February	347.6	478.8	9099	2281.3
March	371.3	512.9	7613	2281.3
April	359	502	4443	2281.3
May	371.2	525.7	2819	2281.3
June	359.5	514.2	2556	2281.3
July	371	533.2	2629	2281.3
August	371.1	532.9	2717	2281.3
September	359.5	509.2	2958	2281.3
October	370.6	522.2	4772	2281.3
November	359.1	497.4	8371	2281.3
December	371.7	511.1	10380	2281.3
Total kWh/y	4383.4	6149.7	69090.0	27375.0
Total kWh/m^2/y	4.0	5.6	63.1	25.0

Table A14: Specific annual energy need per month for the deep renovation with total 72 kWh/m^2/y.

Month	Property electricity		Zone heating / kWh	Domestic hot water / kWh
	Electricity need for lighting and facility / kWh	Electricity need for HVAC aux/ kWh		
January	371	510.1	5324	2281.3
February	347.3	478.8	4516	2281.3
March	370.9	512.9	3403	2281.3
April	359.2	502	2585	2281.3
May	371.4	525.7	2717	2281.3

June	359.5	514.2	2556	2281.3
July	371	533.2	2629	2281.3
August	371	532.9	2717	2281.3
September	359.3	509.2	2556	2281.3
October	371	522.2	2673	2281.3
November	358.5	497.4	3779	2281.3
December	370.7	511.1	5139	2281.3
Total kWh/y	4380.8	6149.7	40594.0	27375.0
Total kWh/m^2/y	4.0	5.6	37.1	25.0

Appendix B

Table B15: Raw data of the operational impact results, for the different environmental categories, retrieved from the openLCA software for: BC: Base Case, 1. ER: Envelope Renovation, 2. HR: Heat Recovery and 3. DR: Deep Renovation cases.

Environmental impact category	**Unit**	**BC**	**1. ER**	**2. HR**	**3. DR**
Global warming (GWP100a)	kg CO2 eq.	2911160.537	2216119	2289160	1634411
Acidification potential (AP)	kg SO2 eq.	1441.882754	1119.952	1153.784	850.5161
Eutrophication potential (EP)	kg $(PO_4)^{3-}$ eq.	589.3203588	448.3413	463.1567	330.3504
Ozone layer depletion (ODP)	kg CFC-11- eq.	0.134476245	0.130712	0.131107	0.127561
Photochemical oxidation potential (POP)	kg C_2H_4 eq.	-8.207336636	-4.37791	-4.78034	-1.17292
Abiotic Depletion Potential for Non-Fossils resources (ADPE)	Sb eq.	0.000173307	0.00022	0.000215	0.000259
Abiotic Depletion Potential for Fossils resources (ADPF)	Sb eq.	0	0	0	0

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