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A cost-optimal analysis for Nearly Zero-Carbon timber Building solutions in line with the EPBD recast 2020 for Belgium

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Abstract

Europe has set carbon reduction targets, aiming for a 55% decrease in emissions by 2030 and carbon neutrality by 2050. The construction sector faces regulations under the Energy Performance of Building Directive recast 2020, which requires all new buildings to be Zero Emission Buildings (ZEBs) by 2030. Anticipating stricter regulations, such as Nearly-Zero Carbon Buildings (NZCB), the focus will shift to the entire lifecycle emissions. Bio-based materials, like timber, will likely replace traditional high carbon footprint materials. A simulation-based multi-objective optimization framework is developed to address the challenge of optimizing building design for minimal carbon impact ($LCCO_2$) at lowest costs. This framework is applied on a case study, with different timber systems, envelope insulations and PV panels parameters as design variables. The set of combinations are effectively explored with NSGA-II, over 4000 simulations. Out of 153 trade-off solutions of Pareto front, 51 optimize the case study, ranging from a reduction of 7% of its $LCCO_2$ at the same cost, to saving more than 63000 €, with a reduction of 1% of $LCCO_2$. CLT and glulam solutions show lower carbon content but higher cost than LVL. Furthermore, embodied carbon results accountable for 48% of total lifecycle carbon on average. Finally, the method is validated by sensitivity and uncertainty analyses. Future research could focus on integrating thermal comfort, together with expanding the choice of timber materials and design variables. Thanks to its high flexibility and adaptability, both professionals and academics can adopt and customize this framework to facilitate early design phase decision making.

Keywords

Multi-objective optimization, Life Cycle Cost, Life Cycle Carbon, Nearly Zero Carbon Buildings, Timber, Green Building

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I am a very lucky person to have you all.

Abbreviations/Acronyms

BR18	Byggeriets Regler 18
CLT	Cross-Laminated Timber
dLCC	Difference in Life Cycle Cost
EA	Evolutionary Algorithm
EC	European Commission
EPBD 2020	Energy Performance of Building Directive 2020
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
GHG	Green-House Gas
GLT or glulam	Glue-Laminated Timber
GWP	Global Warming Potential
LCA	Life-Cycle Assessment
LCC	Life-Cycle Cost
$LCCO_2$	Life-Cycle Carbon
LVL	Laminated Veneer Lumber
MOO	Multi-Objective Optimization
NBN	National Bureau de Normalisation
NCZB	Nearly Zero Carbon Building
NSGA	Non-dominated Sorting Genetic Algorithm
NZEB	Nearly-Zero Energy Buildings
PV	Photovoltaic
RE 2020	Reglementation Environnementale 2020
RES	Renewable Energy Sources
SBD Lab	Sustainable Building Design Laboratory
TMY	Typical Meteorological Year
ZEB	Zero Emissions Building

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1 Introduction

1.1 Background information and problem statement

Europe has set the goals to decrease carbon emissions of 55% by 2030, and achieve carbon neutrality by 2050 (EC, 2019). The construction sector, which is responsible for 36% of total emissions, has the possibility and the duty to assume a key role in this shift towards sustainability.

These requirements have been concretized since 2010 with the Energy Performance of Buildings Directive (EPBD), which aims to improve the energy efficiency of buildings within the EU member states. The directive sets out requirements for energy performance certification, energy efficiency standards, and the inspection of heating and air conditioning systems in buildings. In 2010 the directive imposed that by 2018 all new buildings should have been Nearly-Zero Energy Buildings (NZEB), thus buildings that compensate for their very low energy demand with energy production. This is possible by integrating high-performance materials and passive design solutions with on-site renewable energy sources.

In 2020, an update of the directive was published, the EPBD 2020 recast. The newer version expanded the range of buildings, adding to new buildings and major renovations also non-residential and existing buildings. Higher requirements are targeted for the current decade, together with the goal of all new buildings being Zero-Emission Buildings (ZEB) by 2030. According to the directive's proposal, a zero-emission building is defined as a building with a very high energy performance, where the very low amount of energy still required is fully covered by energy from renewable sources, and without on-site carbon emissions from fossil fuels (EC, 2021a).

Even though they represent a good starting point, operational emissions do not entirely represent the environmental impact of a building (Attia, 2018), and reducing them is thus not sufficient to comply with the European carbon neutrality goal. The other share of emissions is called embodied carbon and is related to the manufacturing, construction, maintenance, and demolition of the building and its components. Furthermore, researchers believe that the virtuous current practice of aiming for the lowest possible energy building to decrease the environmental impact of the industry can end up backfiring, as the higher-performance technologies and materials often carry significantly higher embodied carbon. According to (LETI, 2020), embodied carbon goes from 33% on a code building to 73% on an ultra-low energy building. Similar results are also reported by (Röck et al., 2020), with a share of embodied greenhouse gas (GHG) emissions increasing from 20-25% to 45-50% and in some cases exceeding 90% for highly energy-efficient buildings. Considering both the shares means considering the complete emissions, throughout the full life cycle of the building, thus representing a more valuable methodology to quantify environmental impact indicators.

On a national level, France and Denmark have already embraced the life cycle approach, with RE2020 from 2019, and BR18 from 2018, respectively. France's threshold value is 24 $kgCO2_{eq}/m^2$year until 2024, and will gradually decrease to 15 $kgCO2_{eq}/m^2$year from 2030. Denmark, on the other hand, has set a more ambitious requirement of 12 $kgCO2_{eq}/m^2$year from 2023. These values represent the maximum allowable sum of operational and embodied emissions, spread over the considered lifespan of 50 years.

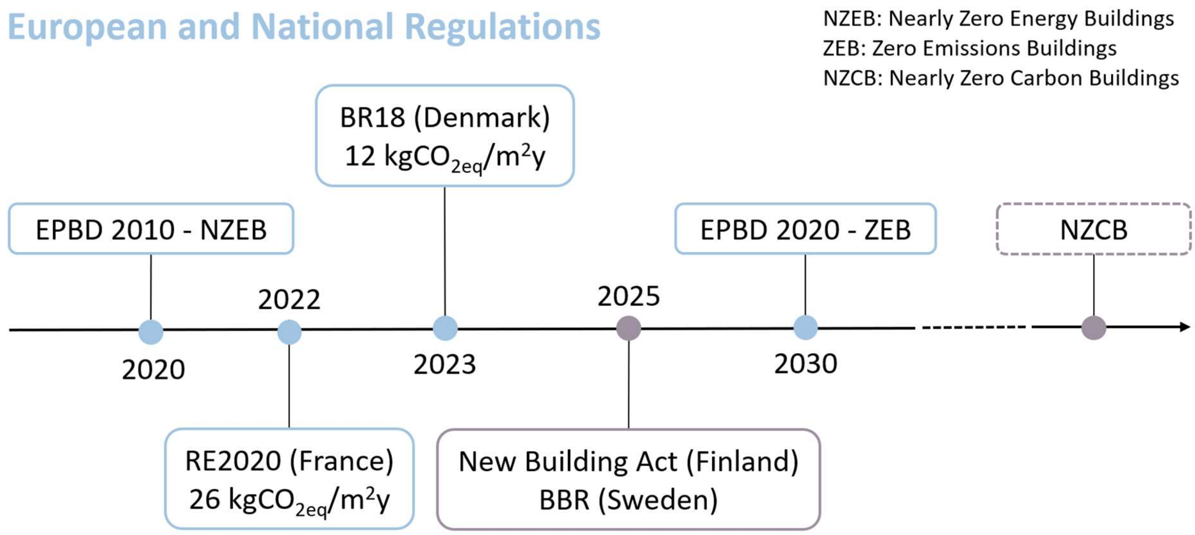


Figure 1-1: European and National current and future regulations

In conclusion, considering recent trends in both European directives and national regulations, which are pushing the sector towards carbon neutrality of buildings, as well as the suggestions from researchers highlighting the importance of embodied carbon share in the overall environmental impact, we can almost certainly expect to see stricter directives and regulations in the next decades, along with requirements for Nearly-Zero Carbon Buildings (NCZB).

1.2 Relevance of the research topic

The study is of significant importance to a variety of stakeholders.

First, the chosen methodology represents an innovation in the research field: there is currently no example of any simulation-based multi-objective optimization with life cycle carbon and life cycle cost as objective functions and timber construction systems as variable. Similar studies use the same methodology to optimize different criteria, such as life cycle cost and energy performance (Hamdy et al., 2013) (Harkouss et al., 2018), or life cycle cost and operational carbon emissions (Fesanghary et al., 2012) (Hamdy et al., 2011).

Traditional optimization problems are characterized by a single objective, however, in many real-world scenarios, there may be multiple objectives that need to be considered, and in addition, they may be competing. This approach allows to optimize simultaneously two conflicting criteria: cost and environmental impact. As optimizing one of the two objectives will have detrimental effects on the second one, a set of solutions that represents the trade-off is expected to be found rather than a single solution.

Furthermore, the evolutionary algorithm (EA) non-dominated sorting genetic algorithm (NSGA-II) is used to efficiently explore the vast solution space and identify the optimal solutions. Besides being widely used in the last decade for a variety of applications, such as engineering, finance, machine learning, transportation planning, and computational biology (Mkaouer & Kessentini, 2014), it still represents one of the hottest research methods to deal with MOO problems (Ma et al., 2023).

Second, this research addresses the construction industry's actors, such as designers and manufacturers, as it explores design solutions obtained from the combination of different dynamic parameters. Each of them is suitable for a specific purpose: timber structure alternatives to explore new materials' embodied carbon, bio-based and traditional insulations to compare passive design solutions' embedded and operational emissions, and finally photovoltaic panels to assess the carbon savings of renewable energy sources integration. By analysing the best solutions, i.e. the results of the MOO, it is possible to provide decision-makers with valuable data, such as overall building best practices and individual impact of each design variable, allowing them to make informed decisions based on their preferences and priorities.

Even the case study, on which the framework itself is applied, has significant importance, as it represents an example of a cutting-edge building. Het Centrum is indeed the first circular building in Belgium, an approximately 2000 m^2 office space, entirely made of wood (except for recycled concrete foundations) designed to be disassembled four times in 15 years, and finally sold as individual reusable components. The circularity is reflected in project conception, economy, design, construction, use, and end of life; and makes this building a pioneering project.

Third, this work can have an impact on governments and society. Anticipating future potential directives' and regulations' requirements can be a basis from which policymakers can withdraw in terms of methodology, rather than results. Finally, this work can offer solutions to the current century climate change problem, as can help every individual to embrace NZCB solutions at their lowest price.

1.3 Research Objectives

The purpose of this thesis is to define a flexible framework to investigate, using cost optimality techniques, where lays the trade-off between economic and environmental life cycle costs of a timber nearly zero carbon building, in line with the European Directive Building Performance 2020 (EPBD 2020) and the EU carbon-neutrality goal.

To achieve this goal a simulation-based multi-objective optimization is applied to the first Belgian circular building, a one-year-old office building located in Westerloo. The aim is to further optimize its already innovative design, decreasing both its environmental impact and its cost, in terms of life cycle carbon and life cycle cost, respectively.

The proposed design alternatives are obtained by combining seven different parameters of the case study: new materials, technologies, and passive design solutions. Therefore, this work aims to characterize each of them in terms of economic and environmental cost. Furthermore, it aims to investigate the influence of each parameter on the defined objective functions. Finally, it aims to elaborate all the aforementioned results in best practices to be provided to the construction sector's main actors.

1.4 Main research question and research sub-questions

The objectives explained in section 1.3 are translated into the main research questions:

- How far can we optimize the design of a building to reduce its carbon impact at the lowest economic cost?
- Is simulation-based MOO a suitable methodology?

For practical purposes, the main questions are subdivided into the following sub-questions:

- Where lays the trade-off between these two objective functions?
- Are they mutually exclusive?
- Which parameters affect them the most?
- How and why?
- Among the considered design alternatives, which are the best practices to be applied? Which is the most sustainable timber technology?

Figure 1-2 is the quad chart that summarizes the research proposal in its key points: aim and objectives, audience, innovation, and impact.

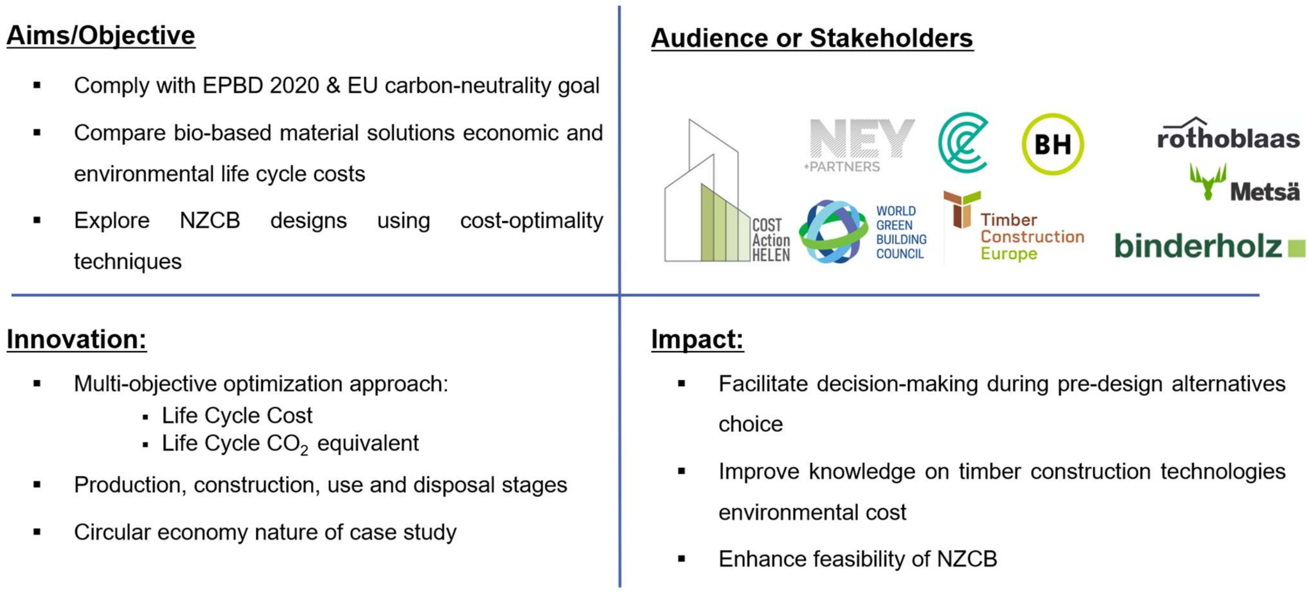


Figure 1-2: Research quad chart

2 Literature review

This chapter updates the reader with a review of existing literature and the current state of the art of timber construction and of multi-objective optimization, providing the theoretical background necessary to understand the topics discussed in the following chapters. First, the state of the art explains the latest technologies, trends, and practices in the construction industry. Furthermore, a brief explanation is given to each concept addressed in this work. Finally, a critical analysis of previous studies aims to identify gaps, contradictions, and thus areas for further exploration within the field.

2.1 State of the art

This section provides an overview of current trends in industry and research, with an analysis of timber role in construction, its properties, construction systems used, and materials employed, as well as a theoretical explanation of the concepts behind the application of optimization algorithms in multi-objective optimization problems.

2.1.1 Timber in construction

The construction of buildings and infrastructure was responsible for emitting 7 $GtCO_{2eq}$ in 2015, with 4 $GtCO_{2eq}$ attributed to material usage in construction (Olhoff & Christensen, 2018). As buildings become more energy-efficient, there's a growing focus on the environmental impact of construction materials. Replacing energy-intensive materials like concrete and steel with low carbon content bio-based materials in building construction can significantly reduce greenhouse gas emissions from material manufacturing and disposal, promoting the expansion of the wood industry as a means to mitigate global warming (Heeren et al., 2015).

Among other advantages, timber construction is characterized by a high level of prefabrication, which results in significantly faster construction process and lower waste. Designers are also choosing timber for its aesthetic value, even without the need of finishing, and its positive effects on indoor air quality. However, the sector is still reluctant to embrace timber as main structural material, with main concerns related to structural and fire safety, durability and higher maintenance required, moisture sensitivity, higher costs, and lower thermal and acoustic properties.

Over the past two decades, a new category of structural wood products has emerged, utilizing manufacturing waste, low-grade, and smaller diameter trees as raw materials. These highly durable and adaptable products are referred to as mass timber (Duan et al., 2022). These materials are used in the three timber construction systems that are dominating the market: panels construction, frame construction, and solid timber panels construction (Kolb, 2008).

In panel construction system, the load-bearing structure is made of structural ribs or joists, of rectangular or I-shaped section, respectively, hold together and stabilized by two wood-based side boards. The vertical members carry the loads from roof and suspended floors, while external boards resist the horizontal forces due to wind and act as bracing system, allowing also to enclose insulation. Suspended floors and roofs are also panels composed of structural ribs which carry the loads. The concept of of modern panel construction is related to prefabrication in factories, where all panels are manufactured and assembled to suit different building uses, and then transported to the site and mounted. Currently, prefabrication has reached the level of manufacturing volumetric units, which need just to be placed with the crane and fixed, significantly increasing the construction speed. Panel construction is quite popular in the United States, Canada, and Scandinavia, especially for one and two storey houses. Their main advantage in exterior wall structures is that a single component layer can cost-effectively combine load-bearing functions with thermal insulation to save space (Kaufmann et al., 2018).

Frame construction is characterized by columns, beams and bracing elements placed on a regular grid to form the load bearing structure. This primary structure supports the suspended floors, made up of timber joist floors or solid timber, prefabricated elements, which are classed as the secondary structure. Concrete or solid timber elements, such as stairs and lift shafts and shear walls, are usually integrated as bracing and to withstand horizontal forces. The external walls can be installed independently of this load-bearing frame, because they do not carry any loads, making large windows and glass facades possible, with the structure left exposed internally, protected from the weather. As the industry is opening to timber multi-storey and large-volume structures, this construction system is gaining importance, especially with new wooden engineered materials that allow for larger spans. The absence of constraining load-bearing walls also leaves the designers freedom of interior layout, and thus higher flexibility of use for the building.

Solid timber panels construction refers to a construction method with solid, uninterrupted (as opposed to spaced beams, columns, ribs) wall, slab, and roof elements. These planar elements serve both as load bearing and enclosing functions. The concept is similar to panel constructions, with the difference that in panel constructions the load-bearing structure is given by the ribs, while in solid timber panels construction, the whole cross-section acts as structure. These panels are indeed made of different layers of wood attached together, with grains parallel or orthogonal, by means of glue, dowels, or nails. The structural behaviour of the panels depends on the direction of their grains: for parallel grains, the panels will show excellent strength along the grain direction, but flexibility if the load is applied on the orthogonal direction; for orthogonal grains, the direction of external layers will have higher strength, with shear resistance also in the perpendicular direction.

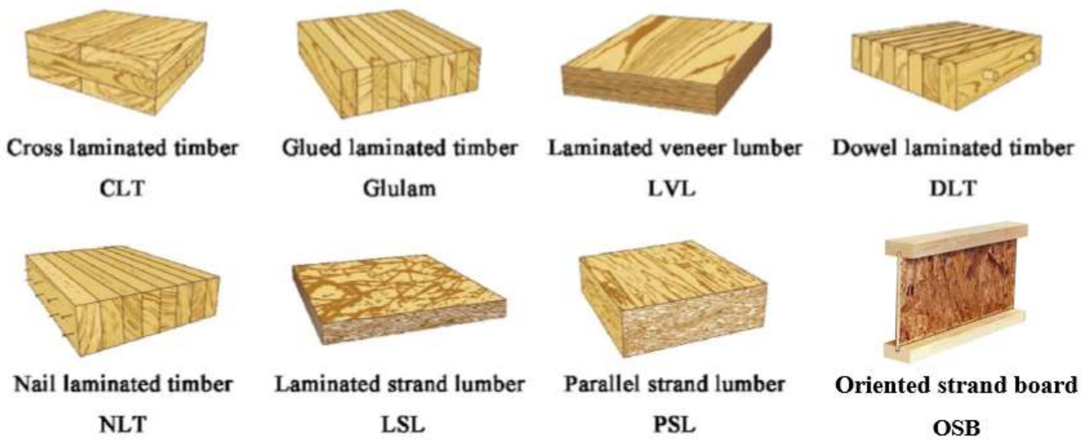


Figure 2-1: Mass timber different materials (Duan et al., 2022)

Cross-Laminated Timber (CLT) is an engineered wood product made by gluing layers (usually three, five, or seven) of wood panels in orthogonal directions with structural adhesives. Each layer, typically made from solid-sawn lumber boards, usually softwood species such as spruce. The alternating layers provide CLT with exceptional strength, stability, and rigidity in both directions, making it suitable for use as load-bearing elements in construction. Thanks to its large mass, CLT can contribute to improved thermal and acoustic performance in buildings. CLT panels can be used for walls, floors, roofs, shear walls, elevator shafts and stair wells, and cantilever balconies. They are mostly employed in solid timber panels systems as main structure, or in frame systems as slabs and shear walls.

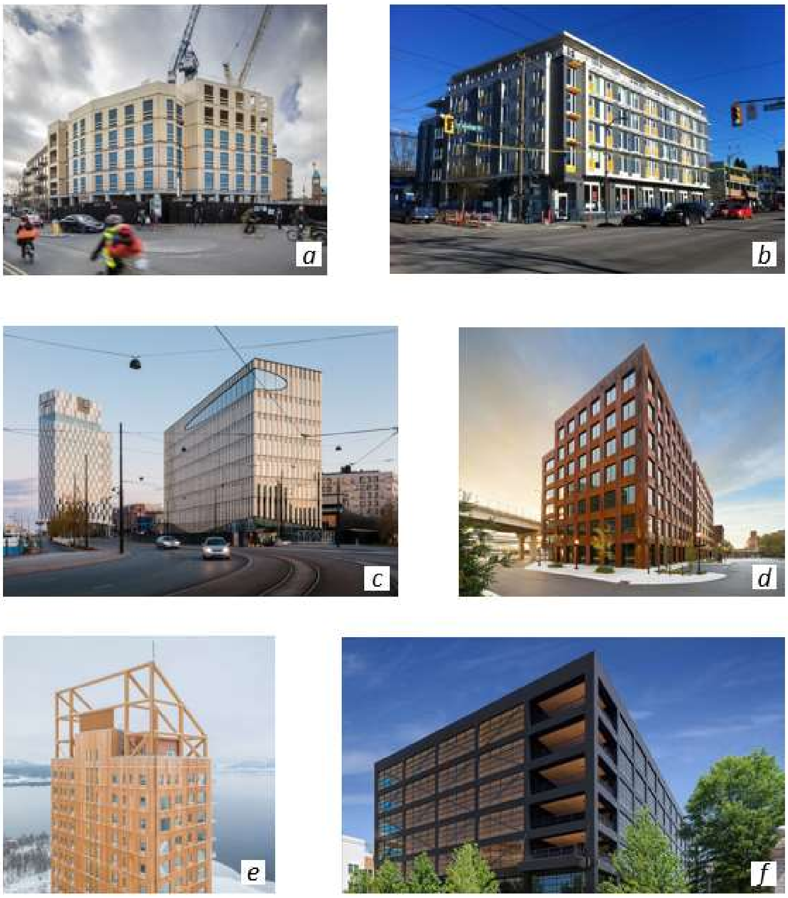
Glue-laminated timber (GLT), also known as glulam, is a product similar to CLT, with layers glued together with structural adhesive. The difference is that in GLT the layers are arranged parallel to each other, forming large structural members, resulting in excellent axial properties. While typically used as beams and columns in frame systems, designers can use glulam in the plank orientation for slab or roof decking (WoodWorks & ThinkWood, 2022). It is commonly used for buildings, as well as bridges, sports arenas, and other structures where strength, durability, and aesthetics are important considerations.

Dowel Laminated Timber (DLT) and Nail Laminated Timber (NLT) are very similar to CLT and GLT, as they are also products obtained by combining together different layers, in both directions. The difference lays in the adhesive mechanism, which for DLT is wooden dowels, while for NLT is nails. According to the layers orientation, they share similar properties and use with CLT and GLT.

Laminated Veneer Lumber (LVL) is made of 3 mm thick veneers bonded together with weather-resistant phenolic adhesive. This means that the dimensions of the final LVL product are not limited by the dimensions of the raw material, and even small-diameter logs can be used to produce large LVL beams and panels. LVL is characterized by high strength and stiffness, lightness, and easy workability (Finnish Woodworking Industries, 2020). According to the orientation of different veneers, LVL can be employed for almost every structural component and systems: beams, columns, and slabs for frame systems, as well as, load-bearing solid walls, slabs, roofs, shear walls and stair wells in solid timber panel system.

Parallel Strand Lumber (PSL) and Laminated Strand Lumber (LSL) are similar to LVL in many ways, with the exception that are made with strands and flakes, respectively, and not layers of veneers. Both strands and flakes, byproducts of LVL manufacturing, are pressed together with heat and bonded by adhesives. PSL shows lower properties than LVL, but given its bending strength, it is used as long-span beams, heavily loaded columns and large headers and is well-suited to applications where high bending or compression stress is required. LSL is a cost-effective solution for a wide range of framing applications but has lower strength and stiffness properties than LVL. It is therefore used as headers and beams, wall studs, boards, and plates.

Oriented Strand Board (OSB) is a structural panel product produced by bonding together thin wood strands with adhesive. The strands are generally oriented with the grain direction in the major longitudinal direction in the outer layers and in the cross direction in the inner layers of the sheet to provide panel dimensional stability. It has similar properties to plywood yet is generally more cost-effective to produce and is also stronger than particleboard. It is used in panel systems as core of the I-shape joists for walls and slabs, as well as outer layer. OBS is part of the Lightweight Timber (LWT) materials.



a. Dalstone Lane, London, UK
Solid timber panels system, CLT
(Ravenscroft, 2017)
b. The Heights, Vancuver, Canada
Panel system, LWT
(PassivehouseCanada, 2019)
c. Wood City, Helsinki, Finland
Frame system, LVL
(Heiskanen, 2021)
d. T3 Minneapolis, US
Frame system, GLT + NLT
(Structurecraft, 2018)
e. Mjostanert, Brumunddal, Norway
Frame system, GLT + CLT
(infobuildenergia, 2020)
f. T3 Atlanta, US
Frame system, GLT + DLT
(Structurecraft, 2019)

Figure 2-2: Timber buildings examples

2.1.2 Optimization algorithms

Decision making involves selecting the best solution from a set of alternatives, considering various criteria, constraints, and objectives. Multi-objective optimization is a specialized approach to decision-making where multiple conflicting objectives are considered simultaneously, unlike single-objective optimization where only one objective is optimized (Augusto et al., 2012). As the different objectives of MOO may be competing, improving one objective may have a negative impact on another. To study the trade-offs between these conflicting design objectives and to explore design options, an optimization problem with multiple objectives has to be formulated, with the goal of finding a set of solutions that balance the conflicting objectives, known as Pareto optimal solutions or the Pareto Front (Tusar & Filipic, 2015). A solution is Pareto optimal if no other feasible solution can improve one objective without worsening at least one other.

The methods for solving multi-objective optimization problems employed are sophisticated and use intertwined computational approaches by integrating several platforms, such as MATLAB, EnergyPlus, artificial neural network, and other optimization algorithms (Amer et al., 2020). This section will focus on the latter, in particular on evolutionary algorithms, swarm intelligence algorithms, and metaheuristic algorithms. Each of these methods propose a different way to efficiently explore the trade-offs between conflicting objectives and identify a diverse set of high-quality solutions along the Pareto front (Kalyanmoy et al., 2016).

Evolutionary Algorithms (EAs) are a set of optimization algorithms inspired by the process of natural evolution, as they simulate the natural selection to find solutions to the problems.

First, a population of individuals, each representing a potential solution is created. Each individual is then evaluated according to how well it performs with respect to the optimization objectives, thus giving a measure of its quality. Individuals are then selected to undergo reproduction based on their evaluation: the higher the suitability, the higher the chance of being selected, as happens in natural selection. Selected individuals undergo reproduction to create offspring, typically involving crossover and mutation operations, where parts of the characteristic of solutions are exchanged or modified to generate new solutions. Offspring solutions inherit characteristics from their parents, potentially leading to solutions of higher quality. The initial population size is thus replaced by new offsprings, according to a predefined replacement strategy, to control population size and ensure diversity of solutions. This cycle repeats for each generation, until a predetermined termination criterion is met, such as maximum number of generations, solutions, or computational time.

Genetic Algorithms (GAs) are a family of EA. The most commonly used GA in building MOO problems is Non-dominated Sorting Genetic Algorithm II (NSGA-II), which uses non-dominated sorting and crowding distance to maintain diversity in the population.

Particle Swarm Optimization Algorithm (PSOA) is a population-based optimization method inspired by social behavior of bird flocks and fish schools.

First, a population of particles (solutions) is created, and each particle is associated with a position and a velocity vector, which determine its location and movement direction in the search space. The final position is evaluated to determine the quality of each solution with respect to the objective functions. Then, each particle adjusts its velocity based on its previous velocity, its personal best-know position, and the best-known position among all particles of the population. These two acceleration coefficients are called cognitive and social coefficient, respectively. At this point each particle updates its position according to new velocity, creating potentially a better solution. Personal and global best-know positions are updated at this point, before a cycle starts with evaluation. The cycles continue until a predetermined termination criterion is met, such as maximum number of generations, solutions, or computational time.

The most common PSOA used for building MOO problems is Multi-Objective Particle Swarm Optimization (MOPSO).

The Harmony Search (HS) algorithm is a metaheuristic optimization algorithm inspired by the musical improvisation process. It was developed to solve optimization problems by mimicking the process of improvising musical harmonies.

First, the algorithm creates a population of potential solutions, named harmonies. Each harmony is evaluated according to how well it performs with respect to objective functions. The best solution of each iteration and the overall best solution are recorded. These harmonies are then iteratively improved through a process of musical improvisation, with new harmonies being generated by combining elements of the existing harmonies. This improvisation process is a combination of random elements and selected elements according to their evaluation quality. The cycle continues with a new evaluation stage, until a predetermined termination criterion is met, such as maximum number of generations, solutions, or computational time.

2.2 Concepts of research

This section collects a summary of the definitions of several concepts that are used and referred to throughout this thesis. It should be used as a glossary, to understand or clarify these concepts in case of need. Even though it has been done as thoroughly as possible, there might still be some gaps. In case of wish to explore the concept further, it is recommended to integrate with other resources too.

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a methodology used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, disposal, and recycling. Figure 2-3 shows the stages as defined in current European standards EN 15978:2012 and EN 15804 + A2:2019 (NBN, 2012, 2019).

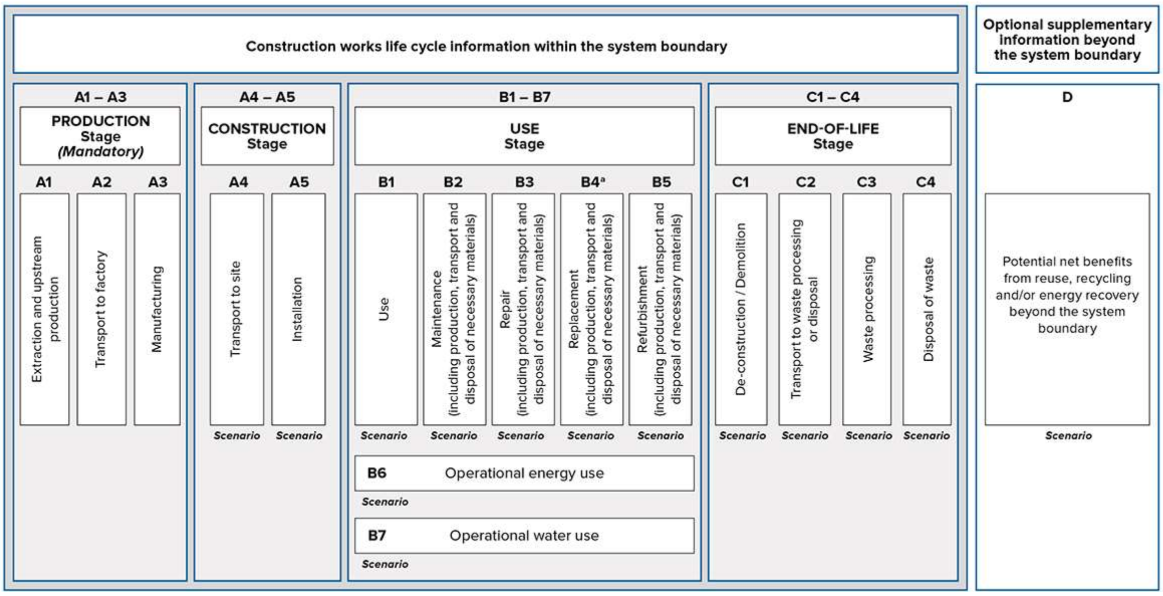


Figure 2-3: Life Cycle Assessment phases according to EN 15978:2012 and EN 15804 + A2:2019

LCA involves quantifying the environmental impacts associated with each stage of the product's life cycle, such as energy consumption, greenhouse gas emissions, water use, air pollution, and resource depletion. This information can be used to identify areas for improvement in the product's design, manufacturing process, or supply chain to reduce its overall environmental footprint.

Greenhouse Gas (GHG) emissions

Greenhouse gas (GHG) emissions are gases in the Earth's atmosphere that trap heat, contributing to the greenhouse effect and global warming. The primary greenhouse gases include:

- Carbon dioxide (CO_2): CO_2 is the most prevalent greenhouse gas emitted through human activities. It is released by burning fossil fuels such as coal, oil, and natural gas for energy, as well as deforestation and other land-use changes.
- Methane (CH_4): Methane is emitted during the production and transport of coal, oil, and natural gas. It is also produced by livestock digestion, rice cultivation, waste decomposition in landfills, and biomass burning.
- Nitrous oxide (N_2O): N_2O is released from agricultural and industrial activities, as well as from the combustion of fossil fuels and biomass. Agricultural activities, such as the use of synthetic fertilizers and biomass burning, are significant sources of N_2O emissions.

Global Warming Potential (GWP)

Global Warming Potential (GWP) is a key impact category of life cycle assessment, used to quantify the environmental impact of greenhouse gas emissions. It compares the effectiveness of different greenhouse gases in terms of their ability to trap heat in the Earth's atmosphere over a specified time period, usually 100 years, relative to that of carbon dioxide (CO_2). The concept of GWP allows for the aggregation of emissions of different greenhouse gases into a single metric, $CO_{2\text{-equivalents}}$, facilitating the comparison of their relative impacts on climate change.

Embodied carbon

Embodied carbon refers to the total greenhouse gas emissions associated with the production, manufacturing, transportation, and disposal of a product or material over its entire life cycle, often expressed in units of carbon dioxide equivalents ($CO_{2\text{-eq}}$).

Operational carbon

Operational carbon refers to the greenhouse gas emissions associated with the operational phase of a building, thus generated during daily use and maintenance of the structure. The primary sources are:

- Energy consumption: Emissions resulting from the use of electricity, natural gas, or other fuels for heating, cooling, lighting, ventilation, and appliances within the building. These emissions are primarily due to the combustion of fossil fuels, which release greenhouse gases into the atmosphere.
- Water consumption: Although not directly related to carbon emissions, water treatment and distribution processes can contribute to operational carbon indirectly through energy consumption. Additionally, energy is required to heat water for domestic use, such as bathing and washing clothes, leading to associated carbon emissions.

- Waste management: Emissions from waste disposal and management processes, including transportation, landfilling, and incineration. Organic waste decomposition in landfills can also produce methane (CH_4).

Biogenic carbon

Biogenic carbon refers to carbon that is part of the natural carbon cycle, typically derived from recently living organisms or their byproducts. In the context of wood construction products, this is the carbon sequestered by the tree as it grows, and that continues to be stored in the wood product over its lifetime. Biogenic carbon entering the system, thus in stage A of LCA, shall be characterized with a factor of -1 (i.e., a reduction in carbon emissions), which represents the removal of carbon from the atmosphere. When the material burns or decays, some or all of that stored carbon is released back to the atmosphere and must be characterized with a factor of +1 (i.e., a carbon emission), in stage C of LCA. This carbon is considered as embodied carbon.

Nearly-Zero Energy Building (NZEB)

A nearly zero-energy building (NZEB) is a building that has very high energy efficiency and aims to meet most of its energy needs from renewable sources. The concept of NZEBs originated from the European Union's Energy Performance of Buildings Directive (EC, 2021a), which encourages member states to promote the construction of buildings with very low energy consumption.

Zero Emission Building (ZEB)

Zero Emission Buildings (ZEBs) are similar in concept to nZEBs, but they focus specifically on eliminating greenhouse gas emissions associated with building operations. According to the directive's proposal (EC, 2021a), a zero emission building is defined as a building with a very high energy performance, with the very low amount of energy still required fully covered by energy from renewable sources and without on-site carbon emissions from fossil fuels.

Nearly-Zero Carbon Building (NZCB)

Nearly Zero Carbon Building (NZCB) are similar in concept to ZEB, but they expand the focus on reducing greenhouse gas emissions associated with the whole building life cycle, from raw material extraction through materials processing, manufacture, construction, use, repair and maintenance, and disposal or recycling. The concept of NZCB is still new, and there is no standard which defines and regulates them. However, to achieve a NZCB, it is necessary the combination of a high energy efficiency building which compensates the operational emissions with renewable energy sources, and which is made low embodied carbon content materials, such as bio-based ones.

Environmental Product Declaration (EPD)

Environmental Product Declaration (EPD) is a standardized and verified report that provides transparent and comparable information about the environmental impacts of a product over its entire life cycle, based on a life cycle assessment (LCA) methodology. EPD usually provide environmental indicators such as GWP, energy consumptions, water usage, resources depletion, emissions, and waste generation. Manufacturers are required by EU to provide EPDs for each product, and they are regulated by EN 15804 + A2:2019.

Life Cycle Cost (LCC)

Life cycle cost (LCC) refers to the total cost associated with a building over its entire life span. This includes all costs incurred from the initial investments for materials and construction through to operation, maintenance, refurbishment, and eventual disposal or decommissioning. LCC provides a comprehensive assessment of its economic viability and allows for informed decision-making regarding investment, procurement, and resource allocation. It helps stakeholders evaluate the long-term cost-effectiveness of different options and identify opportunities to minimize costs and maximize value over time. In EU a comparative methodology framework to calculate LCC is provided with the Cost-Optimal supplementing to EPBD (EC, 2012b).

2.3 Similar studies

This section provides an overview of the most relevant and recent research papers covering the two key topic of this thesis: multi-objective optimization applied on buildings and timber buildings life cycle assessment comparison. The critical analysis of existing literature is essential to understand the strengths and limitations of research methodologies, and thus to identify the knowledge gaps.

Each of the two sub-section provides a short description of the most important aspects of each work, and a literature review matrix which summarizes them all.

2.3.1 Multi-objective optimization for buildings

MOO has been adopted in the construction industry to achieve project improvement for almost every aspect, due to the complex nature of construction projects (Guo & Zhang, 2022). In particular, the focus of this work is Multi-Objective Optimization applied to a building design to improve environmental and economic features. **Error! Reference source not found.** synthetizes the key features of ten papers which applied the same methodological approach as the one used in this thesis. This method is particularly suitable for cost-optimal solution, indeed, all of these optimizations have the cost as one of the two objective functions. Most of these papers' aims were the development of the framework, thus the result itself is the methodology and its applications.

Several works sought to optimize the energy consumption together with the cost. (Hamdy et al., 2013) proposed a three-stages method with 12 design variables, implementing a variation of NSGA-II, which led to a reduction of 47% of primary energy consumption with respect to the reference building of Finnish standards. (Harkouss et al., 2018) applied this methodology to several case studies in different climatic zones of France and Lebanon, aiming at minimizing thermal and electrical demand, and life cycle cost, under thermal comfort minimum conditions. Their results showed that passive design strategies are the most cost-effective to reduce thermal loads, and the remaining energy demand should be covered by RES. (Wu et al., 2018) enriched the framework introducing life cycle energy, thus considering also the embodied energy to manufacture materials, together with the operational energy. (Delgarm et al., 2016) performed the optimization using Particle Swarm MOPSO algorithm instead of genetic algorithm NSGA-II.

(Hamdy et al., 2011) assessed the environmental impact of the building as carbon emissions, instead of energy use. Considering only the operational phase, they managed to reduce the original case study of 32% of carbon emissions and of 26% of the investment cost. (Fesanghary et al., 2012) and (Xue et al., 2022) integrated the methodology with complete life cycle carbon of the building. The former also employed the harmonic search HS algorithm, and results showed that on average operational emissions are responsible for 80% of total life carbon, with foundations accounting for the highest share of embodied carbon. The latter coupled NSGA-II with Artificial Neural Network (ANN), and managed to optimize the base case of 10-18 % LCC and 13- 22% in LCCO$_2$.

(Ciardiello et al., 2020) developed a two-step method, firstly to optimize the energy demand with changing the shape and dimensions, and then to optimize operational emissions by acting on passive and active strategies. The results were 60% energy savings and 32% reduction of carbon emissions. This procedure allows to be used not only for new building design, but also for building retrofit. (Diakaki et al., 2010) and (F. Ascione et al., 2015) also developed two frameworks for building energy retrofit and easier accessibility to industry. Diakaki et al. designed an analytical approach to manually select different retrofit strategies, thus a simple and user-friendly procedure with easier professional implementation. Finally, Ascione et al. developed the framework which produced 6 different retrofit cost-optimal packages for different budgets.

Literature review matrix for multi objective optimization is reported as Table 8-1, in Annex 1.

2.3.2 Timber buildings environmental comparison

In recent years, there has been a growing number of design-related studies on the topic of multi-storey timber construction and its international adoption since the changes in building code in the early 2000s (Salvadori, 2021). The majority of current scientific research on multi-storey timber structures focuses on single building technical aspects such as acoustics (Caniato et al., 2017), structural integrity (Žegarac Leskovar & Premrov, 2021), energy efficiency (Švajlenka & Kozlovská, 2020), and sustainability (Takano et al., 2015). Despite the abundance of literature on these topics, there has been a scarcity of comprehensive comparative design studies until recently (Svatoš-Ražnjević et al., 2022).

Error! Reference source not found. summarizes the existing works which compare the environmental impact of different construction technologies with at least one timber option. The first five papers assess the differences between traditional construction (concrete, steel, and hybrid) and one timber construction (CLT and GLT). On the other hand, the last five compare different timber constructions.

(Liang et al., 2021) found that post-and-column CLT and GLT timber option for a 12-storey building in the US has 2% lower carbon emissions than concrete construction for a lifespan of 60 year, with however 90% of the emissions being due to operational phase. Timber showed 17% lower embodied carbon, but at 9,6% higher price. The same trend is observed also by (Chen et al., 2021), with wall load-bearing CLT option resulting in 25% lower global warming potential than concrete option, mainly due to the smaller material quantity, as only production and construction phases (stage A) were assessed for an eight storey building in China. 22% to 50% is instead the carbon reduction observed by (Puettmann et al., 2021) for three different multi-storey buildings in the US. Also, in this case only stage A was considered, with 90% due to production stage (A1 to A3). Biogenic carbon was not included, resulting in negative carbon impact as timber stores more carbon than it is released to manufacture it. (Allan & Phillips, 2021) included also end of life stages, still neglecting biogenic carbon, however. Timber resulted again the most sustainable choice, with GWP lower of 31% to 41% with respect to steel construction, for 5 and 12 storey residential buildings. However, wood choice also resulted in higher smog, ozone depletion, and acidification potential. Finally, (Al-Obaidy et al., 2022) found that timber solution on the case study selected in this thesis has three times lower carbon emissions than concrete and hybrid construction, and four times lower than steel.

(Lolli et al., 2019) and (Balasbaneh & Sher, 2021) highlighted that CLT has lower environmental impact than GLT, for 100 years lifespan of a multi-storey building in Scandinavia and 50 years lifespan of a single-family house in Malaysia, respectively. However, in the former study only manufacturing carbon were considered, while the latter did not consider the operational emissions. (Dodoo et al., 2014) and (Dodoo, 2019) expanded the timber material technologies integrating wall load-bearing CLT and post-and-column CLT+GLT with post-and-column LVL and prefabricated volumetric light-frame LWT. The calculations were performed on two multi-storey buildings in Scandinavia, for a lifespan of 50 years, with a cradle-to-grave approach. In both cases load bearing CLT wall proved to be the lowest carbon emissions solution, due to the lowest concrete required for shear stability, followed by volumetric LWT modules and LVL. Timber showed to have 8-9% and 39-51% lower carbon emissions than concrete construction, respectively. The latter's results are so high due to the D module included in the calculations. Finally, (Lu et al., 2017) compared three different LVL solutions on a four storey building in Australia for a lifespan of 60 years. LVL from hardwood showed lowest GWP and life cycle costs, the opposite trend was found by (Balasbaneh & Sher, 2021). However, the presence of glue resulted into higher human toxicity potential than steel. LVL low price is due to lower labour and production cost.

Literature review matrix for timber buildings environmental comparison is reported as Table 8-2Table 8-1, in Annex 1.

2.4 Knowledge gap

Analysing the literature review it is possible to define which are the areas and topics to be potentially further explored.

Concerning Multi-Objective Optimization, there is yet not a single work which considers and aims to minimize the life cycle carbon emissions of the whole building as environmental impact factor. On the other hand, concerning life cycle assessment comparison of different timber construction technologies and materials, only two works considered the life cycle of the whole building, i.e. not only of the structure, with a cradle-to-grave approach (stage A to C), without including the D scenario. However, none of the two compared two different timber solutions.

In conclusion, this work aims at filling the knowledge gap, integrating a whole building life cycle comparison of two timber construction solutions within a multi-objective optimization.

3 Methodology

3.1 Description of the research design and methods

This chapter explains the research methodology adopted to answer the research questions:

- How far can we optimize the design of a building to reduce its carbon impact at the lowest cost?
- Where lays the trade-off between the two objective functions ($LCCO_{2eq}$ and LCC)?
- Which parameters influence them the most?
- How do parameters influence the objective functions?
- Among the considered design alternatives, which are the best practices to be applied in the early design phase?

The chosen methodology is inspired by the work of Hamdy et al. (Hamdy et al., 2013). The main differences lay in the first objective function and on some design variables considered: Life Cycle Carbon ($LCCO_{2eq}$) is assessed to evaluate environmental impact instead of Primary Energy Consumption (PEC), and timber construction technology is studied instead of building systems.

The process is a multi-objective optimization based on building energy simulation, aiming to reduce simultaneously both economic and environmental costs. In the energetic model, seven dynamic parameters are defined as ranges of values, which combined create 26 265 600 different solutions. NSGA-II algorithm is used to explore efficiently the total set of combinations, at the lowest computational cost. The final results allow us to identify the trade-off between the two competitive objectives and to draw guidelines for early-design decision-making concerning the studied variables.

3.2 Study Conceptual Framework

The first phase of data collection is done to identify and characterize all the parameters involved in the simulations. Parameters are distinguished into fixed and dynamic inputs: the formers are constant throughout the simulations, while the latter are going to change with each iteration of the optimizations, they are referred to as design variables. This phase is composed of three parts: case study analysis, market analysis, and survey. The case study analysis, done through an on-site survey, BIM, and BEM examination, allows to define the parameters related to the building. Market analysis allows us to characterize the design variables and their alternatives' technical, economic, and environmental data. Finally, a survey is conducted to investigate the service life of timber building components, and thus estimate their replacement rate.

The multi-objective optimization problem is completed by defining the two objective functions: life cycle carbon and life cycle cost. $LCCO_{2eq}$ is defined as the embodied carbon of the product stage and the operational carbon due to emissions for a lifespan of 50 years. On the other hand, LCC is calculated as the initial investment plus the operational costs for 20 years.

The existing energetic model is corrected due to some discrepancies noticed, with respect to the collected data. It is then exported to a parametric energetic simulation software which allows to define the design variables and the objective functions. The first simulation is performed on the case study, thus setting design variables equal to their original value, to define the benchmarks for the results. Finally, the optimization itself is performed, exploiting a genetic algorithm NSGA-II, that allows to explore the huge combinations set in relatively reduced time. The results of each simulation are collected, and once the optimization process is finished, they are compared and analysed.

Finally, sensitivity and uncertainty analyses are performed to verify the robustness of the results. A linear regression method allows to quantify the relative influence of each input parameter on the outputs. On the other hand, uncertainty analyses are carried out on the most unsure parameters: timber material quantity, objective functions lifespans, carbon emission data, and energy supplier.

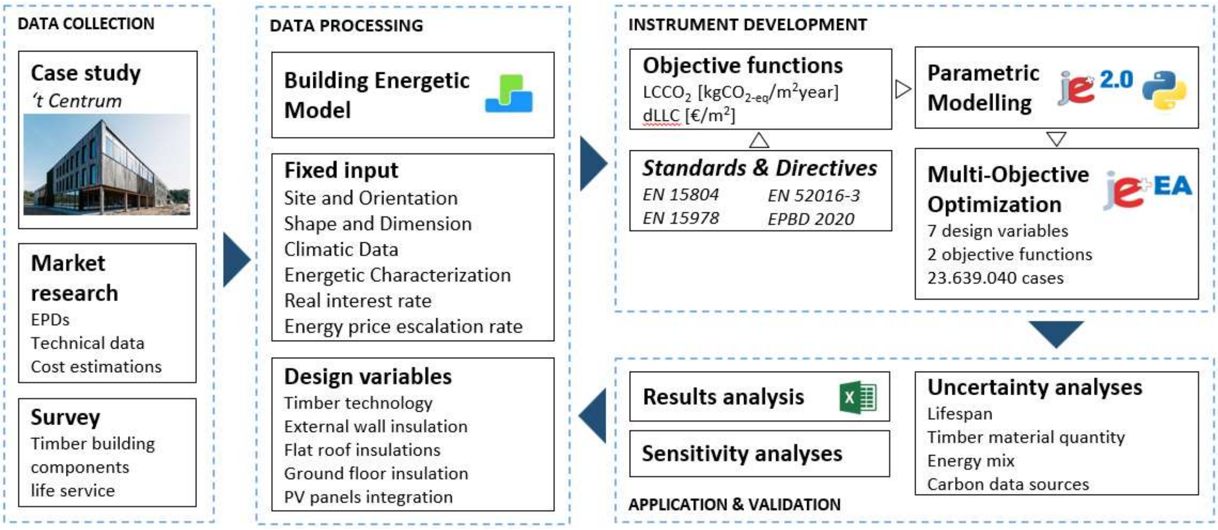


Figure 3-1: Study Conceptual Framework

3.3 Operationalization: variables, indicators

In this section, an overview of the chosen independent and dependent variables is presented. They are addressed as design variables and objective functions, respectively. What follows is only an introduction to these variables, to understand how these conceptual ideas are translated into technical measurable variables. Design variables and objective functions are explained in detail in section 3.5.2 and section 3.5.3, respectively.

The cause variables can be grouped under three categories:

- Structural typology
- Envelope
- PV panels

Each variable is then decomposed into all its sub-variables, with corresponding indicators, which characterize the way each property will affect the effect variables. The choice of sub-variables has to be exhaustive to fully describe these relations, thus for each cause variable both *Cost* and *Embodied carbon* are assessed. Furthermore, for structural typology we have the relative choice of material, for envelope the insulation thickness and thus the U-value, and for PV panels the area and the panel efficiency.

Table 3-1: Cause variables

Variable	Cause Variables Structural typology	 External wall insulation	 Walkable roof insulation
Sub-Variable	Timber choice	Thickness	Thickness
Indicator	Material	m	m
Sub-Variable	-	U-Value	U-Value
Indicator	-	W/m^2K	W/m^2K
Sub-Variable	Cost	Cost	Cost
Indicator	€/m^3	€/m^3	€/m^3
Sub-Variable	Embodied carbon	Embodied carbon	Embodied carbon
Indicator	$kgCO_{2\text{-}eq}/m^3$	$kgCO_{2\text{-}eq}/m^3$	$kgCO_{2\text{-}eq}/m^3$
Sub-Variable	Service life	Service life	Service life
Indicator	Years	Years	Years

Variable	Cause Variables Non-Walkable roof insulation	 Ground floor insulation	 PV panels
Sub-Variable	Thickness	Thickness	Typology efficiency
Indicator	m	m	%
Sub-Variable	U-Value	U-Value	Area
Indicator	W/m^2K	W/m^2K	m^2
Sub-Variable	Cost	Cost	Cost
Indicator	€/m^3	€/m^3	€/m^2
Sub-Variable	Embodied carbon	Embodied carbon	Embodied carbon
Indicator	$kgCO_{2\text{-}eq}/m^3$	$kgCO_{2\text{-}eq}/m^3$	$kgCO_{2\text{-}eq}/m^2$
Sub-Variable	Service life	Service life	Service life
Indicator	Years	Years	Years

The effect variables investigated in this work are energy, carbon emissions, and cost. However, Energy performance is not explicitly an objective function, as it is indirectly contained in Carbon emissions and Cost use phases of life cycle. It is thus measured as Net site energy in kWh/m^2 year. Carbon emissions are instead measured as Life cycle carbon in $kgCO_{2\text{-}eq}/m^2$ year, considering only the product stage (A1-A3) and the use stage (B4 and B6) of the NBN EN 15978 standard for life cycle assessment (NBN, 2012). Finally, the cost is also measured as Life cycle cost, according to the supplement Directive to the EPBD (EC, 2021a), considering the initial investment and the operational cost, in euro/m^2.

All effect variables are evaluated through the software EnergyPlus, integrated, when necessary, with customed Python scripts.

Table 3-2: Effect variables

Variable	Effect Variables Energy Performance	 Carbon emissions	 Cost
Sub-Variable	Net site energy	Life cycle carbon	Life cycle cost
Indicator	kWh/m^2 year	$kgCO_{2\text{-}eq}/m^2$	€/m^2
Sub-Variable	-	Product stage	Product stage
Indicator	-	$kgCO_{2\text{-}eq}/m^2$	€/m^2
Sub-Variable	Use of life stage	Use of life stage	Use of life stage
Indicator	kWh/m^2 year	$kgCO_{2\text{-}eq}/m^2$ year	€/m^2 year
Standard	EN 13970	EN 15978	EPBD 2020 recast
Tool	Energy Plus	Energy Plus + Python	Energy Plus

3.4 Data collection

The input data required for the analyses are collected from several different sources.

Firstly, the case study is investigated to properly characterize the model for the simulation. An on-site survey is conducted, as well as both the BIM and BEM are analysed, to ensure completeness to this characterization.

Concerning the design variables, market research is done with companies' technical data sheet, EPDs, and cost estimates, to assess all the sub-variables explained in section 3.2. Furthermore, a survey is carried out among actors in the timber building construction sector, to investigate the actual lifespan of timber building components.

3.4.1 Case study: ‘t Centrum

Figure 3-2: t' Centrum (Beneens, 2022)

Het Centrum is a three-floor commercial building located in Westerloo, Belgium. It is a project from Kamp C company, built between spring 2021 and May 2022. It is a building of major interest, as it is the first Belgian circular building (E. Ascione, 2023). The circularity was taken under all aspects of construction:

- Circular development
- Circular design
- Circular financing
- Circular work
- Circular materials
- Circular business model
- Circular procurement

In the next 15 years, according to four different phases, the building is planned to “physically experience” circularity, as it will be disassembled and re-assembled in the surrounding areas.

All components of the building are prefabricated, and materials are chosen to have the lowest economic and environmental impact possible. Besides the foundations realized in sustainable recycled concrete, the whole structure is composed of timber: glulam for columns and beams, and CLT for slabs, shear walls, and staircase. Both external and internal walls are timber-framed prefabricated modules, except for two green walls. Triple and vacuum insulation glazings, a water-to-water ground source heat pump, and integration of PV panels, were chosen to increase the energy performance and thus decrease the operational costs, despite higher initial costs.

‘t Centrum is chosen as case study especially due to its circular nature and its conceptual ideas, strongly aligned with this work's objectives: optimize economic and environmental costs of a nearly-zero carbon timber building.

Figure 3-3: Case study plans, West and South elevations (Beneens, 2022)

3.4.1.1 On-site survey

On September 21st an on-site survey was conducted at the case study. The visit was guided by one of the designers of the building, who is also currently working inside the building itself, thus could give us some important feedback, analysing some design choices from the point of view of a future user as well. The building itself, being a prototype to be studied in terms of circularity, sustainability, and re-usability, has an exposition with models of some of its components and their materials. It was thus very useful to better understand the stratigraphy of his envelope (Figure 3-4), as well as connections and structures. Furthermore, it was possible to understand which changes occurred in the construction phase with respect to the original design.

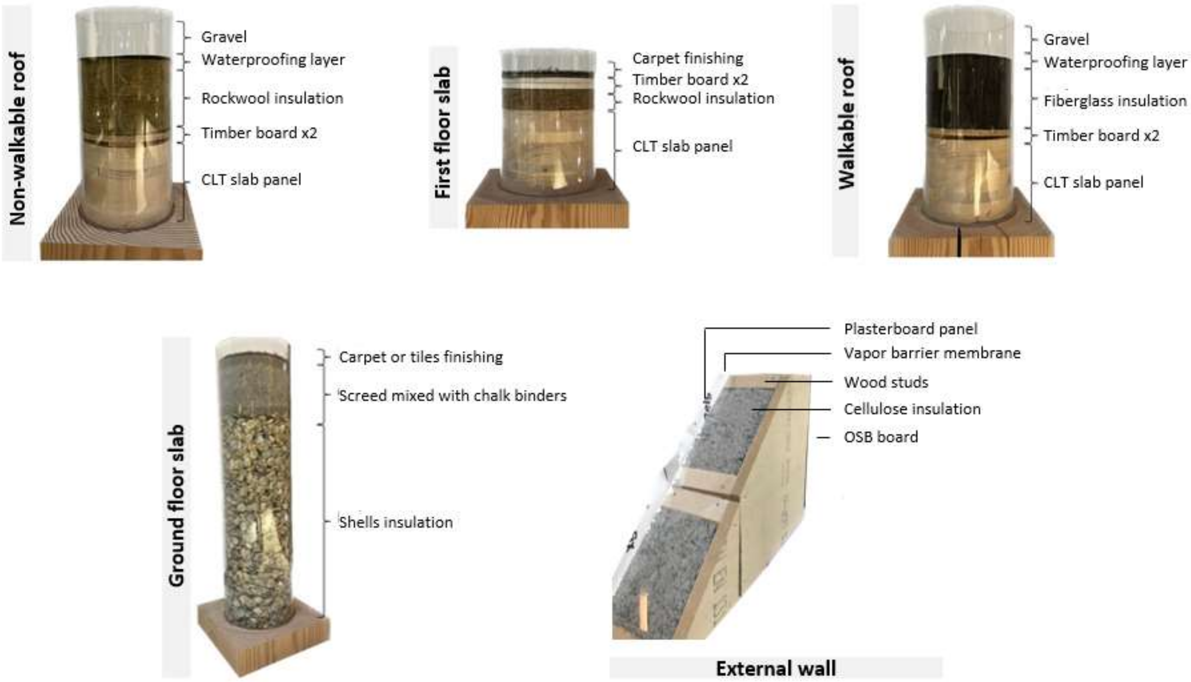


Figure 3-4: 't Centrum envelope stratigraphies (Campain, 2023)

3.4.1.2 Building Information Model (BIM)

The majority of the data was collected from the digital twin of the building, which is accessible online, and made available by the *Provinciaal Centrum Duurzaam Bouwen & Wonen Kamp C*.

From the model is possible to collect geometrical data, such as plans, elevations and sections, quantities of materials, and additional data on each component enriched with a "digital passport": a database with all files related, such as technical data sheets, reports, and EPDs.

Figure 3-5: 't Centrum Building Information Model

3.4.1.3 Building Energy Model (BEM)

Data related to the energy performance of the case study are collected from the Building Energy Model, such as thermal properties of components and materials, systems' coefficients of performance, heating, cooling, lighting, water use, and shading schedules. The BEM was developed by Claeys Louise, according to the EPB report handed over by Kamp C (Claeys, 2022).

However, some components of the BEM are updated in this work with the data collected from the on-site survey, as the model was created before the end of construction works.

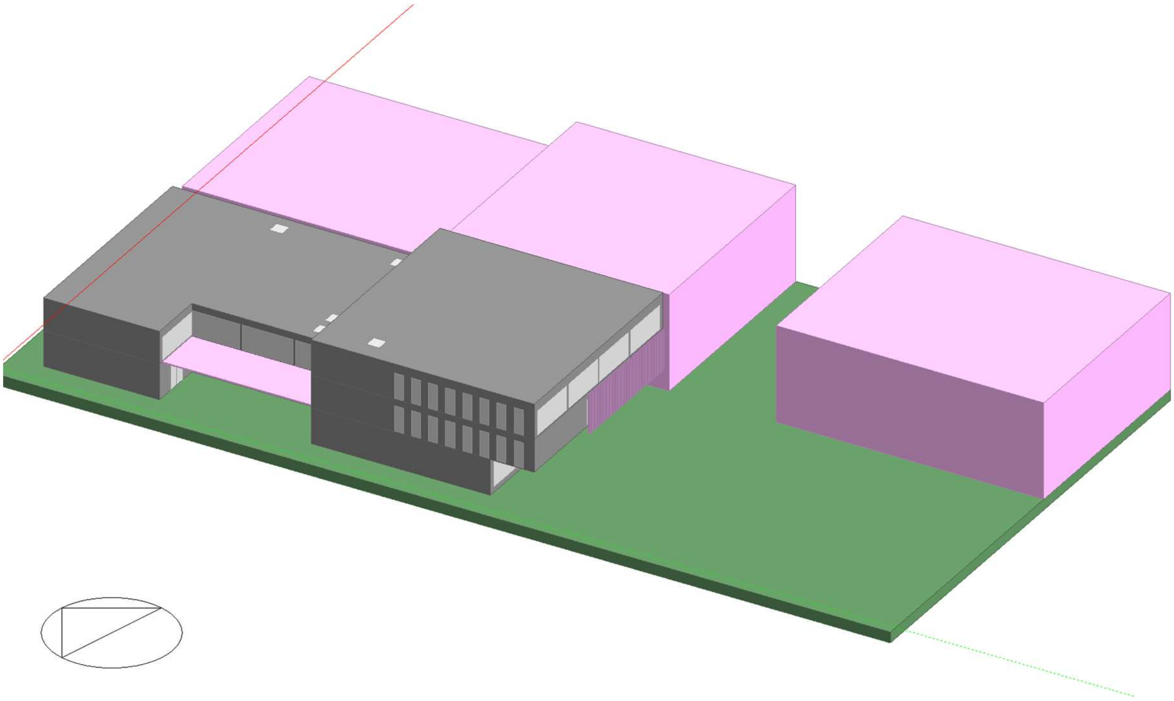


Figure 3-6: 't Centrum Building Energy Model (Claeys, 2022)

3.4.2 Market research

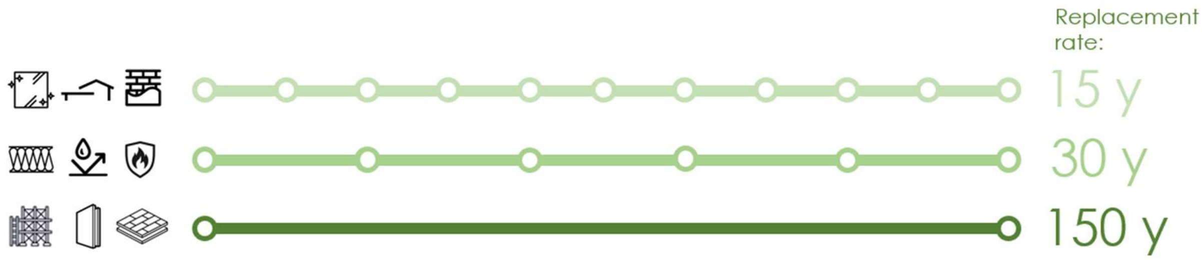
Market research is conducted to characterize the economic, environmental, and technical aspects of the design variables used in this work. Technical data sheets are used to address the specifics of each material, such as resistances for timber, thermal conductivity for insulations, and efficiency for PV panels. Environmental Product Declarations (EPDs) from the specific manufacturers are instead used to calculate the embodied carbon. Finally, price lists from the manufacturers and direct contact cost estimates from the retailers are used to define the unitary cost for each variable.

3.4.3 Survey: Estimation of tall timber building components service life

Finally, a survey is conducted among the timber construction sector's actors to investigate the actual service life of mid and tall timber building components. Manufacturers provide information regarding the expected lifespan of each product, and standards, such as EUROCODE 0, specify the expected lifespan of a building structure to be greater than 50 years (CEN, 2005). However, this survey intends to understand the difference between expected, or theoretical, and actual lifespan. A similar work was done for traditional construction by Comparis (Comparis, 2023), thus the reason for this survey is to integrate this work with timber components.

Each participant was asked to provide a lifespan range for each component (i.e. minimum to maximum years). The results were then statistically processed, assuming a normal distribution. Outliers beyond 5% and 95% of this distribution are cleaned, and the average is considered as the final result.

With a total of 103 responses, the sample cannot be considered representative of the construction sector, thus the results are rather indicative than conclusive. The results shown in Figure 3-7 are thus used in the simulations when considering the replacement rate of components and products, both for life cycle carbon and for life cycle cost.



Wooden cladding coating	12 years	Fire protection layer	25 years
Internal wall finishing	12 years	Waterproofing & Vapor barrier	26 years
Internal floor finishing	12 years	Insulation	34 years
Flat roof cladding	16 years	**Frame timber panels**	**128 years**
External cladding	16 years	**Solid timber panels**	**142 years**
Glazed elements	17 years	**Columns and beams**	**168 years**
Plasterboards	18 years	Concrete foundations	258 years

Figure 3-7: Survey results and suggestion of replacement rate

This work was part of the European COST Action CA20139 HELEN – Holistic design of taller timber buildings, an interdisciplinary research network that brings researchers and innovators together to investigate about engineered timber. In particular, it was part of the subgroup "Durability and Service Life Prediction", which is aiming to reply to the question: "What steps are required to give a high-rise timber building a life of 150 years? And how to predict the service-life in a planning process?" (COST, 2021).

3.5 Data analysis

In this section the optimization problem is explained thoroughly: starting with the description of the data collected, both fixed inputs and design variables, continuing with the definition of the objective functions, and concluding with an overview of the software involved.

3.5.1 Fixed inputs

Fixed inputs are the parameters used in the simulation which are not going to change throughout the optimization process. These factors are not the focus of this work, therefore they are not going to be analysed in every detail. A minor defect in any of these values will equally influence all the results, and thus in relative comparison is compensated. However, it is paramount to properly assess them, to get reliable generic results.

3.5.1.1 Site and Orientation

The case study is located in Westerloo, Belgium, at Latitude 51,13 N, and Longitude 4,86 E, at a height above sea level of 16 m. The main entrance of the building is located on one short side with 11 degrees clockwise inclination from the South. The West and North sides face the external too, while the East side is in contact with an adjacent building.

3.5.1.2 Shape and Dimension

The building has a rectangular plan, with sides 45 m x 20 m, developed on three floors with a total surface area of 1930 m^2 and a maximum height of 9,6 m. The third floor is only partially enclosed, as more than half of it is an accessible flat roof with a terrasse and PV panels.

3.5.1.3 Energetic characterization

The energetic characterization is provided by the BEM, which defines: the energetic properties of the green wall, adjacent external wall, glazed components, and internal partitions; the occupancy schedules, building systems, DHW and ventilation requirements; heat recovery unit, air tightness, shading schedules and external shading devices.

3.5.1.4 Weather file

The weather file chosen for the simulation is a Typical Meteorological Year (TMY) annual weather file, containing hourly weather values for a 1-year period, produced from data collected from multiple past years. It represents typical conditions, rather than extreme, and it is very suitable for comparison of alternatives during design, compliance with standards, or calculations of green building rating system points.

The closest weather station is located in Antwerp, at about 20 km from the case study, however, the weather station of Brussels National Airport, located at 35 km in Zaventem, is chosen, due to higher reliability. This weather data file is in format .epw and it is available from the opensource database of *Climate.OneBuilding.Org*.

3.5.1.5 Economic parameters

The last two fixed inputs are related to the economic life cycle evaluation: energy price escalation rate and real discount rate.

The former is related to the expected percentual annual increase in the energy market, and it is necessary for the simulation to estimate the operational costs related to energy. According to the directive, by processing the values from the EU reference scenario report of 2020 (EC, 2021b), a starting value of 0,197 €/kWh for 2023, and a growing rate equal to 3,01% are obtained.

The latter is the interest rate that adjusts for inflation, it is the rate at which the value of money decreases over time due to inflation, thus it is needed to convert in present terms the future values of money. The real discount rate is taken from the European Central Bank, equal to 4,5% (ECB, 2023).

3.5.2 Design variables

The design variables are the dynamic inputs of this study: during each iteration of the optimization, they assume different values. As the interest of this work is to optimize the environmental and economic cost, each variable is characterized by its unitary embodied carbon and investment cost.

The choice of design variables is inspired by (Hamdy et al., 2013). Envelop parameters are included to understand how to optimize the energy performance of the building with passive techniques and PV panels to explore how to improve the economic and environmental viability of these solutions. Finally, timber technology is added to explore new biogenic construction materials and their impact on the challenge to achieve NZCB.

Some other variables were initially implemented in the process, however, they were excluded for lack of data and thus for inconsistency of results. Among these, we have window type, air tightness, heat recovery unit, and primary heating/cooling system. Such parameters represent a potential future work.

3.5.2.1 Timber technology

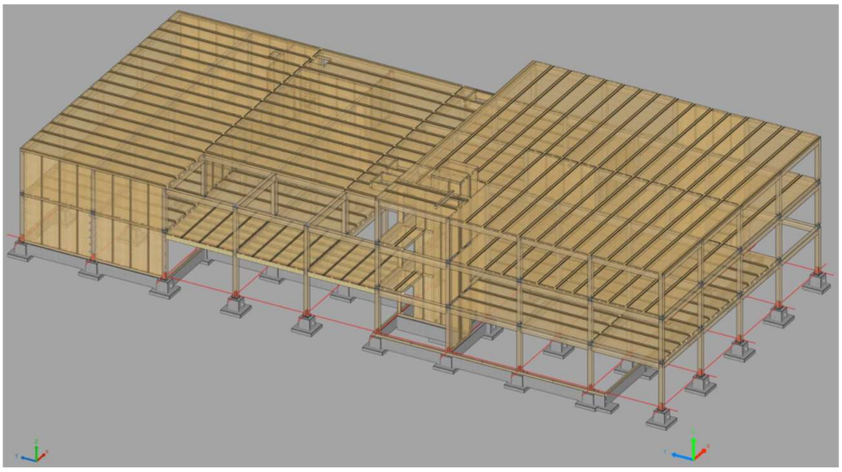


Figure 3-8: Structural CADWork model (Binderholz Bausysteme GmbH, 2021)

The case study structural typology is a post and beam structure. It is composed of glulam linear components as columns and beams, which form a 5x5 m grid, and CLT planar components as slabs, shear walls, stairs, and elevator shaft. The BIM is used for the material take-off of the structure elements, while (Binderholz Bausysteme GmbH, 2021) is used for structural characterization.

The post and beam typology was chosen because it allows maximum flexibility of the internal space, in line with the resilient and circular nature of the building. Therefore, the alternative choice recalls the original structure, with glulam columns and beams replaced by LVL linear elements, and CLT slabs by LVL open box slabs.

The embodied carbon values are extracted from the EPDs of the different products. The costs are provided by a retailer, Leidorf, through direct contact. The values are reported in Table 3-3.

Table 3-3: Timber technology (design variable no. 1)

	Columns and beams			Slab panels		
Timber technology	Volume [m^3]	Cost [euro/m^3]	Embodied carbon [$kgCO_{2-eq}/m^3$]	Volume [m^3]	Cost [euro/m^3]	Embodied carbon [$kgCO_{2-eq}/m^3$]
Glulam + CLT	98,98	700	110,20	307,48	535	109,51
LVL	82,55	785	404,72	154,35	885	380,72

In line with the purpose of this work, the pre-design of the alternative structural system is performed on three different components: a ground floor column, a beam, and a slab. The column is chosen on the ground floor as we expect the highest loads, thus calculations are conservative. The beam and the slab, on the other hand, are generic, as the load capacity is independent of their location. The LVL components are pre-designed with some assumptions, according to the following conditions. Any potential flaw in the calculations is later assessed with uncertainty analysis.

- Column: ensuring an axial compression resistance higher than the base case, under the hypothesis of pure axial compression. Detailed results are reported in Table 8-3, in Annex 1.
- Beam: ensuring a mono-axial bending moment resistance higher than the base case, under the hypothesis of mono-axial bending. Detailed results are reported in Table 8-4, in Annex 1.
- Slab: ensuring compliance with standard EN 1995-1-1 with the National Annex of Belgium (CEN, 2005), according to technical design tables of the product. Detailed results are reported in Table 8-5, in Annex 1.

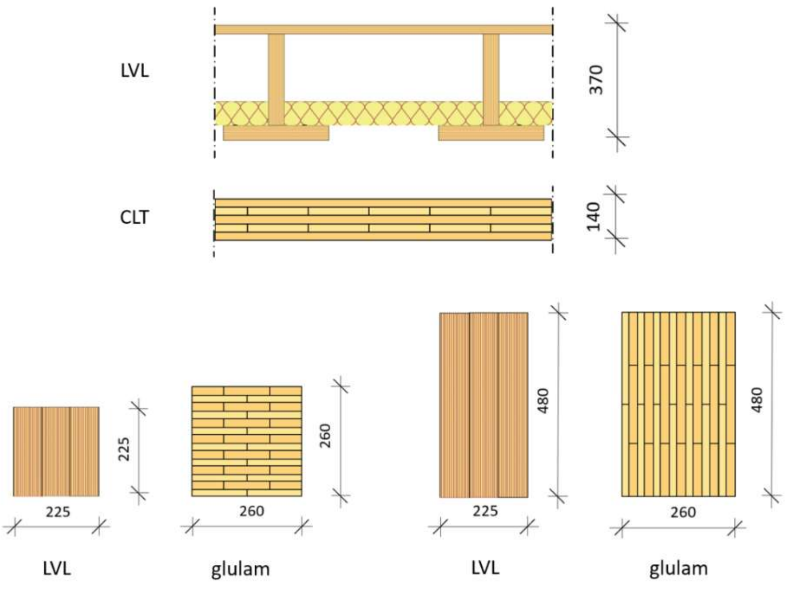


Figure 3-9: LVL and CLT-glulam structures compared: slabs (top), columns (bottom left), beams (bottom right)

3.5.2.2 External wall insulation

The external wall insulation is composed of cellulose, produced from Isoproc, in Belgium. It is a bio-sourced recycled material made of newspaper, with additives to protect against fire and insects. The flakes of cellulose are blown to the enclosed space using a blowing machine, hoses, and air pressure. In the case study, the blowing space is enclosed between a layer of compressed wood fiber panels and one of plasterboards. This technical solution limits the range of thickness of the insulation in practice to a value of 40 cm, however, higher values up to 80 cm are considered, to fully explore the problem.

The base case external wall has 23,5 cm of cellulose, with a total U value of 0,17 W/m^2K. The conductivity of the insulation is 0,038 W/mK, thus ranging from 10 cm to 80 cm, the total U value ranges from 0,25 W/m^2K to 0,04 W/m^2K, respectively.

The embodied carbon is extracted from the EPD and is equal to 5,87 $kgCO_{2\text{-}eq}/m^3$, while the cost is provided by a retailer, eurabo.be, and is equal to 37,32 €/m^3. All the data are summarized in Table 3-4.

3.5.2.3 Walkable roof insulation

The walkable roof insulation is made of rigid fiber glass panels from Foamglas, which can withstand high loads, it is thus used in second floor terrasse. The panels have 1,2 x 0,6 m dimensions, and a thickness ranging from 60 mm to 180 mm. In the case study, the panels are not chemically attached, to ensure the complete disassembly potential in the future. Considering the possibility of overlapping two different panels, the range of this thickness implemented is 60 mm to 360 mm.

The base case walkable roof has 14,0 cm of fiber glass, with a total U value of 0,23 W/m^2K. The conductivity of the insulation is 0,036 W/mK, thus ranging from 6 cm to 36 cm, the total U value ranges from 0,43 W/m^2K to 0,09 W/m^2K, respectively.

The embodied carbon is extracted from the EPD and is equal to 189,96 $kgCO_{2\text{-}eq}/m^3$, while the cost is extracted from the company price list and is equal to 518,73 €/m^3. All the data are summarized in Table 3-4.

3.5.2.4 Non-walkable roof insulation

The non-walkable roof construction is similar to the walkable roof, with the difference that the insulation is made of mineral wool, from Rockwool. This solution cannot withstand continuous high loads, it is thus used on the second-floor roof and under the PV panels. In this case, the panels have dimensions 1 x 0,6 m and thickness ranging from 60 mm to 200 mm. The range of thickness implemented is still 60 mm to 360 mm.

The base case non-walkable roof has 14,0 cm of mineral wool, with a total U value of 0,23 W/m^2K. The conductivity of the insulation is 0,038 W/mK, thus ranging from 6 cm to 36 cm, the total U value ranges from 0,46 W/m^2K to 0,10 W/m^2K, respectively.

The embodied carbon is extracted from the EPD and is equal to 110,78 $kgCO_{2\text{-}eq}/m^3$, while the cost is extracted from the company price list and is equal to 349,03 €/m^3. All the data are summarized in Table 3-4.

3.5.2.5 Ground floor insulation

The ground floor insulation is another representation of the circularity and innovation of the case study, as it is made of shells, from Ecoschelp in Belgium. As shown in Figure 3-4, the shells are blown into the cavity and insulate the ground floor slab screed from the ground, performing draining and moisture control features, too. However, this material has relatively low insulation value and thus requires high volume and to be combined with other insulating layers, screed in this case. The chosen range of thickness for this insulation layer is from 10 cm to 100 cm.

The base case ground floor has 60,0 cm of shell insulation, with a total U value of 0,14 W/m^{2}K. The conductivity of the insulation is 0,106 W/mK, thus ranging from 10 cm to 100 cm, the total U value ranges from 0,23 W/m^{2}K to 0,10 W/m^{2}K, respectively.

As no EPD is available for this product, following the lead of (Al-Obaidy et al., 2022), the material is considered a natural material with product stage carbon impact equal to 0 kg$CO_{2\text{-eq}}$/m^3. The cost is extracted from the company price list and is equal to 143,1 €/m^3. All the data are summarized in Table 3-4.

Table 3-4: Envelope insulations (design variables n.2-5)

Design variable n., Insulation of…	Material	Thermal conductivity [W/mK]	Range of insulation thickness [m]	U-value of the construction [W/m^{2}K]	Cost [euro/m^3]	Embodied carbon [kg$CO_{2\text{-eq}}$/m^3]
2. External wall	Cellulose	0,038	0,10 to 0,80	0,25 to 0,04	37,32	5,87
3. Walkable roof	Foam glass	0,036	0,06 to 0,36	0,43 to 0,09	518,73	189,96
4. Non-walkable roof	Mineral wool	0,038	0,06 to 0,36	0,46 to 0,10	349,03	110,78
5. Ground floor	Shell insulation	0,195	0,10 to 1,00	0,23 to 0,10	143,1	0,00

3.5.2.6 PV panels

The last two design variables are related to the type of PV panels integrated in the building and their total surface area. The base case has 342 m^2 of Mono-crystalline panels, thus an alternative of cheaper and more sustainable, but less efficient Poly-crystalline panels is chosen. The area, on the other hand, is explored from 0 to the maximum value of 344 m^2 to investigate whether the chosen surface is justified, or a lower area could be more effective.

The embodied carbon data are extracted from the EPD and are equal to 144,18 kgCO_{2eq}/m^2 and 123,58 kg$CO_{2\text{-eq}}$/m^2 for the mono-crystalline and the poly-crystalline, respectively. On the other hand, the costs are provided by a retailer, *secondsol.com*, and are equal to 65,35 €/m^2 and 46,58 €/m^2 for the mono-crystalline and the poly-crystalline, respectively. All the data are summarized in Table 3-4.

Table 3-5: PV panels (design variables no. 6-7)

Option	Max. Power Output (W_p)	Efficiency (%)	Photovoltaic system	Size	Cost [euro/m^2]	Embodied carbon [kg$CO_{2\text{-eq}}$/m^2]
1	385	19,8	Mono-crystalline panels	From 0 to 342 m^2	65,35	144,18
2	330	17	Poly-crystalline panels	From 0 to 342 m^2	46,58	123,58

3.5.3 Objective functions

In this section, the two objective functions are explained. They are needed to define the optimization problem and thus find the cost-optimal curve (Hamdy et al., 2013):

$$Min\,\{f_1(\bar{x}), f_2(\bar{x})\} \qquad \bar{x} = [x_1, x_2, x_3, x_4, x_5, x_6, x_7]$$

Where:

f_1 : life cycle equivalent carbon, $LCCO_{2eq}$

f_2 : difference in life cycle cost between any design option and the reference design, dLCC

$\bar{x}$: combination of the design variables

3.5.3.1 Life Cycle Carbon ($LCCO_{2eq}$)

The Life Cycle Carbon is chosen as the indicator in evaluating the environmental impacts of different design solutions. Throughout this work, this indicator is addressed as Life Cycle Carbon or $LCCO_{2eq}$, it should be specified however, that it refers to total Global Warming Potential (GWP-total). It therefore considers all different greenhouse gas emissions and expresses them as $kgCO_{2\text{-equivalent}}$ (Stocker et al., 2013).

$LCCO_{2eq}$ is defined as the sum of all carbon-equivalent emission output from a building over different phases of its life cycle (Chau et al., 2015), as in equation (1).

$$LCCO_2 = CO_{2,product} + CO_{2,\ construction} + CO_{2,\ use} + CO_{2,\ end\ of\ life} + CO_{2,\ recycling} \qquad (1)$$

According to the European standard EN 15804 (NBN, 2019), the minimum content of an Environmental Product Declaration should include cradle-to-gate A1-A3 with modules C1-C4. Module D is also to be included, however it should be considered separately as beyond the system boundary stage. The sources of carbon data are manufacturers' EPDs, which do not provide all life cycle stage values: the effects of design variables on the construction stage are therefore not considered. On the other hand, the use stage is considered as the sum of annual emissions, related to the net site energy usage, and the product carbon, related to the replacement of building components. Finally, as the recycling phase (module D) is considered in standard EN 15978 as supplementary information beyond the building life cycle (NBN, 2012), and as it is out of the scope of this work, it is not included.

The approach chosen is therefore a cradle-to-grave, with the objective function calculated as equation (2).

$$LCCO_2 = CO_{2,product,A1-A3} + CO_{2,construction\ A4-A5} + CO_{2,replacement,B4} + CO_{2,energy,B6} + CO_{2,end\ of\ life,C} \qquad (2)$$

The reference study period RSP is 50 years, which represents a compromise between ensuring that impacts from replacements of shorter-lived building materials will be reflected in the results, and between encouraging that more emphasis can be put on the crucial material-related emissions that affect the global carbon budget (Rasmussen et al., 2020).

The replacement carbon is evaluated by considering the replacement rate of each design variable, evaluated as equation (3), according to EN 15978.

$$r_i = \left\lceil \frac{RSP}{ESL_i} - 1 \right\rceil \qquad (3)$$

Where:

r_i : replacement rate of design variable *i*

RSP *: reference study period of 50 years*

ESL_i : estimated service life of design variable *i*

The equivalent operational carbon is evaluated multiplying the Net Site Energy consumption, i.e. the energy delivered from the grid, by the average Belgian emission factor, equal to 51,94 gCO_{2eq}/MJ (Nowtricity, 2023).

In order to allow a comparison with the existing benchmarks regarding the environmental impact of buildings, the $LCCO_{2eq}$ is expressed in $kgCO_{2eq}/m^2$year, dividing the total value for the duration of the reference study period.

3.5.3.2 Difference in Life Cycle Cost (dLCC)

Life Cycle Cost is the tool chosen to assess the financial viability of solutions, as suggested in the EPBD (EC, 2021a), as in equation (4). LCC allows to take into account the discounted cash flows throughout the entire lifetime of the building: initial investment, running costs, energy costs, and finally disposal costs. All these Future Values (FV) are thus discounted and referred to the Present Value (PV) in the current year, i.e. 2023, according to equation (5).

$$LCC = IC + OC + EC + DC \qquad (4)$$

Where:

IC : initial investment cost

RC : running costs, including costs for periodic replacement of building elements and earnings from energy produced, if appropriate

EC : energy costs

DC : disposal costs, if appropriate

$$PV_{2023} = \frac{FV_{20xx}}{(1+r)^n} \qquad (5)$$

Where:

PV_{2023} : present value referred to year 2023

FV_{20xx} : future value occurring in year 20xx

r : real discount rate, equal to 4,5%, see section 3.5.1.5

n : number of years occurring between FV occurring 20xx and PV 2023

Following the lead of the work from Hamdy et al. (Hamdy et al., 2013), as the aim is to compare designs with changes in the design variables, the absolute value of LCC is not evaluated. Instead, the difference between the LCC of the reference design (base case) and each solution is used, as in equation (6). In this way, there is no need to include cost data for all components of the building, but only the differences produced by the variation of specified parameters.

Furthermore, in line with the scope of this work, running costs are considered only as the replacement cost of components, and disposal costs are not assessed. The second objective function is thus defined as equation (7), and is reported as €/m².

$$dLCC_i = LCC_i - LCC_{base\ case} \qquad (6)$$

$$dLCC_i = \sum_{j=1}^{7} IC_j + \sum_{j=1}^{7} RC_j + EC_i \qquad (7)$$

Where:

$dLCC_i$: difference in life cycle cost of design solution *i*

IC : initial investment cost of design variable *j*

RC : replacement cost of each design variable *j*

EC : energy cost of design solution *i*

The replacement cost and energy cost are evaluated with the same methods described in section 3.5.3.1. In the case of energy cost, the average Belgian price for electricity are considered instead of the emission factor, see section 3.5.1.5.

According to the directive for commercial, non-residential buildings, the lifespan considered is 20 years. Longer calculation periods are not recommended, as assumptions on interest rates and forecasts on energy prices become very uncertain (Constantinescu, 2010).

3.5.4 Building reference design

According to the EPBD comparative framework, the economic and environmental feasibility of the proposed solution should be compared to the building reference design. In this case, as the case study itself is a new building complying with current national standards, it is chosen as a real reference building (Corgnati et al., 2013).

The first energetic simulation is thus performed on the parametrized model with the design variables values set equal to the case study values, as reported in Table 3-6.

Further details on the case study's energetic characteristics can be found in section 3.4.1.

Table 3-6: Case study design variable values

Variable n.	Design variable	Case study value	
1	Timber technology	CLT and glulam	
2	External wall insulation	t = 23,5 cm	U = 0,17 W/m²k
3	Walkable roof insulation	t = 14 cm	U = 0,23 W/m²k
4	Non-walkable roof insulation	t = 14 cm	U = 0,23 W/m²k
5	Ground floor insulation	t = 60 cm	U = 0,14 W/m²k
6	PV panel type	Mono-crystalline	
7	PV panel area	A = 342 m²	

The results obtained from the case study simulation, which are going to be used for solution relative comparison, are summarised in Table 3-7.

Table 3-7: Case study reference values

Primary Energy Consumption	52,3	kWh/m^2year
Operational carbon	6,25	$kgCO_{2eq}/m^2year$
Embodied carbon	372	$kgCO_{2eq}/m^2$
$LCCO_{2-eq}$ (50 years)	13,7	$kgCO_{2eq}/m^2year$

These values are all below the standards' requirements.

In the case of PEC, the maximum allowed value is equal to 82 kWh/m^2year for Belgium (EC, 2012a), while $LCCO_{2-eq}$ does not yet have a national standard reference. We can however compare it to the most ambitious currently existing standards, such as French RE2020 (AFNOR, 2022) and Danish BR18 (DS, 2023), which have respective values of 15 $kgCO_{2eq}/m^2year$ and 18 $kgCO_{2eq}/m^2year$ for Life Cycle Carbon. Also Operational and Embodied Carbon are below French requirements, which are 11,2 $kgCO_{2eq}/m^2year$ and 740 $kgCO_{2eq}/m^2$, respectively.

3.5.5 Software

The different software used in the simulations and the steps done with each of them are explained in this section.

The modelling starts in DesignBuilder. The existing BEM is used as a basis, new constructions are modelled for external walls, ground floor slab, walkable and non-walkable roof slab, according to the data collected from the on-site survey. PV panels are also added to the model in this phase. A first attempt of multi-objective optimization is tried on this software, but it is abandoned as it shows low flexibility to changes in parameters and objective functions, different from the pre-set ones.

The model is thus exported as a text file (.idf) and imported into JE+, a Java software that implements Energy+ as building energy simulation engine. It is a less user-friendly interface than DesignBuilder, as you directly program on the text file, but allows a simpler parametrization of the design variables and statement of the objective functions. Python custom scripts are also implemented in the process.

Finally, the multi-objective optimization per se is performed on JE+EA, a version of JE+ which is implemented with the Evolutionary Algorithm (EA) NSGA-II and thus allows to explore the set of combinations at lower computational costs.

The results are finally processed in Excel.

3.5.6 Hardware

The state-of-the-art Super COmputeR ProcessIng wOrkstatioN (SCORPION) is used with a processor of 64 cores, 128 threads, and a 256MB cache for computing power and performance. This is in combination with 128GB (4 x 32GB) of memory (RAM) and a graphics card of 24GB allowed to perform the intensive computations. Its main components are:

- CPU: AMD Ryzen Threadripper 3990X, 64 x 2.9GHz, 256MB Cache, 280W TDP, TRX40

- RAM: 64GB - 2 x 32GB Kit DDR4-3200 CL16, Corsair Vengeance LPX (2 x 32GB Kit x 2 St. = 128GB)
- Graphics card: NVIDIA GeForce RTX 3090, 24GB

3.6 Boundary conditions

All the simplifications and assumptions considered in this work are listed and explained in this section.

3.6.1 BIM and BEM assumptions

- Some discrepancies are noted between the Building Information Model, the Building Energy Model, and the data collected from the on-site survey. For practical reasons it is not possible to check all of them, thus the BEM is used as a starting point as it is essential for the energetic simulation. Any discrepancy related to design variables was corrected with the data from the on-site survey, which is considered as most reliable.
- PV panels are integrated in the BEM, as they are not present. They are modelled as horizontally oriented, simple photovoltaic panels using a standard converter of DesignBuilder.
- The surface considered for the walkable roof is the whole first-floor roof, however in the case study only a part of it is walkable.
- The energy mix considered is a generic Belgian energy mix. Uncertainty analysis with a green energy mix is carried out to better reflect the case study, however, a single supplier estimation is used as the price of the green energy mix. The same energy price escalation rate is assumed also for green energy.
- Thermal discomfort and thermal inertia are not considered.
- The software used is an old version which is thus not updated to the newest standard for energy performance calculations. The standard used in this work is EN 13790, instead of EN 52016.

3.6.2 Variables assumptions

- LVL alternative for timber technology calculations are rough, and not detailed. However, they are higher resistance areas are always considered, to ensure conservative results.
- The same thermal insulation is verified for the LVL slab, but acoustic insulation is not considered.
- No timber connection is considered.
- The effects that insulation thickness variation has on the quantity of the other materials of the same construction technology is not considered.
- PV panels' efficiency is considered constant throughout their service life.

3.6.3 Objective functions assumptions

- Only the $LCCO_{2eq}$ of the design variables is computed in this work, the $LCCO_{2eq}$ of the remaining components of the building is taken from a previous work (Al-Obaidy et al., 2022).

- Changes due to design variables are not considered for construction stage carbon (Phase A4-A5).
- Replacement carbon (Phase B4) is calculated only for design variables.
- Use and recycling stages (Phases B1, B2, B3, B5, B7, and D) of Life Cycle Assessment are not considered.
- End of life stage (Phases C) is considered under the following scenarios: biogenic material (CLT, glulam, LVL and cellulose) are used for energy recovery in a plant at a distance of 20 km; roof insulations (mineral wool and foam glass) are landfilled at a distance of 50 km; PV panels metal parts are recycled, while plastic parts are incinerated in a plant at a distance of 50 km.
- Carbon cost data comes from the manufacturers. High discrepancies for the same product between different manufacturers are noticed, which also leads to uncertainty analysis.
- Cost values are taken from personal contacts, price lists from companies and online retailers. A proper market analysis may better reflect the real costs.
- A simple interest rate is assumed in the cost calculation of the Present Value.
- No income earnings from extra energy produced by PV installed are considered.
- The service life of components is obtained through a survey. The survey is conducted on generic tall timber buildings and a limited number of answers are obtained, the results are thus indicative rather than qualitative.

3.7 Quality criteria

Due to the complexity of the problems, the many assumptions, number of fixed inputs and variables included, it is necessary to carry out some investigation that can provide valuable information regarding the reliability and robustness of results, and thus of the conclusions that are drawn from them.

In this framework, sensitivity and uncertainty analyses offer a precious tool to provide a clearer and more detailed understanding of the individual components of such a complex system, their influences, and their relationships.

3.7.1 Sensitivity analyses

Sensitivity analysis is performed on the result outputs to understand which design variables affect them the most. It is chosen to use a regression method, as it is widely used in literature as a method for sensitivity analysis in building energy analysis (Tian, 2013). Standardized Regression Coefficient (SRC) is chosen as an indicator: it represents the linear relation between the input and the output, thus how much the output will change based on a unitary change in the input.

3.7.2 Uncertainty analyses

As highlighted by (Cellura et al., 2011), the outcome of a building life cycle approach may be influenced by many sources of uncertainty, such as the definition of the boundary conditions, or the reliability of the available data. Uncertainty analyses are thus performed on some main input parameters, whose reliabilities are questioned.

These inputs are:

- Timber material quantity: being calculated with a “rule of thumb” pre-design approach, and being a key parameter of this work, the final volume of the LVL alternative is increased/decreased by 20%.
- Lifespan of life cycle calculation: the standard values of 20 years for LCC and 50 years for $LCCO_{2eq}$ are used in the simulations, however, as very likely the case study may last longer, these calculation periods are both extended by 20 years and 50 years, in two different scenarios.
- Design variable carbon data source: as these values are extracted from specific product manufacturers' EPDs, they are expected to be biased. Ecoinvent is a neutral Life Cycle Assessment inventory database used to produce EPDs, which is considered as more reliable. For those EPDs not base on this dataset, carbon data are extracted from literature (Hill et al., 2018) and from other manufacturers’ EPDs, based on Ecoinvent database. All data are reported in Table 3-8.

Table 3-8: Original case and uncertainty analysis carbon data comparison

	Original case: Manufacturers' EPD	Uncertainty Analysis: Ecoinvent based data sources	Unit
CLT	109,51	268,76	$kgCO_{2\text{-}eq}/m^3$
glulam	110,2	114,39	$kgCO_{2\text{-}eq}/m^3$
LVL	404,72	281	$kgCO_{2\text{-}eq}/m^3$
Cellulose insulation	5,87	3,7	$kgCO_{2\text{-}eq}/m^3$
Mineral wool insulation	110,78	141	$kgCO_{2\text{-}eq}/m^3$
Foam glass insulation	189,96	234	$kgCO_{2\text{-}eq}/m^3$
Shell insulation	0	0	$kgCO_{2\text{-}eq}/m^3$
PV panels Mono-Crystalline	144,18	144,18	$kgCO_{2\text{-}eq}/m^2$
PV panels Poly-Crystalline	123,58	123,58	$kgCO_{2\text{-}eq}/m^2$

- Energy supplier: in the original simulations a Belgian average energy mix supplier is chosen. However, according to the plans of the company, the case study is supplied only by green energy. This sustainable alternative from Cociter, with significantly higher costs (0,41 €/kWh) but negligible emissions, is chosen to be assessed.

Each of these inputs is varied independently in a new simulation, using as model the best solution of the multi-objective optimization. The results of these simulations are then compared to the best solution results to understand which is the percentage variation of the two objective functions.

4 Results: Multi-Objective Optimization

In this chapter are presented the results of the multi-objective optimization performed on the case study, according to the methodology explained in Chapter 3. The analysis of these results enables us to answer the following research questions:

- How far can we optimize the design of a building to reduce its carbon impact at the lowest cost?
- Where lays the trade-off between the two objective functions ($LCCO_{2eq}$ and LCC)?
- How do parameters influence the objective functions?
- Among the considered design alternatives, which are the best practices to be applied in the early design phase?

4.1 Multi-Objective Optimization

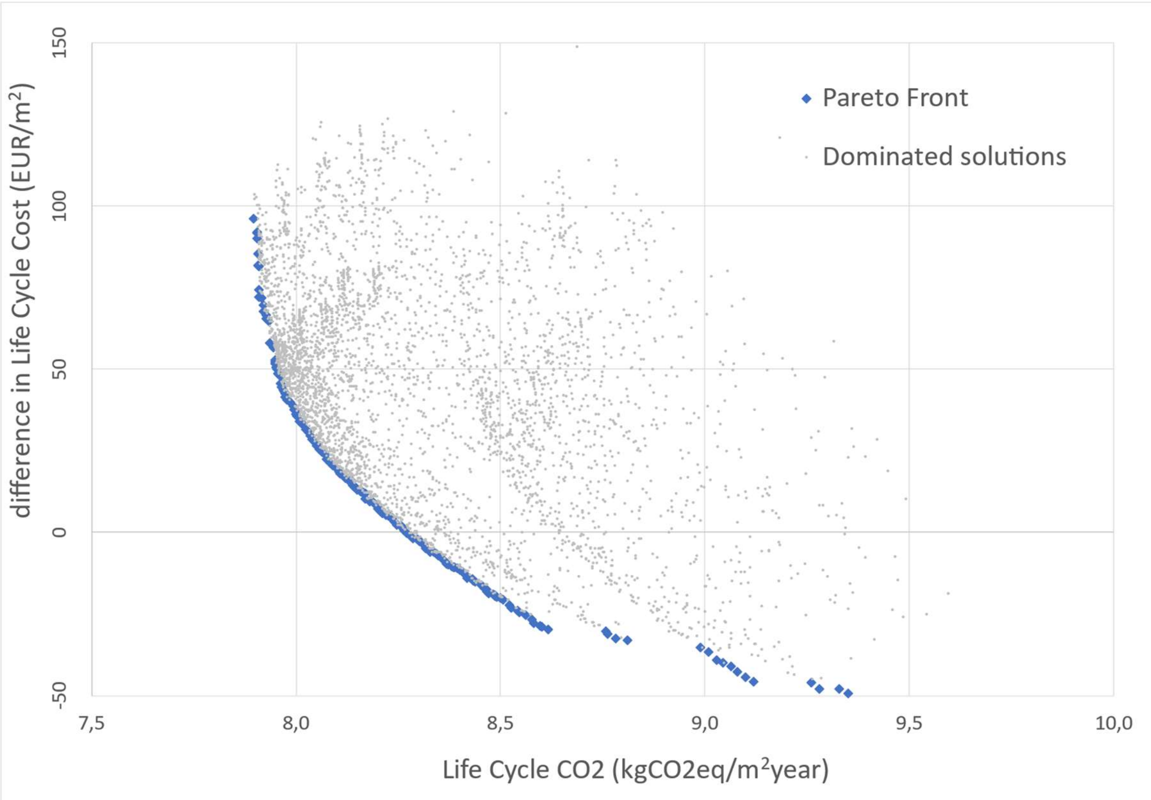


Figure 4-1: Multi-Objective Optimization results

Figure 4-1 shows the results of the multi-objective optimization performed on the case study, a larger image can be found in Annex 2.

The combination set is explored effectively through 4176 simulation runs. 4023 are the so-called “dominated solutions”, non-optimal design solutions, as for each of them exists at least another solution which is better in terms of the two objective functions. Vice versa, the remaining 153 solutions are called “non-dominated” and form the Pareto Front, which represents the set of trade-offs.

Solutions in the Pareto Front range from low carbon-content higher-cost to lower-cost higher-carbon solutions. The lowest carbon solution has **7,90 $kgCO_{2eq}/m^2year$**, a reduction of 11% with respect to the original design, but at a **cost 96,14 €/m^2 higher** (185 000 €). On the other hand, the cheapest solution shows a cost decrease with respect to the case study of almost **-50 €/m^2** (-95 000 €), but also a carbon content of **9,35 kgCO$_{2eq}$/m^{2}year**, corresponding to an increase of 5%.

Figure 4-2 compares the results with the current and future regulations' environmental requirements. Being the case study a new and sustainable design, all the proposed design solutions fall below these threshold values, for future French regulations and for stricter Danish ones, too.

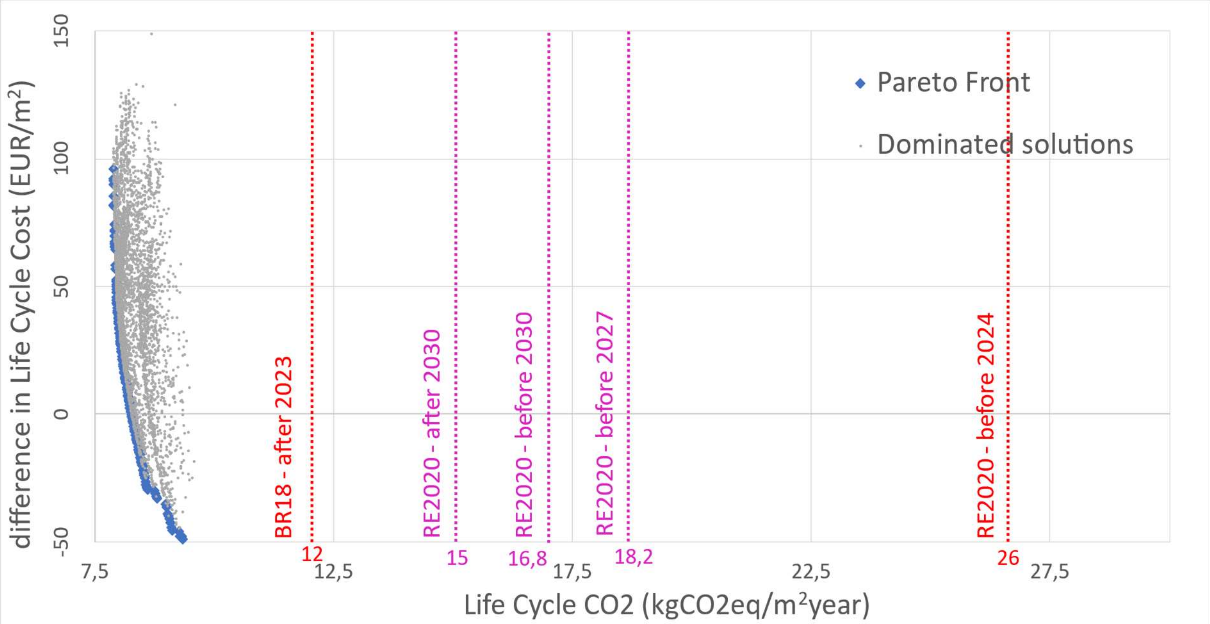


Figure 4-2: Comparison of MOO results with regulations' limits

Figure 4-3 shows the distribution of each design variable in the Pareto Front solutions, a larger image can be found in Annex 2.

Most of these solutions use **CLT-glulam timber technology**, meaning that the lower cost of LVL is not compensated by the higher carbon content. In Figure 4-1 a second "Pareto Front-like" shape can be noticed on the right part of the dominated solutions: this set of points suggests which would be the optimal solutions for LVL technology.

Furthermore, Figure 4-3 tells us that it is advisable to **maximize bio-based insulation**, i.e. cellulose for external walls, and reduce higher carbon content materials, such as mineral wool and foam glass. These results are expected, as cellulose minimizes both the two objective functions, unlike the roof materials. However, it should be noted that thermal comfort is not assessed, and that wall insulation values are theoretical. Ground floor shell insulation is also minimized, suggesting that, despite the zero carbon content, the high cost and the low thermal properties make it a non-optimal solution.

Finally, concerning PV panels, results suggest that **poly-crystalline modules** should be **preferred**, meaning that their lower initial investment and embodied carbon, are dominating over lower operational costs and emissions of Mono-crystalline. On the other hand, all the surface ranges are included, with small areas resulting in low-carbon high-cost solutions and large areas vice versa.

Figure 4-3: Pareto Front design variables distributions

As the goal of this work is to optimize the case study, it is necessary to compare all the non-dominated solutions with the original design, i.e. find those solutions of the Pareto Front which dominate the case study.

Figure 4-4 shows that out of 153, only 51 design solutions are actually optimizing the original case study, a larger image can be found in Annex 2. Analysing the full set would be unnecessarily long, thus it is studied by three representatives: the **cheapest solution** (solution **A**), the **most sustainable solution** (solution **B**), and the **trade-off solution** (solution **C**), chosen as the closest to the median values.

Solution A shows an environmental impact of **8,27 $kgCO_{2eq}/m^2year$**, **7% less** than the case study, at approximately the same cost (500 € less). On the other hand, **solution B** shows a **cost reduction** of more than **63000 €**, with an environmental impact slightly lower than the case study, 1,1%. Finally, **solution C** shows a **reduction** of more than **5% of $LCCO_2$** (8,44 $kgCO_{2eq}/m^2year$) at a **cost** of around **30000 € lower** than the original design.

All these values are summarized in Table 4-1, while Table 4-2 shows their distribution of the design variables. All the solutions have CLT-glulam timber structure, this is because LVL alternative higher-carbon content does not allow for any of its solutions to optimize environmentally the original case study. Furthermore, we can see how the envelope variables follow the previously observed Pareto distribution: high values of bio-based cellulose wall insulation, and low values for more polluting mineral wool and foam glass for roof insulations. Moreover, we can observe how the variation of PV panels typology and area slightly influences the Net Site Energy and thus the Operational Carbon, with larger surfaces and Mono-Crystalline panels being more sustainable, but more expensive too. Finally, it should be noted how the **embodied carbon** (calculated over 50 years) and the **operational carbon**, almost represents the **same share on the $LCCO_2$**, for all the cases solutions considered.

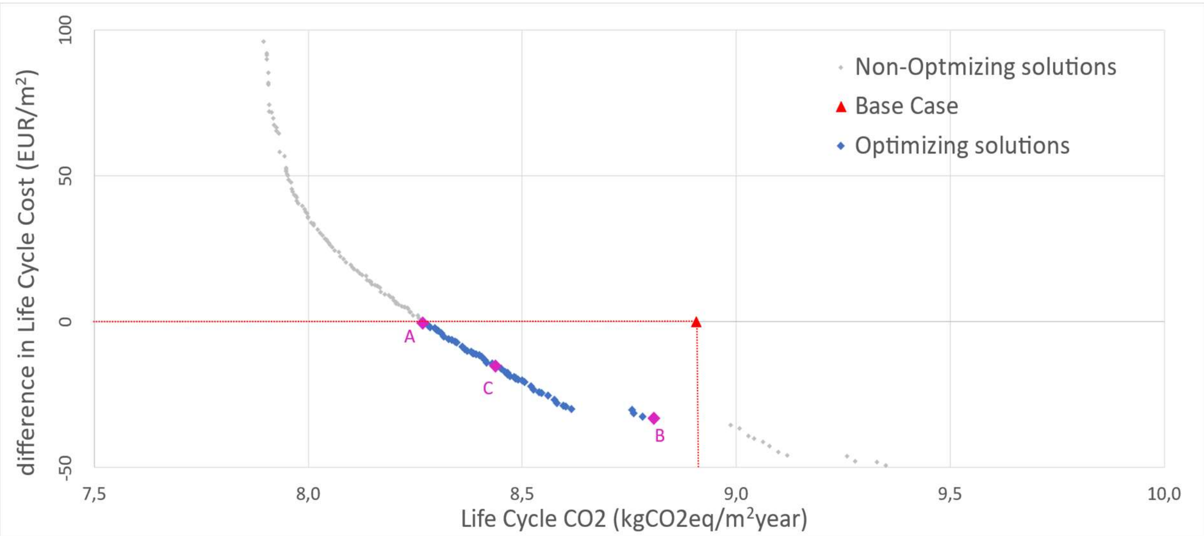


Figure 4-4: Base case optimized design solutions

Table 4-1: Optimized solutions objective functions and output values

	$LCCO_2$ ($kgCO_{2eq}/m^2year$)	dLCC (EUR/m2)	Net site energy (kWh/m^2year)	Operational carbon ($kgCO2eq/m^2year$)	Embodied carbon ($kgCO2eq/m^2$)
Solution A	8,27	-0,26	22,56	4,22	202,51
Solution B	8,81	-32,97	22,36	4,18	231,48
Solution C	8,44	-15,19	22,51	4,21	211,15
Base case	8,91	0	21,93	4,09	240,39

Table 4-2: Optimized solutions design variables

	Timber technology	Ext. wall ins (m)	Walkable roof ins (m)	Non-Walkable roof ins (m)	Ground floor ins (m)	PV type	PV area (m2)
Solution A	CLT-glulam	0,80	0,08	0,12	0,20	Poly	234
Solution B	CLT-glulam	0,75	0,06	0,10	0,20	Mono	342
Solution C	CLT-glulam	0,80	0,06	0,12	0,20	Poly	288
Base case	CLT-glulam	0,24	0,14	0,14	0,60	Mono	342

In conclusion, the multi-objective optimization successfully optimizes the already state-of-the-art design of the case study, proposing a total of **51 trade-off design solutions** that **range from reducing 7% of the $LCCO_2$** at the same cost **to saving more than 63000 €**, with a reduction of 1% of $LCCO_2$.

5 Results: Model verification analyses

In this chapter are reported the results of the sensitivity and uncertainty analyses. As described in section 3.7, these analyses allow us to better understand the quality of the optimization and thus the reliability of its results. The two sensitivity analyses investigate about the influence of design variables on each objective functions, while the six uncertainty evaluates the robustness of the MOO results with respect to a change in the uncertain parameters. Therefore, these results allow us to answer to the following research questions:

- Which parameters influence the most the objective functions?
- How does each parameter influence them?

5.1 Sensitivity analyses

As described in Section 3.7.1, sensitivity analyses allow to define how parameters affect the objective functions. The method chosen for these analyses is linear regression, with SRC as indicator, thus each objective function is simplified as the sum of linear contribution of each design variable, where SRCs represent the coefficient to multiply the value assumed by each variable. Timber technology and PV panels type are non-numeric variables, thus the meaning of their SRC could be less trivial: it represents the binary change between CLT-glulam and LVL for the former, and between Mono-Crystalline and Poly-Crystalline for the latter.

5.1.1 Life Cycle Carbon

Figure 5-1 summarizes the SRC for the $LCCO_2$ objective function. Timber technology is the most influencing variable, followed by external wall insulation and PV panels area.

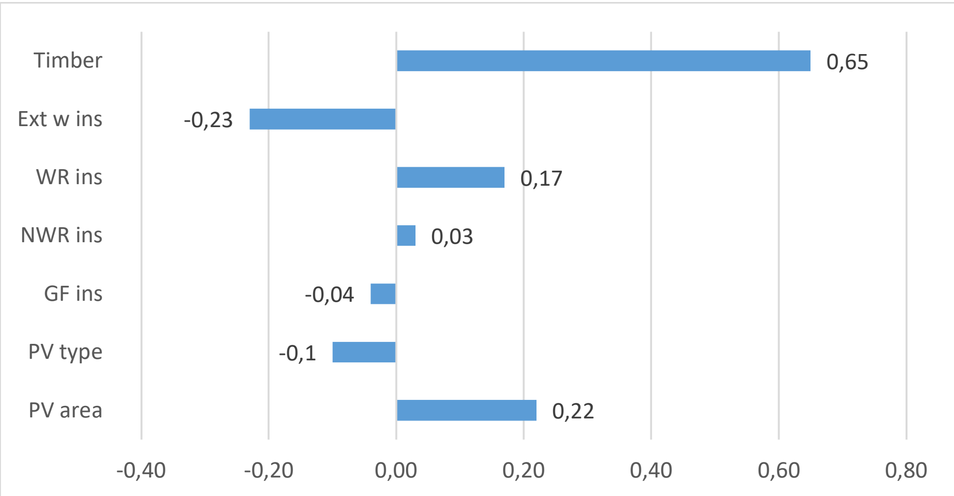


Figure 5-1: Life Cycle Carbon sensitivity analysis

As we expect, switching from CLT-glulam to LVL alternative increases remarkably the $LCCO_2$. Adding external wall insulation, on the other hand, decreases it significantly, as the additional embodied emissions are compensated by the reduced operational ones. The opposite occurs for roof insulations: adding more insulations increases the embodied carbon content more than higher thermal properties reduces the energy consumption, and thus operational emissions. Adding ground floor insulation has a slightly positive impact, as the embodied carbon content is zero. Finally, Poly-Crystalline PV panels have a positive impact, meaning that the lower embodied carbon compensates the lower energy produced, and thus the higher operational carbon. However, the opposite trend is observed for their area: the higher embodied carbon is not compensated by the lower operational emissions.

5.1.2 Difference in Life Cycle Cost

Figure 5-2 summarizes the SRC for the dLCC objective function. Ground floor insulation, PV panels area and timber technology are the most influencing parameters.

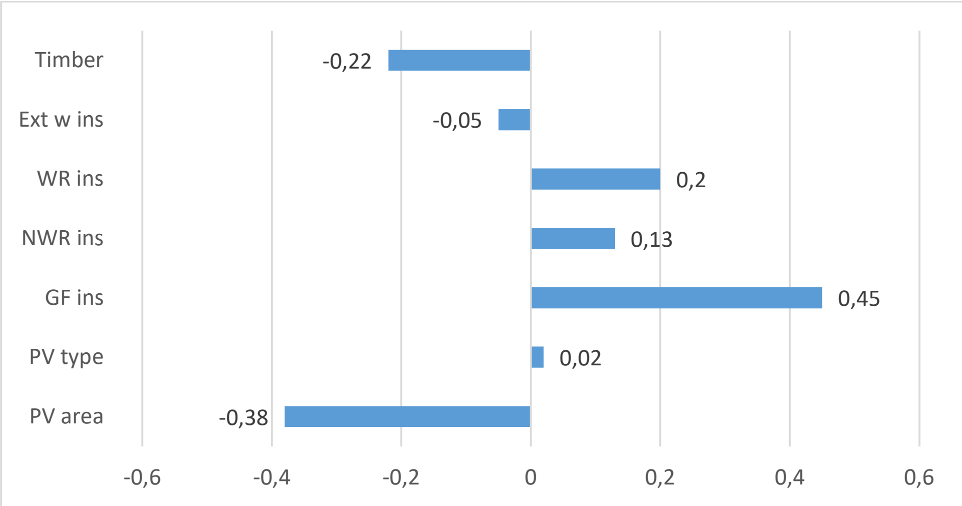


Figure 5-2: difference in Life Cycle Cost sensitivity analysis

As we expect, the LVL alternative has a positive impact in reducing the dLCC, due to the lower cost. Adding external wall insulation also contributes to decrease the objective function, as the higher initial investment costs are compensated by the lower energy use, and thus lower operational cost. On the other hand, increasing roof and ground floor insulations has a negative impact, suggesting that the higher initial cost is not compensated by the energy savings throughout the period of 20 years considered. Furthermore, shell insulation is significantly influencing negatively the dLCC, meaning that such a high cost is not justified by those low thermal properties. Finally, the initial savings of cheaper Poly-Crystalline PV panels actually lead to an overall higher dLCC, while the higher initial costs for additional area is compensated by lower operating costs.

To sum up, sensitivity the two sensitivity analyses allow to determine which are the most influencing parameters for each objective function, and how they influence them, the results are summarised in Table 5-1.

Table 5-1: Sensitivity analysis summary

Design variable	Cause	Effects LCCO$_2$	dLCC
Timber technology	CLT-glulam to LVL	↑ ↑ ↑	↓ ↓
External wall insulation - cellulose	increase thickness	↓ ↓	↓
W Roof insulation - foam glass	increase thickness	↑ ↑	↑ ↑
NW Roof insulation - mineral wool	increase thickness	↑	↑
Ground floor insulation - shells	increase thickness	↓	↑ ↑ ↑
PV panels type	Mono to Poly crystal	↓	↑
PV panels area	increase area	↑ ↑	↓ ↓

5.2 Uncertainty analyses

Uncertainty analyses are performed to evaluate the robustness of MOO results to low-reliable parameters, by changing these parameters' values, performing a new optimization, and finally comparing the original and the new results, as explained in section 3.7.2.

In total, six analyses are carried out over four parameters: timber material quantity for the LVL alternative is varied by +/-20%, lifespan considered is increased by 20 and 50 years, a green-energy mix is considered as energy supplied, and finally carbon data from manufacturers are replaced by only Ecoinvent-based data sources.

5.2.1 Timber material quantity

Figure 5-3 and Table 5-2 show the result of the MOO considering a quantity of timber 20% lower for the LVL alternative. This implies that LVL solutions are cheaper and have lower embodied carbon, thus they are all shifted down-left in the graph. More LVL solutions are present in the Pareto Front, among which there is also the best solution. By comparing it with solution C, the **LCCO$_2$ does not vary** significantly, while **LCC saving** are further decreased of **- 67%**, due to cheaper LVL.

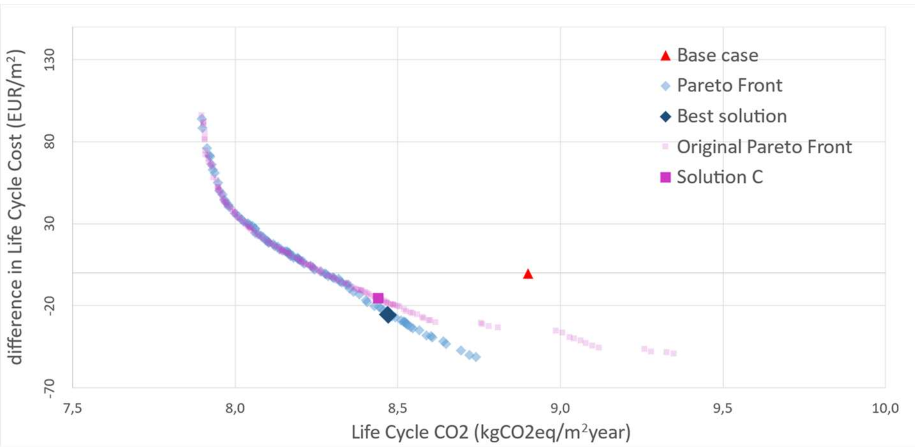


Figure 5-3: Uncertainty analysis MOO, timber -20%

Table 5-2: Uncertainty analysis results, timber -20%

	$LCCO_2$ ($kgCO_{2eq}/m^2year$)	dLCC (EUR/m^2)	Net site energy (kWh/m^2year)	Operational carbon ($kgCO2eq/m^2year$)	Embodied carbon ($kgCO2eq/m^2$)
Base case	8,91	0	21,93	4,09	240,39
Solution C	8,44	- 15,19	22,51	4,21	211,15
Best solution	8,47	- 25,38	22,89	4,28	209,55
	+ 0,36%	**- 67,08%**			

On the other hand, Figure 5-4 and Table 5-3 show the result considering a quantity of timber 20% higher for the LVL alternative. The trend observed is the opposite: the LVL solutions are more expensive and contain more embodied carbon, their "Pareto Front-like" distribution is thus shifted higher and towards the right, and none of them is present among the Pareto Front. The best solution is thus very close to the solution C, with a relative **increase** in **dLCC** of **1,65%** and a decrease in **$LCCO_2$** of **-8,37%**.

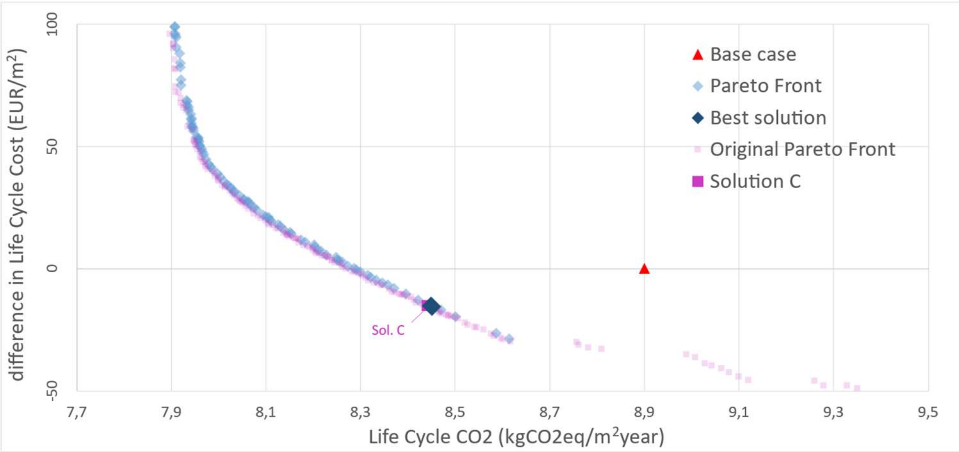


Figure 5-4: Uncertainty analysis MOO, timber +20%

Table 5-3: Uncertainty analysis results, timber +20%

	$LCCO_2$ ($kgCO_{2eq}/m^2year$)	dLCC (EUR/m^2)	Net site energy (kWh/m^2year)	Operational carbon ($kgCO2eq/m^2year$)	Embodied carbon ($kgCO2eq/m^2$)
Base case	8,91	0	21,93	4,09	240,39
Solution C	8,44	- 15,19	22,51	4,21	211,15
Best solution	8,45	- 14,94	22,25	4,16	210,42
	- 8,37%	**+ 1,65%**			

5.2.2 Lifespan

The two analyses on lifespan propose two alternative scenarios with both objective functions' lifespans increased by 20 and 50 years, thus being for dLCC and $LCCO_2$ 40 and 70 years, and 70 and 100 years, respectively. Increasing the service period causes a variation also in case study results, it is important to report them as the dLCCs are evaluated with respect to the new base case LCC value. The dLCCs of the original Pareto Front solutions, i.e. as described in section 4.1, are also adjusted with respect to the new base case LCC value.

Figure 5-5 and Table 5-4 report the results if we increase the lifespan of 20 years. This leads to a reduction in the $LCCO_2$ with respect to the original case, as the embodied carbon is spread over a larger period, while operational carbon is constant. On the other hand, as we can expect, the dLCC is higher than the original case, due to the higher operating and replacement costs. The best solution thus shows a significant decrease of **-13,6%** in **$LCCO_2$**, while the **dLCC** results **76,1% higher**.

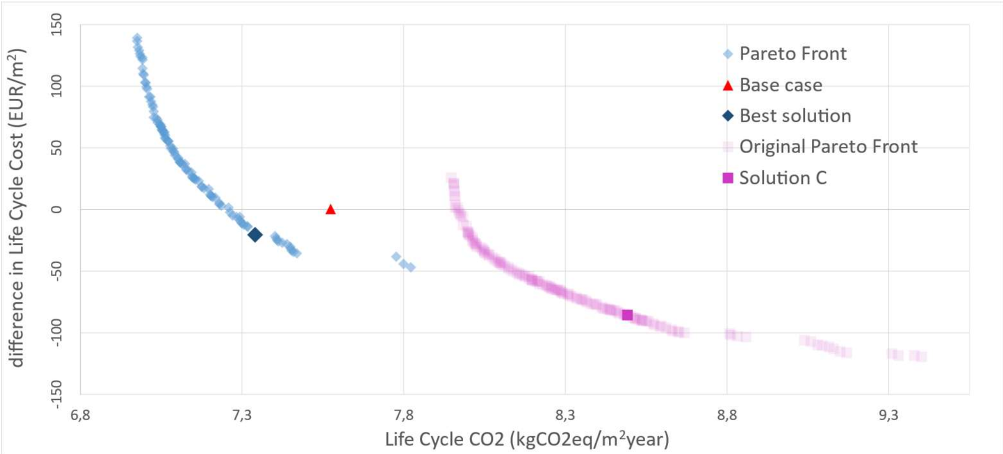


Figure 5-5: Uncertainty analysis MOO, lifespan +20 years

Table 5-4: Uncertainty analysis results, lifespan +20 years

	$LCCO_2$ ($kgCO_{2eq}/m^2year$)	dLCC (EUR/m^2)	Net site energy (kWh/m^2year)	Operational carbon ($kgCO2eq/m^2year$)	Embodied carbon ($kgCO2eq/m^2$)
Base case	8,91	0	21,93	4,09	240,39
Solution C	8,44	- 85,92	22,51	4,21	211,15
Best solution	7,25	- 10,30	22,14	4,14	224,51
	- 13,6%	**+ 76,1%**			

The same trends observed increasing the lifespan of 20 years, is reflected in Figure 5-6 and Table 5-5 for 50 years lifespan increase, with even greater magnitude. The best solution indeed shows a decrease of **-18%** in **$LCCO_2$** and an **increase** of **82,7%** in the **dLCC**.

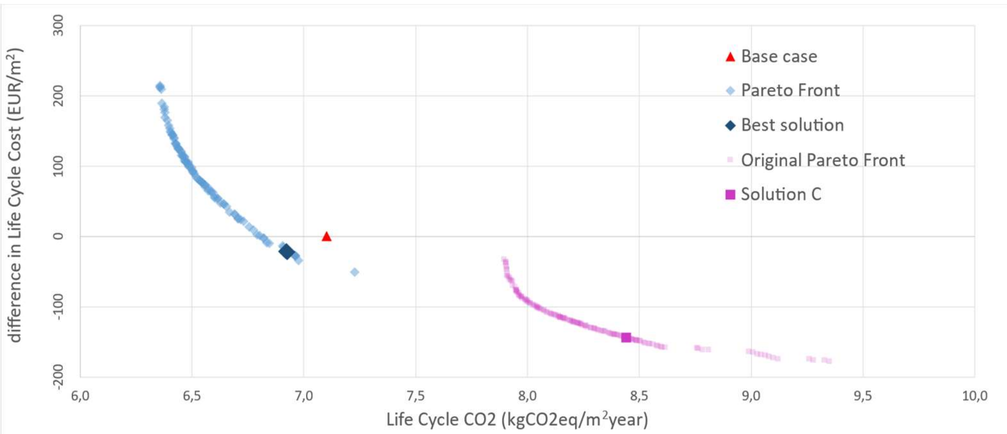


Figure 5-6: Uncertainty analysis MOO, lifespan +50 years

Table 5-5: Uncertainty analysis results, lifespan +50 years

	$LCCO_2$ ($kgCO_{2eq}/m^2year$)	dLCC (EUR/m^2)	Net site energy (kWh/m^2year)	Operational carbon ($kgCO2eq/m^2year$)	Embodied carbon ($kgCO2eq/m^2$)
Base case	7,10	0	21,93	4,09	301,01
Solution C	8,44	- 85,92	22,51	4,21	211,15
Best solution	6,92	- 22,23	21,50	4,02	290,59
	- 18,01%	**+ 82,70%**			

While the effects of lifespan on the $LCCO_2$ are relatively limited, causing only a variation in embodied and operational carbon shares, the influence on the dLLC is not negligible. These results thus confirmed the indication of the EPBD 2020 (EC, 2021a), which suggests not to exceed a period of 20 years for the lifespan in LCC analysis.

5.2.3 Carbon database

Figure 5-7 and Table 5-6 shows the results for the optimization run with more reliable carbon data sources. As we could expect from the comparison of carbon data in section 3.7.2, a general increase in the $LCCO_2$ can be observed, suggesting that manufacturers' EPDs might be too conservative. However, the opposite trend occurs for the LVL technology, which shows lower carbon content. It results with more than 80% of Pareto Front solutions having this construction technology. Its shape results skewer, with high cost CLT-glulam solutions being closer in terms of $LCCO_2$ with low cost LVL solutions, shifted downwards and to the right. The best solution selected shows a small **1% increase** in **$LCCO_2$** and a remarkable decrease of **dLCC** of **-60%**.

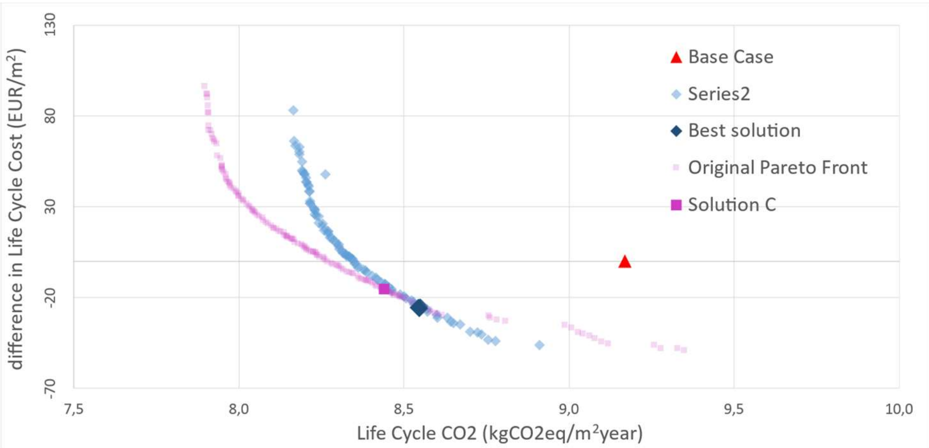


Figure 5-7: Uncertainty analysis MOO, Ecoinvent data source

Table 5-6: Uncertainty analysis results, Ecoinvent data source

	$LCCO_2$ ($kgCO_{2eq}/m^2year$)	dLCC (EUR/m^2)	Net site energy (kWh/m^2year)	Operational carbon ($kgCO2eq/m^2year$)	Embodied carbon ($kgCO2eq/m^2$)
Base case	9,17	0	21,93	4,09	254,00
Solution C	8,44	- 15,19	22,51	4,21	211,15
Best solution	8,55	- 24,36	23,05	4,31	212,41
	+ 1,30%	**- 45,38%**			

5.2.4 Energy mix

Figure 5-8 and Table 5-7 shows the results considering the green-energy mix scenario, with 100% sustainable delivered electricity, and thus negligible operational carbon emissions. The significantly lower $LCCO_2$, which now corresponds only to the embodied carbon, and the higher LCC can be observed, with the Pareto Front being shifted towards the left and upwards. Furthermore, it is interesting to see how the shape changed from a hyperbole to a straight line, resulting in a linear relation between the two objective functions. Analysing the design variables distributions, the parameters responsible for this variation are those related to the PV panels: low surfaces and poly-crystalline panels decrease the $LCCO_2$ at higher costs, while large areas and mono-crystalline panels lower the operational costs more than they increase the initial investment but lead to higher embodied carbon content. The best solution thus significantly **decreases** the **carbon content** of **-45%** with respect to Solution C, but at a **65% higher cost**.

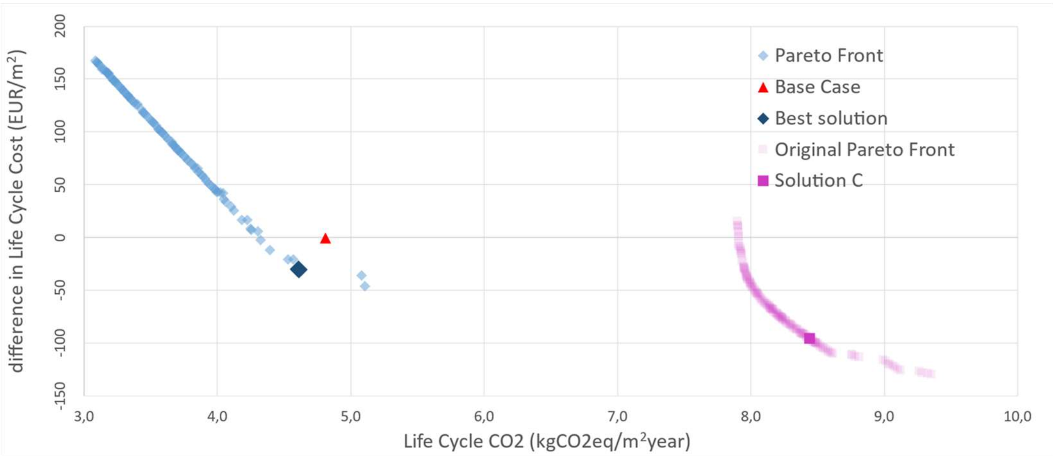


Figure 5-8: Uncertainty analysis MOO, green-energy mix

Table 5-7: Uncertainty analysis results, green-energy mix

	$LCCO_2$ ($kgCO_{2eq}/m^2year$)	dLCC (EUR/m^2)	Net site energy (kWh/m^2year)	Operational carbon ($kgCO2eq/m^2year$)	Embodied carbon ($kgCO2eq/m^2$)
Base case	4,81	0	21,93	0,00	240,39
Solution C	8,44	- 95,45	22,51	4,21	211,15
Best solution	4,61	- 30,89	22,59	0,00	230,49
	- 45,38%	**+ 67,64%**			

In conclusion, the energy mix results being the most uncertain parameter, causing a remarkable variation in both two objective functions. The second less reliable parameter is lifespan, with important variation in dLCC and significant changes in $LCCO_2$, too. Overall, $LCCO_2$ appears relatively stable, while dLCC is characterized by very high uncertainty, as shown in Table 5-8.

Table 5-8: Uncertainty analyses Hotspot table

Objective function	Timber Material Quantity - 20%	Timber Material Quantity + 20%	Lifespan +20 years	Lifespan +50 years	Carbon data source Ecoinvent	Energy mix 100% green energy
Life Cycle Carbon	+ 0,36%	- 8,37%	- 13,63%	- 18,01%	+ 1,30%	- 45,38%
d Life Cycle Cost	- 67,08%	+ 1,65%	+ 76,10%	+ 82,70%	- 60,37%	+ 67,64%

6 Discussion

This chapter enriches the discussion of results of chapters 4 and 5, analysing and interpreting them in the context of the research questions, objectives, and existing literature. The findings are thus summarized and best practices for the construction sector's actors are extrapolated from them. A critical evaluation of the results obtained, and the methodology used to get them is then articulated through strengths and limitations. Finally, implications for practice and future work provides an overview of how this work could influence society, economy, policymakers and suggests future steps for academics to further develop the topic.

6.1 Restatement of Study Purpose

Europe has answered the century challenge of climate change with the European Green Deal goals: 55% carbon emissions reduction by 2030 and carbon neutrality by 2050.

The construction sector, currently accountable for 36% of these emissions, has been framed with Energy Performance of Building Directive, calling for increase in energy performance and efficiency of the built environment. The first edition required all new buildings after 2020 to be Nearly Zero Energy; latest version has stricter requirements and makes Zero Emission Buildings compulsory for all new buildings from 2030.

However, as highlighted by the academics, aiming to maximum energy performance, thus decreasing operational emissions of a building, does not correspond to the most sustainable solutions. High-performance materials and products do indeed reduce the emissions during the use of the building, but at the same time carry higher production and disposal environmental cost, so called embodied carbon.

Life cycle assessment is an approach that considers both the two shares of emissions, from raw materials' extraction to end of life disposal. This method seems a more suitable solution to properly assess the environmental impact of buildings, and thus a more efficient answer in complying the EU Green Deal Goals. As France and Denmark have already implemented overall carbon emissions thresholds in their national regulations, we can expect this to be the direction also for next Directive updates, with ambitious goal of all new buildings to be Nearly Zero Carbon.

This thesis complies with current and future European directives, exploring with a simulation based multi-objective optimization nearly zero carbon buildings design solutions, such as innovative materials, passive strategies and renewable energy sources.

More than 23 million solutions are efficiently explored with the Evolutionary Algorithm NSGA-II. These alternative designs are obtained combining seven different variables:

- Structural timber: Glue Laminated Timber with Cross Laminated Timber and Laminated Veneer Lumber
- Insulations: bio-based cellulose for external walls, fiberglass and mineral wool for walkable and non-walkable roof, respectively

- Mono and Poly Crystalline PV panels with a total surface ranging from 0 to 344 m^2

The multi-objective optimization is performed on the first Belgian circular building, aiming to reduce simultaneously its environmental impact and cost, in terms of life cycle carbon and life cycle cost, respectively. The study of the design variables distributions in the optimal solutions, together with sensitivity and uncertainty analyses, allows to define the influence of each parameter on the objective functions, from which it is possible to provide best practice for the industry.

Recalling the research questions stated in section 1.4, it can be affirmed that simulation-based optimization proves to be a suitable methodology for the early-design phase of a building. The already cutting-edge case study was successfully optimized both in terms of environmental and economic cost, with a set of 51 trade-off solutions, ranging **from a reduction 7% of the $LCCO_2$** at the same cost, **to saving more than 63000 €**, with a reduction of 1% of $LCCO_2$.

6.2 Findings and Recommendations

In this section, the key findings derived from the analysis of the data collected in this study are presented. Additionally, based on these findings, we offer recommendations for future action or decision-making. These recommendations aim to address any identified challenges or opportunities and guide construction sector's actors towards supported solutions.

Analysing the results of the multi-objective optimization, including the best solutions and the distribution of design variables, alongside the findings of sensitivity and uncertainty analyses, leads to the following conclusions. It should be underlined that all these findings apply for the current year and for Belgium, and that they are influenced by the boundary conditions, as reported in section 3.6.

- The **trade-off** between the two competitive objective functions is characterized by a set of 153 design solutions. The **most sustainable** one has a $LCCO_2$ equal to **7,90 $kgCO_{2eq}/m^2year$**, a reduction of -11% with respect to the original design but has a **cost 96,14 €/m^2 higher** (185 000 €). The **cheapest solution** has a cost decrease of almost **-50 €/m^2** (-95 000 €), but also a carbon content of **9,35 $kgCO_{2eq}/m^2year$**, corresponding to an increase of +5%.
- Among this trade-off, **51 solutions optimize the case study** in terms of both objective functions, ranging from a reduction 7% of the $LCCO_2$ at the same cost, to saving more than 63000 €, with a reduction of 1% of $LCCO_2$.
- Considering all Pareto front solutions, **embodied carbon** accounts on average for **48% of total $LCCO_2$**. This result highlights the importance of integrate this share of total emissions to properly address the building environmental impact.
- Structural solution **glulam and CLT** has **cost 16% higher than LVL**, but an **embodied carbon** content slightly **lower than 50%**. In absolute terms these correspond to +16,17 €/m^2 and -0,49 $kgCO_{2eq}/m^2year$. The maximum differences in terms of $LCCO_2$ and dLCC of pareto front solutions are 145 €/m^2 and 1,45 $kgCO_{2eq}/m^2year$, thus the timber cost difference accounts for 12%, while the carbon difference for 34%. This leads to glulam and CLT being

dominant over most of LVL solutions, with 141 solutions in the pareto front against 12.

- Bio-based **cellulose insulation for external walls** is a very effective solution, as a thicker layer **decreases** both the **environmental impact and the life cycle cost**. Just by replacing the 23,5 cm of insulation with 80 cm, the case study can theoretically be optimized of 6% of its $LCCO_2$ saving 3,2 €/m^2. On the other hand, considering a more realistic value of 40 cm still results in 5% lower $LCCO_2$ at a cost of 1,6 €/m^2 less.
- High-performance but low-sustainable **insulation materials for roof**, such as mineral wool and foam glass, **should be minimized**, as they increase both $LCCO_2$ and LCC. Just by replacing the 14 cm of walkable and non-walkable roof insulations with 6 cm and 12 cm, respectively, the case study can theoretically be optimized of 5% of its $LCCO_2$ saving 7,0 €/m^2.
- **Bio-based shell insulation** for ground floor is **not an effective solution**, as a larger thickness of this layer results in higher $LCCO_2$ and LCC. Just by replacing the 60 cm of insulation with 20 cm, the case study can theoretically be optimized of 5% of its $LCCO_2$ saving 22,6 €/m^2.
- **Poly-Crystaline PV panels** show a **positive environmental impact** but at overall **higher cost**. Replacing just Mono-crystalline PV panels in the case study results in a decrease of 7% of its $LCCO_2$, at a cost higher of 3,45 €/m^2.
- Decreasing the surface of PV panels results in a more sustainable but more expensive solution, too. Removing the 344 m^2 of PV panels from the case study results in a decrease of 9% of its $LCCO_2$, at a cost higher of 89,7 €/m^2.
- Among the considered design variables, **timber technology is the one that influences $LCCO_2$ the most**. On the other hand, **shell insulation is the most accountable for LCC**.
- **Energy mix** plays a **key role in** influencing the **optimization results**, acting both on operational emissions and costs. This finding is particularly influenced by the grid carbon emissions. In low carbon emitting grids, like nuclear-dominated Belgian ones, PV panels do not represent a sustainable solution. In higher carbon emitting grids, like Italian ones which is three time as polluting as Belgian, all Pareto front solutions tend to maximize PV panels.

These findings can be translated into best practices to be provided to the industry professionals. However, due to the very high dependency of the results on the input parameters, and due to the very high fluctuation of these parameters' values, the results themselves should not be accepted and applied as absolute (Hamdy et al., 2017). Therefore, the advice is to implement the whole process in the early-design phase, tailoring and updating each variable of the specific project, both fixed and dynamic. This procedure ensures the maximum reliability of the results, together with a wide set of design trade-off alternatives to be evaluated according to the client's preferences.

Nevertheless, the following advices should be considered by Belgian professionals who are designing three-storey timber office buildings of approximately 2000 m^2 in the current year:

- **Glulam and CLT** solution is **generally** to be **preferred over** the **LVL** alternative. However, in case of reduced budget, the latter can be chosen for a cheaper but less sustainable solution.

- Employ and **maximize** as much as possible **cellulose** for **wall insulations**, **reducing** high-performance but low-sustainable **roof insulations** to the minimum value that ensures thermal comfort.
- **Avoid** bio-based **shell insulations**, as its low thermal properties are not worth the price.
- **If** the client's **priority** is limiting the **cost**, implement **large areas of high-efficiency mono-crystalline PV panels**, as the initial investment cost is repaid by the reduction in energy bills.
- On the other hand, **if** the **priority** is to achieve the lowest possible **environmental impact**, **small areas of low-efficiency poly-crystalline PV panels** are better solutions. The components' embodied carbon is not compensated by the reduction in operational carbon, as the Belgian grid is already characterized by a low emissivity.

6.3 Strengths and Limitations

Hereby, the strengths and limitations of the methodology employed in this study are critically examined. Their evaluation is essential to properly assess the reliability of the research findings. Identifying the strengths allows us to comprehend the methodological suitability and potential contributions of the study. On the other hand, pointing out the limitations provides insights into the boundaries and constraints that may influence the interpretation and generalization of the results, as well as suggesting future steps.

The main strength of this work is the development of a replicable methodology to optimize design proposals in early-design phase, considering both the economic and the environmental cost. This procedure is not only aligned with European and National directive and standards, but also potentially to future updates. Indeed, it builds upon Hamdy's work (Hamdy et al., 2011), which is already consistent with EPBD 2020, integrating it by considering not only the operational phase for GHG emissions, but the whole life cycle. Furthermore, the method is validated in this work by its successful application on an already state-of-the-art design, resulting in 51 optimized solutions which comply with current and future regulations.

The framework is also characterized by high flexibility, as it can be easily applied to other case studies, allowing further validation of the methodology itself and comparison of the results obtained. The replicability is also characterized by relatively easy customization, as all objective functions and design variables can be changed according to the researcher's or the professional's needs.

Finally, including timber structural technology among the design variables represents an advantage for this work. The new engineered timber materials are very likely to become of paramount importance in the near future, as their negative biogenic carbon content is the only one capable of complying with environmental standards, as witnessed by the French industry.

On the other hand, the main limitation of this work is the lack of assessment of thermal comfort, which strongly influences the results. Thermal comfort refers to the state based on each individual subjective feeling of how comfortable they feel in the occupied thermal environment, i.e. the building. Ensuring thermal comfort means that the space is perceived as neither too hot nor too cold, and this is an essential condition for occupants' well-being and productivity. The influence of this lack is evident in Pareto front solution insulations' thickness distributions, which maximize cellulose thickness in external walls, and minimize mineral wool and foam glass on roofs. Overall, the heat transfer is balanced, with high roof thermal transmittance compensated by low walls' one; but actually top floors' spaces are constantly excessively exposed to outdoor conditions. In thermal comfort terms this results in the indoor environment being too cold in winter and too hot in summer, thus forcing occupants to mitigate the discomfort with additional HVAC. This system overwork is not considered in the calculations, thus the operational energy, and therefore the operational costs and carbon, too, are lower than their real values.

Thermal inertia is a second factor not considered in this work, which influences the results in a similar way to thermal comfort. Thermal inertia is a property of envelope components related to dynamic heat transfer, describing how quickly each enclosure part will heat up or cool down in response to changes in external temperature conditions. In other words, it quantifies the capacity of each element to shift in time the heat transfer, by temporarily storing the heat in its own mass and releasing it after. Thermal inertia of a building is linearly dependent on the thermal mass, which is the total amount of heat that can be stored, likewise, thermal mass is dependent on the component mass. Unlike traditional construction, with thermal mass provided by heavy masonry or concrete, prefabricated frame timber external walls with cellulose insulation, are characterized by a very light weight, and thus little thermal inertia (Verbeke & Audenaert, 2018). This results in higher risk of overheating, thus higher energy demand due to additional HVAC to compensate for the thermal discomfort (Rodrigues et al., 2016). Once again, as this overwork is not considered, the results have values which are lower than reality.

Another flaw is the evaluation of carbon emissions in the C phase. As described in section 3.6.3, each material is disposed in a different way, according to the scenarios provided by each EPD. These scenarios do not correspond to the actual disposal strategy that the building components will undergo in the future years, thus the results are not accurate. Carrying a proper life cycle assessment for the case study would certainly lead to more reliable results. However, as LCA can be time consuming and beyond the resources, integrating a parametric LCA model of End-of-Life scenarios, such as the one developed by (Quéheille et al., 2022), could increase the reliability of this methodology results.

Furthermore, the data uncertainty related to carbon and cost is an important factor affecting the precision of results. Carbon data sourced from manufacturers' EPDs, as highlighted previously in section 3.7.2, can be significantly biased, with industry-favorable values. On the other hand, cost of design variable and economic related fixed inputs are extremely fluctuating due to a variety of external factors. Two examples are energy prices after 2022 Ukraine invasion and the solid timber market, with prices that doubled from January 2021 to September 2022, and now are almost halved again (Baltpool, 2023). A more reliable database, constantly updated with geo-located and time-referenced research market, would highly increase the correctness of the cost results. On the other hand, to increase the accuracy of carbon results, it is suggested to conduct proper LCA based on internationally recognized database, such as Ecoinvent.

Finally, the last limitation of this framework is related to the high computational cost. First, approximately 6 hours were required to complete the optimization (4000 simulations) using the powerful workstation described in section 3.5.6. Such a hardware is rarely available in design companies, thus the computational time may not be insignificant. Second, the parametric model is based on the building energetic model that was already available at the Lab, saving a significant amount of time for the procedure. It is true that design firms develop their own BEM, however this may result in additional costs and time, especially if different shape and geometric design proposals want to be evaluated. Third, time was saved also on the $LCCO_2$ computation, as the case study had already been evaluated at the Lab. Analogously to BEM development, performing a complete LCA from scratch can incur additional cost and time, ensuring more reliable results, however.

6.4 Implications for practice and future work

This thesis results underline the importance of considering the whole life cycle of a building when assessing the environmental impact. Therefore, operational emissions should be integrated with the embodied share, as they account on average around 48% of the total. This translates into two suggestions for policy makers. First, they should reflect on implementing the life cycle approach, as current regulations which consider only the operational emissions may not be enough to satisfy the EU carbon goals. Second, actions should be taken to make grids more sustainable, as operational of high-performance building still accounts for half of the total emissions. Furthermore, more resources should be dedicated at European level to Life Cycle Assessment. The current practice, as described in EN 15804 and EN 15978, leaves too much space for interpretation to the practitioner, such as phases considered, system boundaries, different scenarios, which strongly impacts the overall results, their comparison and thus the whole methodology validity.

Another important reflection should be done on what happens at End of Life of timber. Currently, only 31% of wood waste from the construction sector is recycled, the remaining 69% is either landfilled or burnt for energy recovery (EC & bio intelligence service, 2020). On a long-term perspective, continuing with this practice means that we are not actually reducing carbon emissions, we are just delaying them in time, as after 75 to 100 years of building life, the majority of carbon absorbed and stored in the material is released back into the atmosphere. Policymakers should therefore act to reverse this practice, increasing the share of recycling over energy recovery and landfill.

In addition to the environmental benefits, timber shows many potential advantages for a shift towards Lean construction. Prefabrication ensures manufacturing quality that would not be achievable on a construction site, and significantly reduces construction time with respect to traditional construction. Timber is also advantageous in terms of life cycle cost, as timber building designs are estimated to be more than 20% cheaper than their concrete alternative, with higher initial cost compensated by end-of-life demolition savings (Gu et al., 2020). However, the industry is still reluctant to embrace this technology, especially for taller buildings, with main concerns regarding fire and structural safety. In terms of structure, designers are hindered by timber sensitivity to moisture, low stiffness, brittle behaviour and creep (Voulpiotis et al., 2021). Fire safety is also a major concern, with countries changing their regulations either to make timber construction easier (US, France, Switzerland) or to make it tougher (UK). Experts warn that the consequences of a fire in a timber building can be more severe than in a concrete or steel construction, as the wood structure and the facades could become a source of fuel, speeding and spreading the fire (Barker, 2023). Due to the novelty of timber engineered materials, and thus lack of sufficient data, there is a limitation to the understanding of the complexity related to using wood. Finally, other sector concerns are related to low thermal mass, as discussed in previous section, low acoustic insulation and high sensitivity to moisture, thus faster degradation and higher maintenance required.

In conclusion, timber construction proofs to be an efficient answer for the construction sector to reply to the environmental challenges. Policy makers should therefore take actions to encourage its use. Developing supporting regulations, including updating building codes, together with investing in research and development, can help to address the major challenges of this material. Furthermore, providing incentives, education, and training can encourage the sector to embrace this technology, filling the gap for the higher initial costs and missing skills required. Finally, collaborating with industry stakeholders, promoting communication and cooperation, such as COST Action HELEN for tall timber building design, can help address its barriers, identify its opportunities, and develop solutions to them.

As highlighted by the limitations expressed in the previous section, the following steps are suggested future work to improve this thesis methodology and results validity.

First, integrating thermal comfort into the simulation and optimization is the most advisable step to start with. This could be done by imposing in the optimization some constraint conditions, such as defined by ASHRAE standard 55, which discard the solutions for which these conditions are not satisfied. A very trivial evolution of this work can be achieved by integrating new design variables. Already for this work glazings, shadings, air tightness and heat recovery unit were added, but then discarded for lack of cost and carbon data. Other options can be to include internal components, options for green roofs and walls, to explore different systems, or renewable energy sources. It would also be very interesting to expand the timber technologies and materials. Keeping the same structural typology, i.e. post and column, CLT slabs could be replace by its alternatives Dowel Laminated Timber and Nailed Laminated Timber, as well as different combinations of materials used, such as LVL columns with CLT slabs, or glulam columns and LVL slabs. In terms of structural typology, considering a wall load-bearing structure could expand the choice to full CLT solid panels structure, full LVL panels structure, as well as frame panels structure. Finally, considering the full life cycle cost of the building, instead of the difference with respect to the original design, could produce very useful data to inform about nearly zero carbon timber buildings and set benchmarks for comparison with traditional construction.

7 Conclusions

Europe has set the goals to decrease carbon emissions of 55% by 2030 and achieve carbon neutrality by 2050. The consequence on the construction sector, which is responsible for 36% of total emissions, was the enforcement of the Energy Performance of Building Directive. The latest version, EPBD 2020 recast, set the requirement for all new buildings to be Zero Emission Buildings by 2030. ZEBs are a building that have very high energy efficiency and compensate completely their low operational greenhouse gas emissions with renewable sources.

However, we can expect stricter requirements for the next decade, such as mandatory nearly-Zero Carbon Buildings. NZCB considers the whole life cycle emissions of a building, thus also embodied ones, related to the products manufacturing, maintenance, and disposal. Traditional construction, such as concrete and steel, carry extremely high life cycle carbon, thus will likely not meet future requirements. One solution are bio-based materials, such as timber.

Therefore, this work was developed to answer to the following question:

How far can we optimize the design of a building to reduce its carbon impact at the lowest economic cost?

To reply to the question, a simulation-based multi-objective optimization methodological framework was developed. The MOO problem was defined by seven design variables: timber technology, four insulation thicknesses, and two PV panels parameters, which combined created more than 23 million solutions. The Non-dominated Sorting Genetic Algorithm II was used to efficiently explore the set of solutions aiming at the two competitive objectives: reducing life cycle caron and life cycle cost. Sensitivity analyses on the two objective functions and six uncertainty analyses were performed to validate the model.

Applied on a case study, the procedure managed to produce a set of trade-off solutions, and successfully optimized the base case study.

- 153 design solutions were obtained, with the **most sustainable** one **reducing $LCCO_2$ by 11%** (7,90 $kgCO_{2eq}/m^2year$) at cost 96,14 €/m^2 higher (185 000 €), and **the cheapest reducing cost by -50 €/m^2** (-95 000 €), but at 5% higher emissions (9,35 $kgCO_{2eq}/m^2year$).
- Among this trade-off, **51 solutions optimize the case study** in terms of both objective functions, ranging from a **reduction 7% of the $LCCO_2$ at the same cost**, to **saving more than 63000 €, with a reduction of 1% of $LCCO_2$.**
- Considering all Pareto front solutions, **embodied carbon** accounts on average for **48% of total $LCCO_2$**. This result highlights the importance of embodied carbon share in environmental impact of buildings.

As the results are highly dependent on the inputs, which are highly fluctuating, the results themselves should not be accepted and applied as absolute. The recommendation to professionals is to apply the developed methodology for they own case. The replicability of this framework is itself the main strength of the work, as it allows high flexibility to customize parameters. Further applications will help in the model validation, too. The main limitations are instead linked to the absence of thermal comfort and thermal inertia integration, together with data uncertainty of cost and Environmental Product Data carbon information. Future works should focus on the integration of a thermal comfort constrain condition, as well as thermal inertia in calculations. Furthermore, additional design variables should be implemented, such as different timber material and technologies, or other building’s components and systems.

In conclusion, this works contributes to the industry embracing of timber construction systems in the future decades, by highlighting the importance of embodied carbon and providing a tool to enhance the feasibility of Nearly-Zero Carbon Buildings, in line with European Goals and potentially future European Directive. At the same time, also arises the request to policymakers for a clearer Life Cycle Assessment methodology, especially regarding scenarios of End of Life and Recycling stages.

8 References

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Annex 1: Tables

Table 8-1: Multi-objective optimization Literature Review Matrix

No.	Reference	Design Variables	Objective functions	Optimization strategy	Limitations	Findings
1	Hamdy et al. (2013), "A Multi-Stage Optimization Method for Cost-Optimal and Nearly-Zero-Energy Building Solutions in Line with the EPBD-Recast 2010."	Insulations (external walls, roof, floor) Air tightness level Windows types Shading options Heat recovery unit Cooling Options Primary heating systems Solar thermal panels PV panels	Primary energy consumption Difference in Life Cycle cost Overheating risk condition Single family house, Finland	Multi-stage optimization: - best passive solution - Heating and cooling - RES integration Variant of NSGA-II	Complies with older version of EPBD Considers only PEC No environmental impact considered	Cost-optimal solutions at 47% lower PEC than standards Solar thermal not cost-optimal Mechanical cooling not cost-optimal Viable to achieve nZEB with PEC up to 70 kWh/m2year
2	Harkouss et al. (2018), Multi-objective optimization methodology for net zero energy buildings.	Insulations (external walls, roof) Windows types Cooling and Heating setpoints WWR Solar thermal panels PV panels	Different climatic zones in France and Lebanon, Single family house PMV constrain condition Thermal demand Electrical demand Life cycle cost	Multi-criteria optimization (MOBO) NSGA-II Decision making technique to chose optimal solution (ELECTRE III)	LCC considers only design variables Only energy considered, not emissions	Minimize thermal load through passive strategies Cover remaining energy demands with RE Focus on air conditioning set points control, for occupants comfort
3	Wu et al. (2018), A multi-objective optimization design method in zero energy building study: A case study concerning small mass buildings in cold district of China.	Envelope components RES	Life Cycle energy Life cycle cost Prototype residential, China	NSGA-II	dLCC	Methodology development
4	Delgarm et al. (2016), "Multi-Objective Optimization of the Building Energy Performance."	Building orientation Shading options Window size Windows types Wall material properties	Heating Cooling Lighting Total annual demand Single room, 4 climate of Iran	Particle swarm optimization MOPSO algorithm	Single room only No cost consideration Thermal comfort Environmental impact	Cooling decrease of 20-33 % Heating increased 2-5% Electricity increased 0,5-3% Total 1-11% electricity demand
5	Hamdy et al. (2011), Applying a multi-objective optimization approach for Design of low-emission cost-effective dwellings.	Insulations (external walls, roof, floor) Air tightness level Windows types Shading options Heat recovery unit Heatin/cooling system	Carbon emissions Investment cost Single family house, Finland Overheating risk condition	Three cases of thermal comfort optimization PR_GA_RF genetic algorithm	Considers only operational phase for environmental Considers only initial investment for economic	Case study optimized of: 32% emissions and 26% investment cost Heating system most influent Heat recovery good solution Cooling systems and shading required for overheating thermal comfort
6	Fesanghary et al. (2012), Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm.	Building envelope roof, ceiling, floor, foundation, walls and windows	Life cycle cost Life cycle carbon Single family house, USA	HS (Harmony Search) algorithm	Only envelope as design variable LCCO2 and LCC only for design variable parameters	Foundation has highest GWP Operative phase accounts on average for 85% of total emissions

7	Xue et al. (2022), Multi-objective optimization of building design for life cycle cost and CO2 emissions: A case study of a low-energy residential building in a severe cold climate.	Insulation (Wall, roof) Windows types WWR Shading options Building orientation	difference Life cycle cost Life cycle carbon Residential building, cold climate China	NSGA-II	LCCO2 based on emissions factors End of life not considered	10 to 18 % reduction in LLCC and 13 to 22% reduction in LCCO2 Optimization improved building performance reduce wall and roof insulation thickness Optimal orientation 0-6° from S to E Heating load reduced of 75%, cooling load of 40%
8	Ciardiello et al. (2020), "Multi-Objective Approach to the Optimization of Shape and Envelope in Building Energy Design."	Shape Shape proportion WWR orientation Windows types Insulation thickness (wall roof floor) External layer optic properties Sunspaces and greenhouses Shading options Number and tilt angle of PV and thermal panels	Total energy demand Life Cycle cost (initial + annual) Operational Carbon emissions	Two phase optimization: - geometry - passive and active strategies NSGA-II	Results are specific, not absolute Non-user friendly tool Only operational phase considered for LCCO2	Framework with 2 phases for new construction and retrofitting 60% energy saving with geometry optimization CO2 reduced of 23% with second optimization
9	Diakaki et al. (2010), A multi-objective decision model for the improvement of energy efficiency in buildings.	Insulation thickness (wall roof floor) Envelope type (wall roof floor) Windows and doors types Heating, cooling, DHW systems Solar collector	PEC Carbon emissions Initial investment cost Single family house, Greece	Building retrofit Analytic approach	Analytic approach, non-simulation based Only operational phase considered for LCCO2 Only initial phase considered for LCC	Design variables are combined critically No need to be integrated with other method, such as GA Simplicity of the model
10	Ascione et al. (2015), "A New Methodology for Cost-Optimal Analysis by Means of the Multi-Objective Optimization of Building Energy Performance."	Roof solar absorption Insulation thickness (wall roof) Mechanical ventilation Cooling and Heating setpoints Windows types Heating and cooling systems	PEC Thermal discomfort Initial investment cost Apartment, Italy	Variation of NSGA II EnergyPlus + Matlab building retrofit Different budget scenarios	No RES No life cycle considerations	Retrofit evaluation framework 6 retrofit cost-optimal packages for each budget

Table 8-2: Timber buildings environmental comparison Literature Review Matrix

No.	REFERENCE	Case study & alternatives	Software and Data sources	Boundary conditions	Limitations	Findings
1	Liang, Gu, and Bergman (2021), "Environmental Life-Cycle Assessment and Life-Cycle Cost Analysis of a High-Rise Mass Timber Building."	12 storey mix use building, US Concrete construction Post-and-column (GLT + CLT)	TRACI methodology Athena's Life Cycle Inventory Database DATASMART SimaPro LCA software	60 years lifespan Cradle-to-grave (A to C) Electricity, gas and water for B phase	Values of operational carbon disagreeing with other literature	Timber has 53 kgCO2eq/m2year Concrete has 54 kgCO2eq/m2year Over 90% GHG emissions due to operational phase Timber 17% lower embodied carbon Timber 9,6% more expensive than concrete, due to higher material cost
2	Chen et al. (2021), "Comparative Life Cycle Assessment of Mass Timber and Concrete Residential Buildings."	8 storey residential building, China Concrete construction Wall load bearing mass timber (CLT)	SimaPro LCA sofware USEI database Ecoinvent	Cradle-to-gate (A) Only floors, foundations and walls considered Biogenic carbon neglected	No operational phase End of life phase No cost consideration	Timber has 25% lower GWP than concrete, due to lower material quantity, despite higher travelled distance
3	Puettmann et al. (2021), "Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration."	8, 12, 18 storey buildings, 3 areas of US Concrete and steel construction Mass timber construction (glulam + CLT)	CORRIM US life cycle Inventory Database Ecoinvent 3 LTS DataSMart SimaPro LCA software	Cradle-to-gate (A) 50 years lifespan Biogenic carbon neglected	Only pre-use carbon considered No cost consideration	Carbon reduction of 22-50% with timber Differences due to three regions considered Timber stores more carbon than used 90% carbon due to manufacturing (A1-A3)
4	Allan and Phillips (2021), "Comparative Cradle-to-Grave Life Cycle Assessment of Low and Mid-Rise Mass Timber Buildings with Equivalent Structural Steel Alternatives."	5 storey office building, 12 storey residential building, US Post-and-column (GLT + CLT) Steel construction	TRACI methodology Athena's Life Cycle Inventory Database EPDs	Cradle-to-grave (A to C) B phase not considered D scenario included Biogenic carbon neglected 60 years lifespan	No operational phase No cost consideration	31-41% lower GWP for timber With D included, timber close to zero carbon, excluding operational Timber has higher smog potential Timber has higher ozone depletion potential Timber has higher acidification potential
5	Al-Obaidy, Courard, and Attia (2022), "A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint."	Office building, Belgium Mass timber construction (glulam + CLT) Steel construction Concrete construction Hybrid construction	OneClick LCA plug in Revit (BIM) TOTEM tool indicators MMG method EPDs	20 years lifespan Cradle-to-cradle (A to D) D 100% reuse scenario	No cost consideration OneClick reuse is poorly developed Case study is going to be dismantled and reassembled at 20 m distance, as a prototype cannot really be compared	Timber construction carbon emissions three times lower than concrete and hybrid, four times lower than steel Operational stage most accountable for carbon emissions
6	Lolli, Fufa, and Kjendseth Wiik (2019), "An Assessment of Greenhouse Gas Emissions from CLT and Glulam in Two Residential nZEBuildings."	nZEB residential , Sweden and Norway 9 storey CLT-concrete 8 storey GLT-concrete	EPD Norway EPD Environdec Swedish	100 years lifespan Cradle-to-gate (A1-A3) Energy use (B6) Average emission factor considered	No cost consideration Embodied carbon only manufacturing Systems not considered	CLT highest carbon reduction, replacing structural concrete (stairs, elevator shaft) Electricity grid 8 times more polluting then district heating CLT floors lower emission than glulam

7	Balasbaneh and Sher (2021), “Comparative Sustainability Evaluation of Two Engineered Wood-Based Construction Materials.”	Single family house, Malaysia Wall load bearing mass timber (CLT) Post-and-column mass timber (GLT) Hardwood and softwood	SimaPro LCA software Ecoinvent 3.1	Cradle-to-cradle (A to D) B only maintenance Not reuse scenario for D 50 years lifespan	Emissions related to building operation (energy use) not considered	CLT 7% more expensive than GLT CLT 40% lower emissions than GLT Softwood less environmental impact than hardwood
8	Dodoo, Gustavsson, and Sathre (2014), “Lifecycle Carbon Implications of Conventional and Low-Energy Multi-Storey Timber Building Systems.”	Multi-storey timber buildings, Sweden Wall load bearing mass timber (CLT) Prefabricated volumetric light-frame (LWT) Post-and-column mass timber (GLT and LVL)	Ecoinvent 2.2 VIP+	50 years lifespan Cradle-to-grave (A to C) A4-A5 calculated as 4% A1-A3 90% recovered recycled for C Biomass fuel for electricity	No cost consideration	CLT 9% LCCO2 saving wrt traditional GLT and LVL 8% LCCO2 saving wrt traditional, 36% more concrete used Volumetric LWT 9% LCCO2 saving wrt traditional Production stage largest share of emissions
9	Lu, El Hanandeh, and Gilbert (2017), “A Comparative Life Cycle Study of Alternative Materials for Australian Multi-Storey Apartment Building Frame Constructions.”	4 storey residential building, Australia LVL hardwood LVL mature hardwood LVL softwood Concrete construction Steel construction	SimaPro LCA software Primary Data Data from literature and LCI databases	Cradle-to-cradle (A to D) B phase not considered D module: timber energy recovery, steel recycled, concrete landfilled 60 years lifespan Only beams, columns and connections considered Life cycle cost	No operational phase Only structural LCCO2 and LCC assessed Data source	LVL hardwood lowest GWP and LCC, less than 25% of concrete construction LVL higher Human Toxicity Potential than steel for glue LCC of LVL lower due to labour and production cost Concrete lowest LCCO2 and LCC scores
10	Dodoo (2019), “Lifecycle Impacts of Structural Frame Materials for Multi-Storey Building Systems.”	4 storey residential building, Norway Light-frame timber (LWT) Reinforced concrete frame Wall load bearing mass timber (CLT) Post-and-column timber (GLT and LVL) Volumetric modular timber (LWT)	Ecoinvent 3.0 EPDs	Cradle-to-grave (A to C) D module included 50 years lifespan	D module considered in calculations No cost consideration	District heating lower emissions than heat-pump Timber based solutions have 4-18% less primary energy for production Timber based solutions have39-51% less GHG emissions for production Timber solutions benefits of biomass residue recovery Recovered energy content higher than production and construction for timber District heating lower emissions than heat-pump

Table 8-3: Timber variable, column design

Material	Width [mm]	Height [mm]	Area [cm^2]	$f_{c,0,k}$ [Mpa]	$R_{c,0,k}$ [kN]	Reduction factor	Tot volume [m^3]	Cost [€]	Embodied Carbon [$kgCO_{2eq}$]
Glulam	260	260	676	24	1623	-	26,68	18676	2940,03
LVL	225	225	506	35	1772	0,75	19,98	15684	8086,31

Table 8-4: Timber variable, beam design

Material	Width [mm]	Height [mm]	J_{yy} [cm^4]	$f_{m,0,k}$ [Mpa]	$R_{m,0,k}$ [kNm]	Reduction factor	Tot volume [m^3]	Cost [€]	Embodied Carbon [$kgCO_{2eq}$]
Glulam	260	480	239616	24	240	-	72,31	50617	7968,27
LVL	225	480	207360	35	380	0,87	62,57	49117	25323,33

Table 8-5: Timber variable, slab design

Material	Thickness [cm]	Area [m^2]	Thermal R [m2K/W]	Tot volume [m^3]	Cost [€]	Embodied Carbon [$kgCO_{2eq}$]
CLT	16	25	1,17	307,48	164502	33671,52
LVL	314	25	1,37	154,35	136600	58764,13

Annex 2: Results

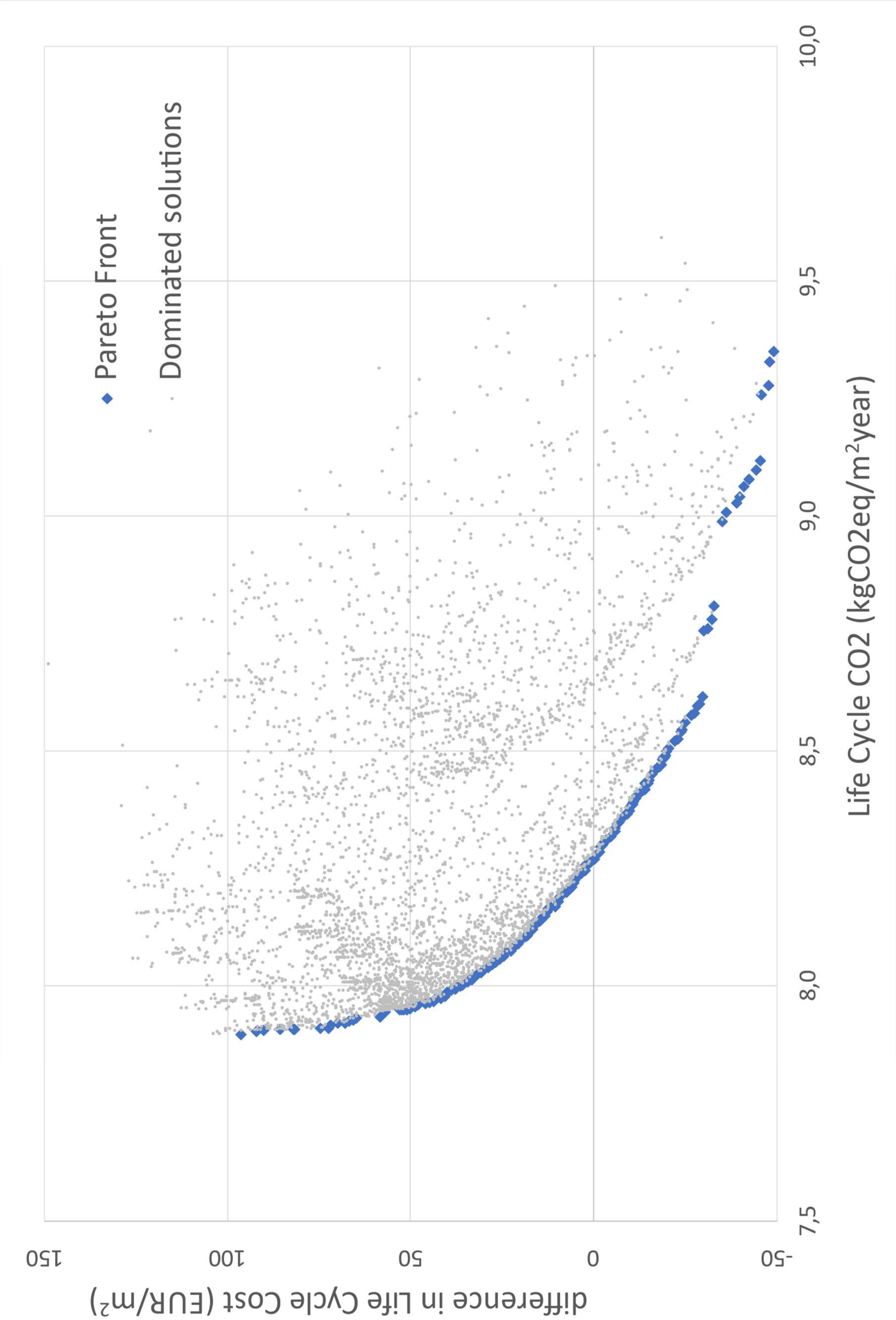


Figure 8-1: Multi-objective optimization results

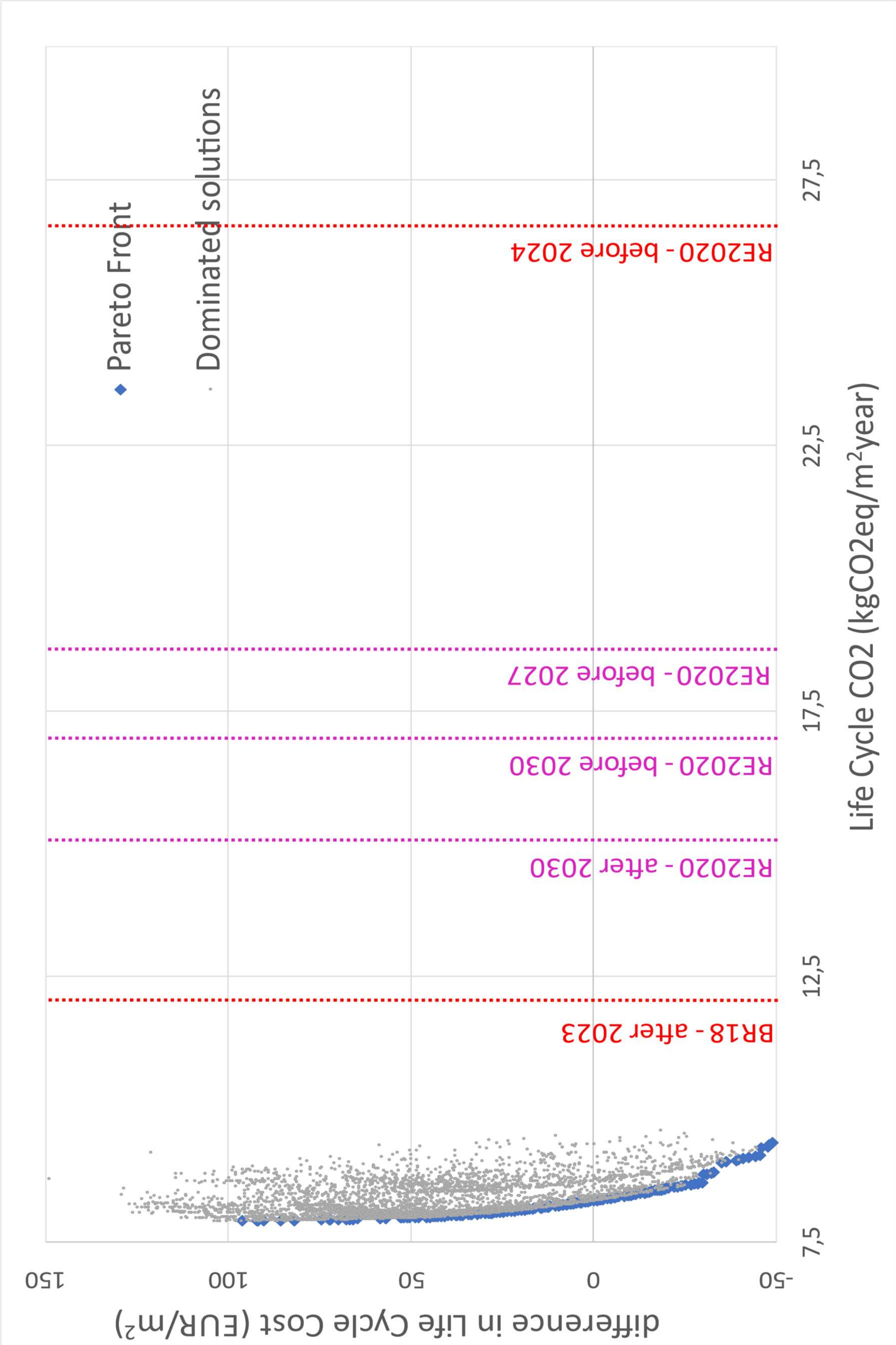


Figure 8-2: MOO results comparison with regulations

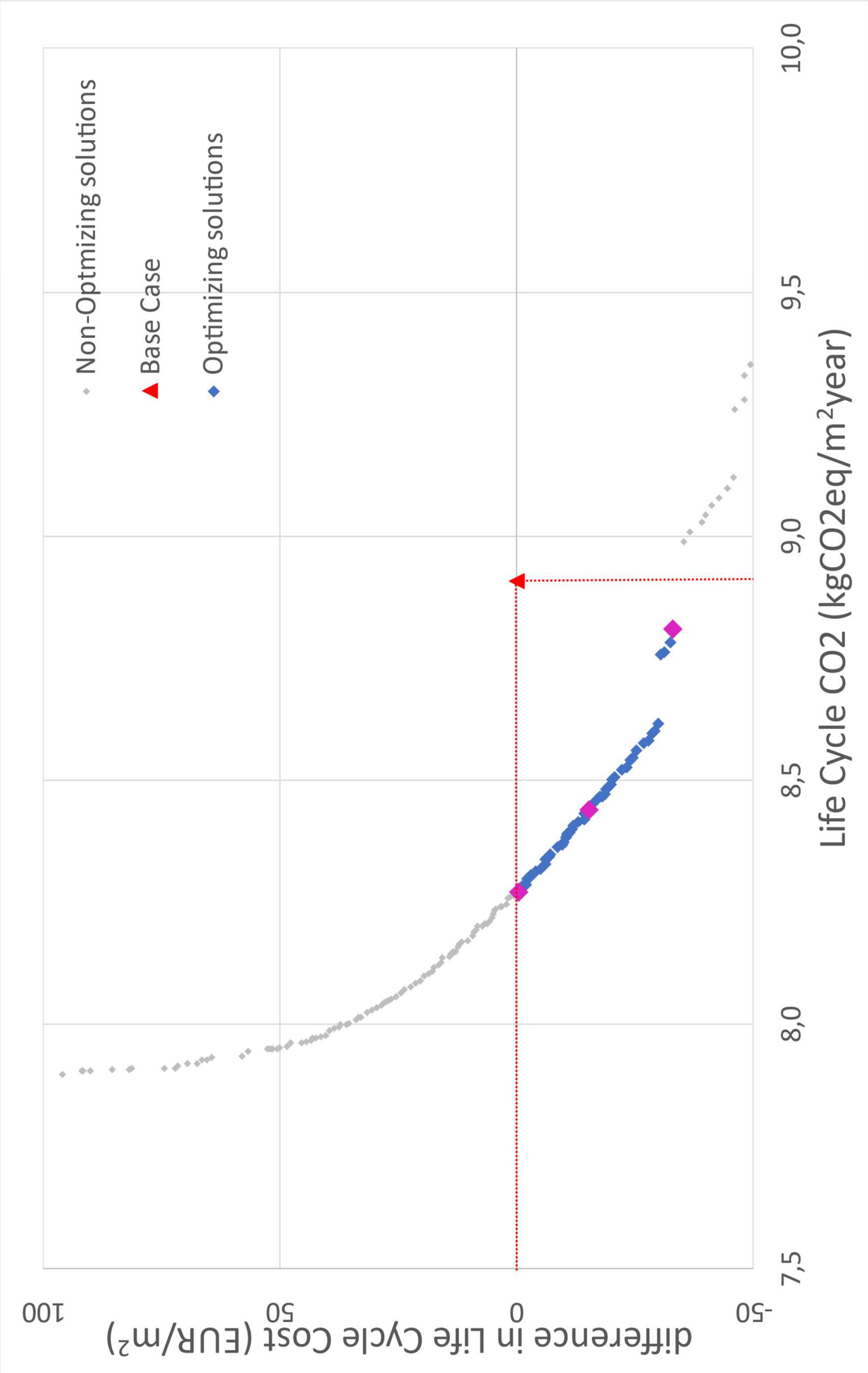


Figure 8-3: Base case optimizing solutions

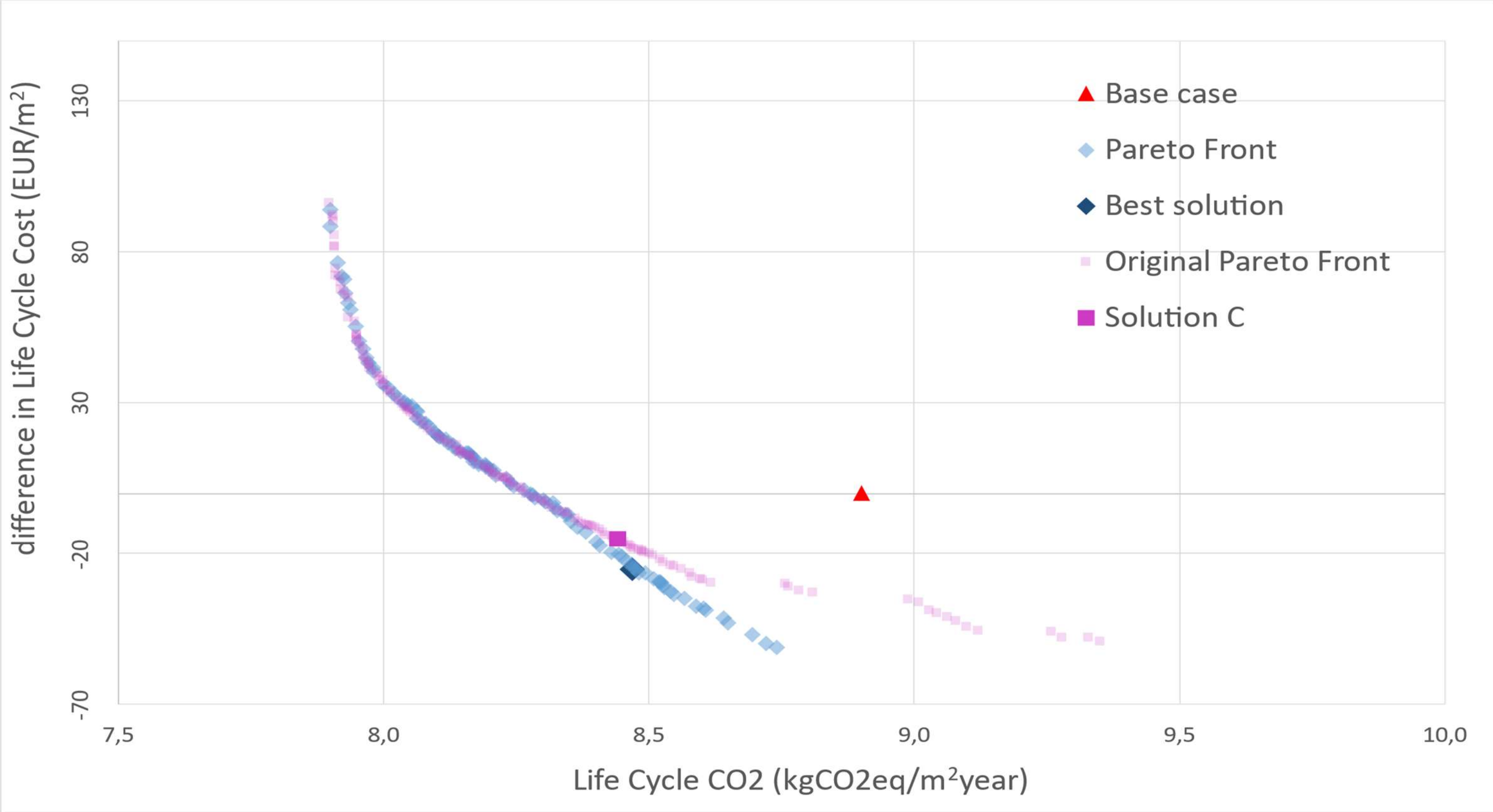


Figure 8-4: Sensitivity analysis, timber -20%

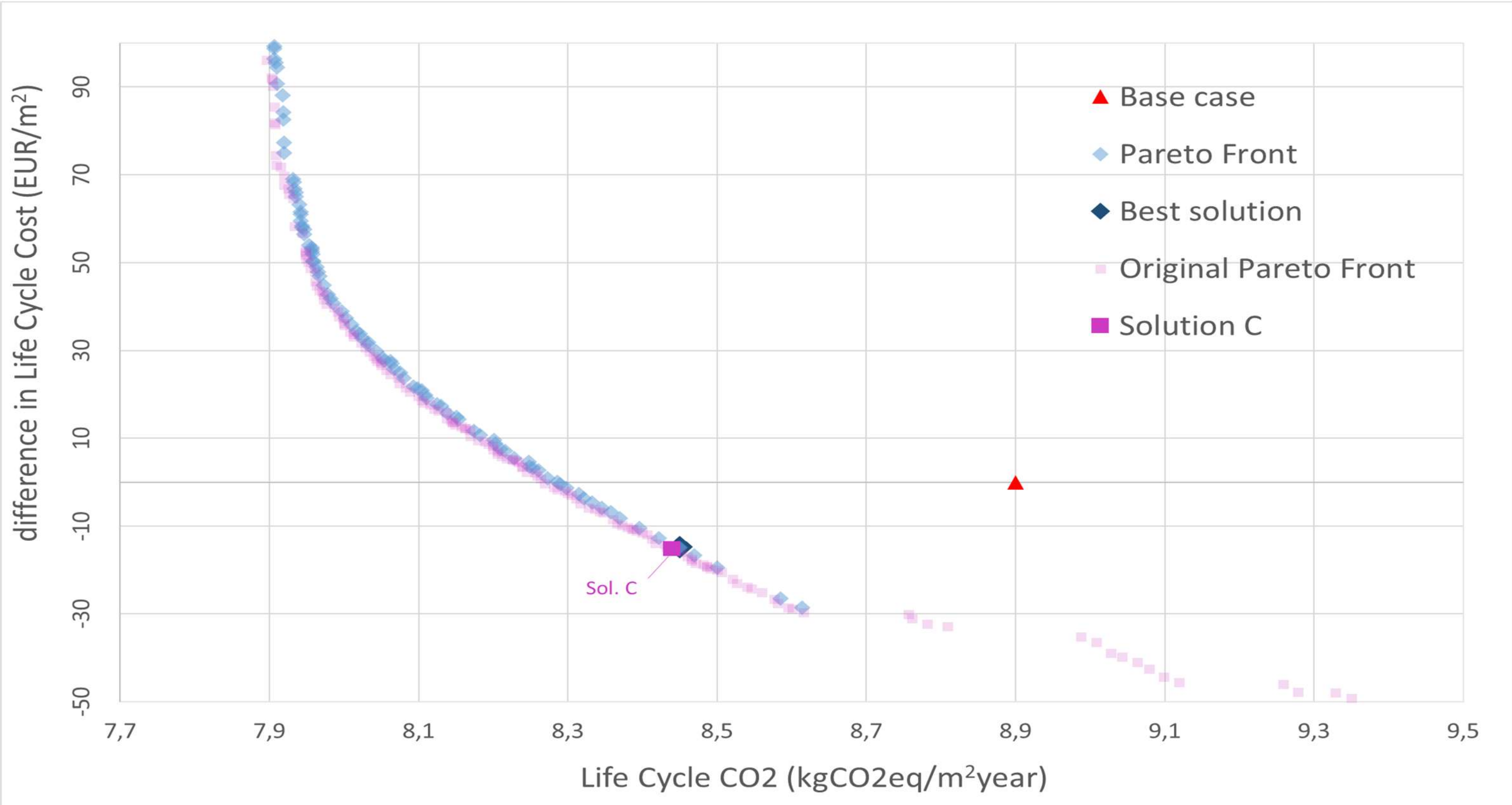


Figure 8-5: Sensitivity analysis, timber +20%

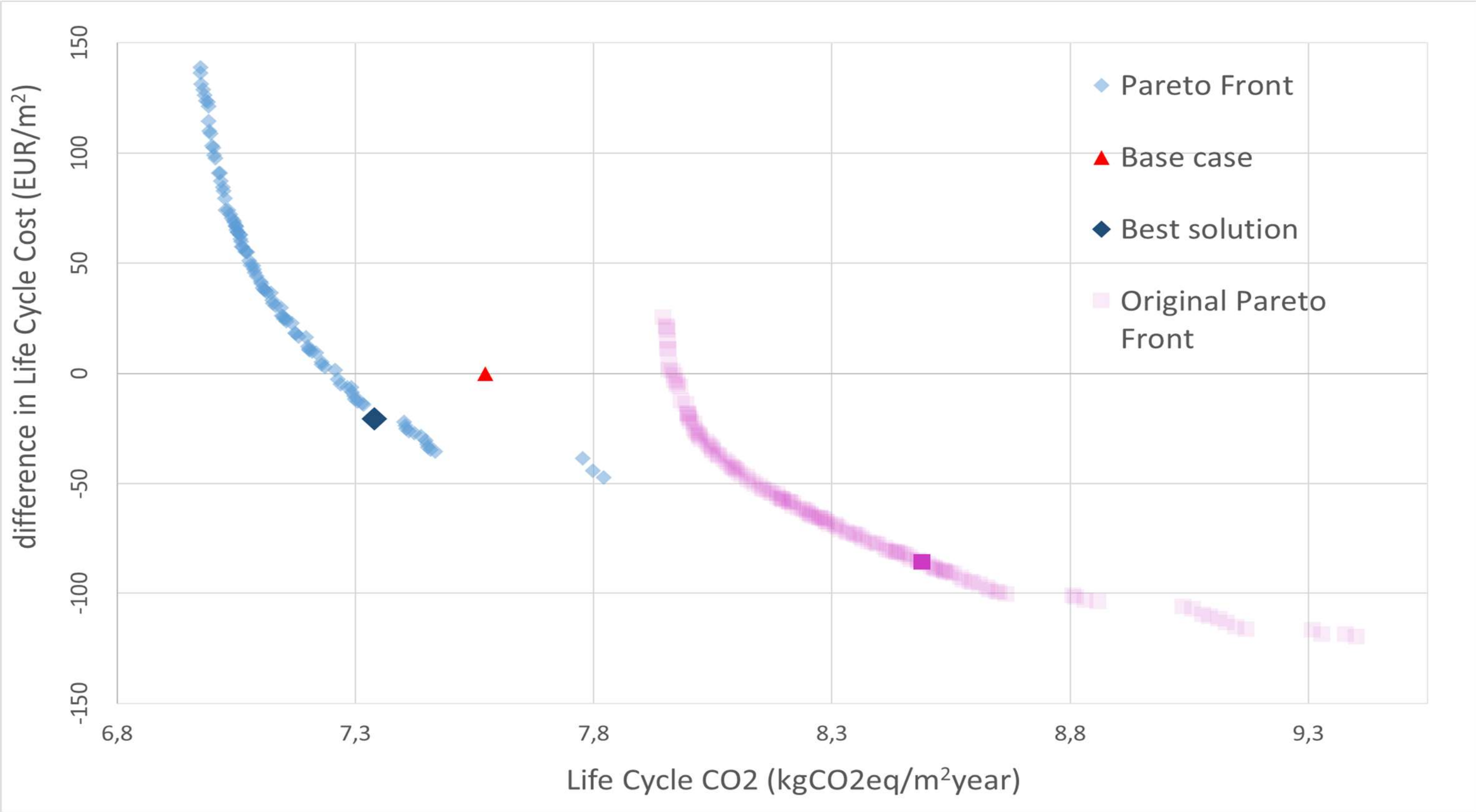


Figure 8-6: Sensitivity analysis, Lifespan +20 years

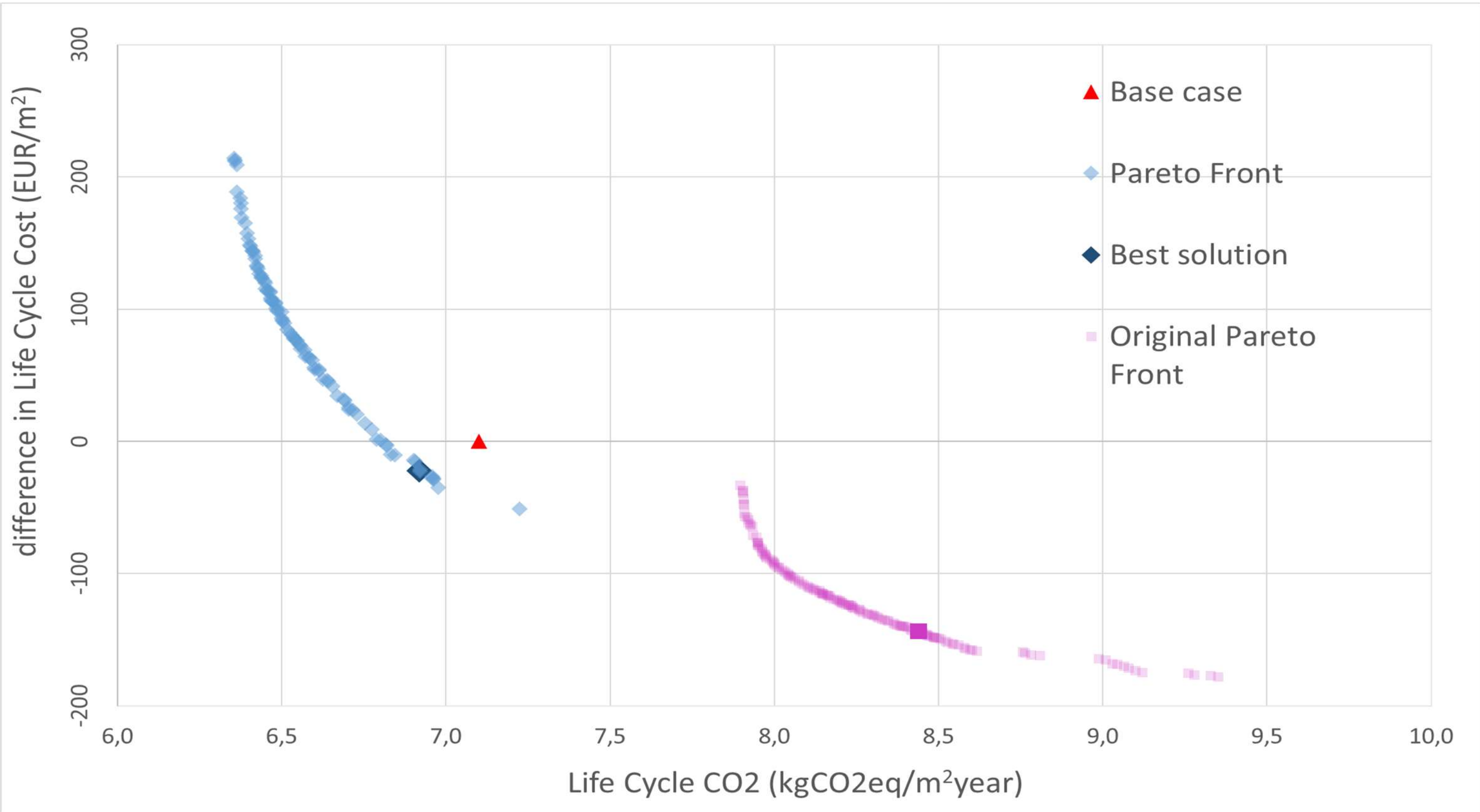


Figure 8-7: Sensitivity analysis, Lifespan +50 years

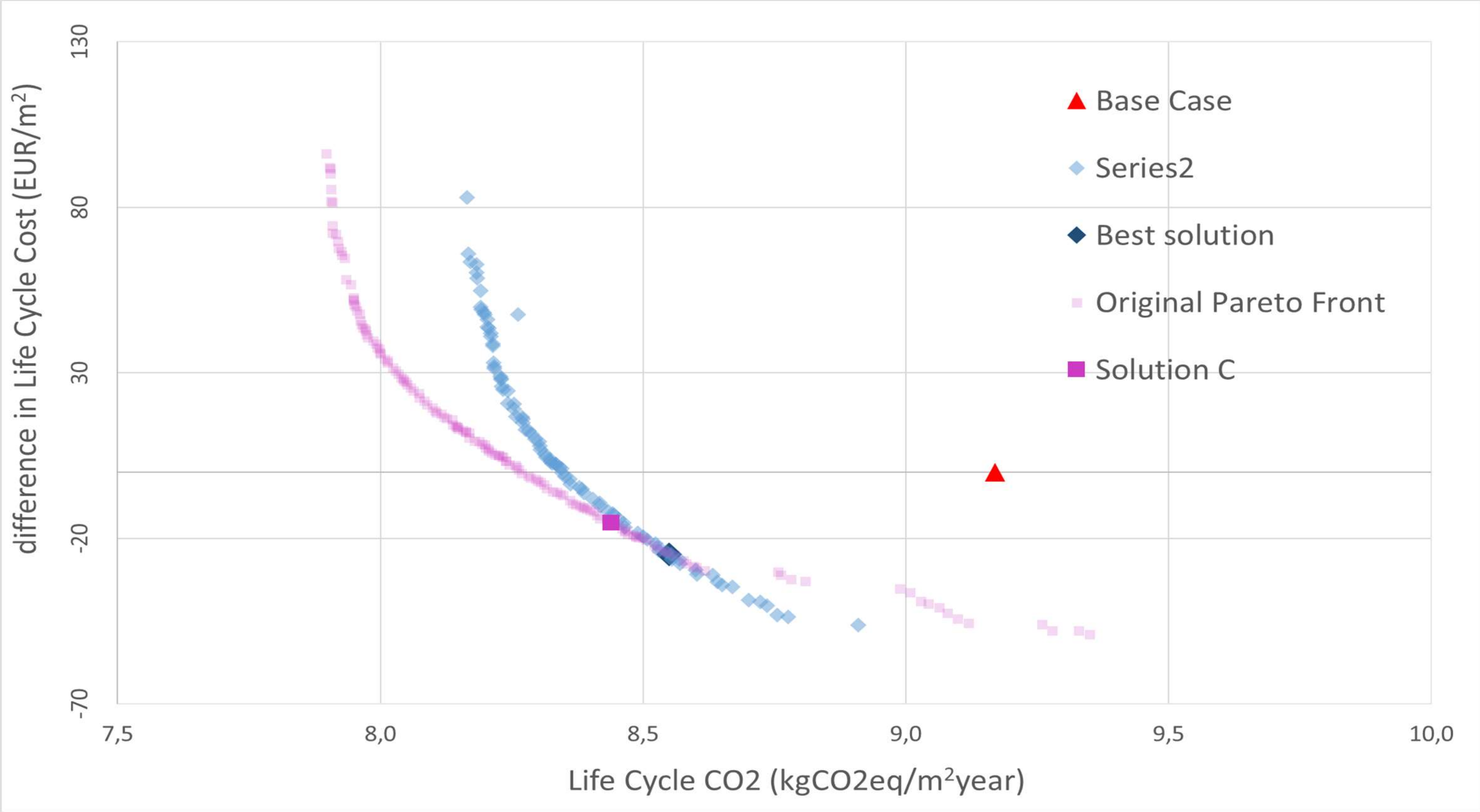


Figure 8-8: Sensitivity analysis, Carbon data source

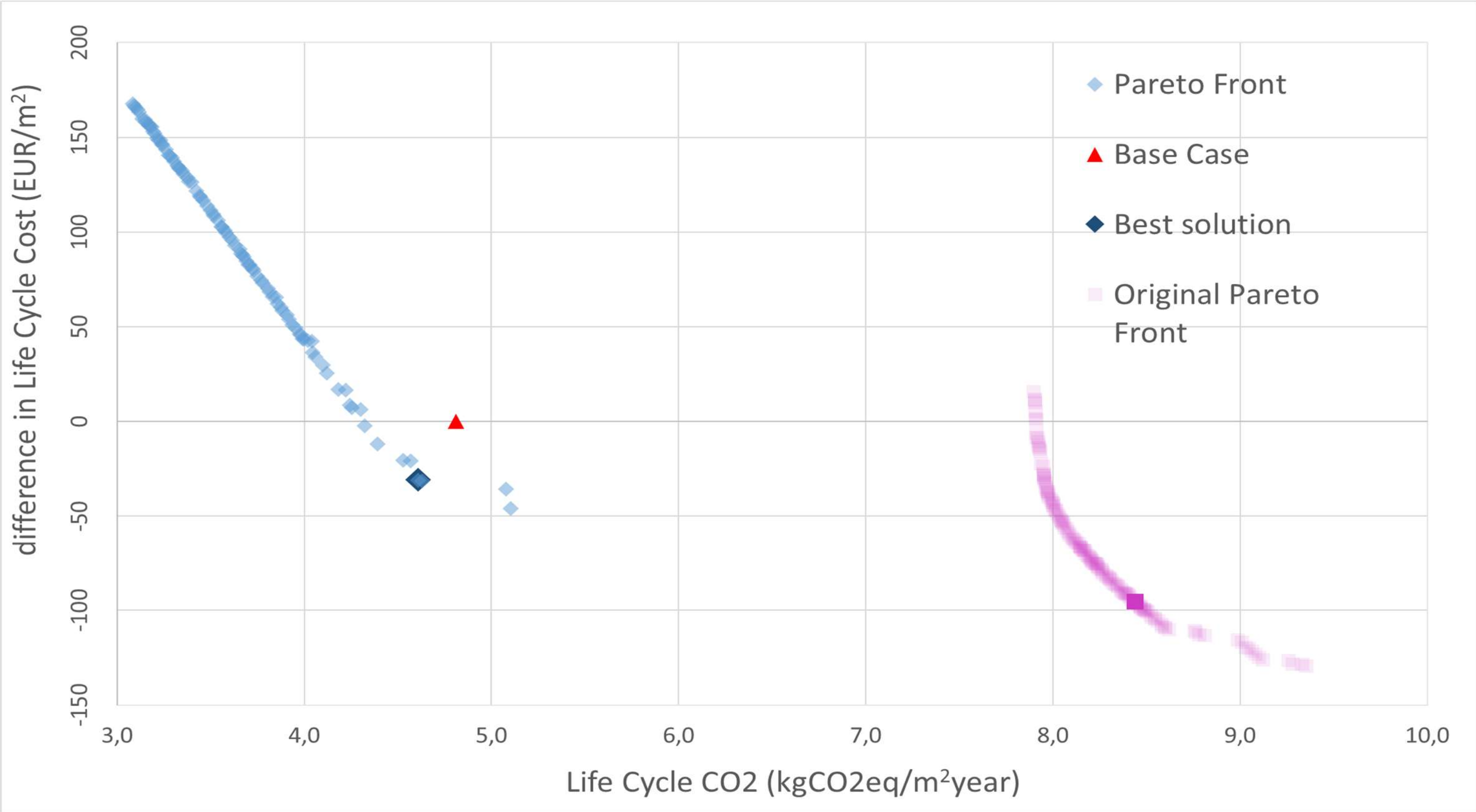
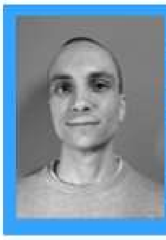


Figure 8-9: Sensitivity analysis, energy mix

Annex 3: SBD Lab Poster



A cost-optimal analysis for nearly zero-carbon timber building solutions in line with the EPBD recast 2020 for Belgium

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ABSTRACT

Europe has set carbon reduction targets, aiming for a 55% decrease in emissions by 2030 and carbon neutrality by 2050. The construction sector faces regulations under the Energy Performance of Building Directive recast 2020, which requires all new buildings to be Zero Emission Buildings (ZEBs) by 2030. Anticipating stricter regulations, such as Nearly-Zero Carbon Buildings (NZCB), the focus will shift to the entire lifecycle emissions. Bio-based materials, like timber, will likely replace traditional high carbon footprint materials.

KEYWORDS

NZCB, Multi-Objective Optimization, Life Cycle Cost, Life Cycle Carbon, Timber, Green Building

PROBLEM

New construction materials and technologies offer an opportunity to embrace the EU 2050 carbon neutrality goal.

Engineering timber, passive design solutions and Renewable Energy Sources (RES) integration allow to decrease operative costs. However, these solutions often carry higher embodied cost, highlighting the need for a life cycle approach to fully assess the economic and environmental feasibility of Nearly Zero Carbon Buildings (NZCB).

OBJECTIVES / HYPOTHESIS

- Comply with EPBD 2020 & EU carbon-neutrality goal
- Compare bio-based material solutions economic and environmental life cycle costs
- Explore NZCB designs using cost-optimality techniques

AUDIENCE

Timber construction sector actors: timber engineering companies and timber material manufacturer

RESEARCH QUESTIONS

- How far can we optimize a timber nearly zero-carbon building life cycle cost and carbon?
- Where lays the trade-off between the two functions?
- Which parameters affect them the most?

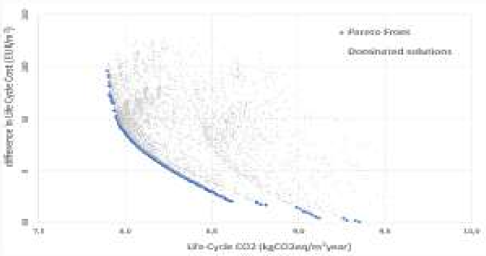
INNOVATION

- Multi-objective optimization approach:
  - Life Cycle Cost (LCC)
  - Life Cycle CO2 equivalent emissions ($LCCO_{2eq}$)
- Production, construction and use stages
- Circular economy nature of case study

METHODOLOGY

A simulation-based multi-objective optimization framework is developed to address the challenge of optimizing building design for minimal carbon impact ($LCCO_2$) at lowest costs. This framework is applied on a case study, with different timber systems, envelope insulations and PV panels parameters as design variables. The set of combinations are effectively explored with NSGA-II, over 4000 simulations.

RESULTS



- 153 Pareto front solutions, most sustainable being 7,90 $kgCO_{2eq}/m^2year$, cheapest being 9,35 $kgCO_{2eq}/m^2year$
- 51 optimize case study, ranging from 7% $LCCO_2$ reduction at the same cost, to 63000 € reduction at same carbon
- CLT and glulam shows higher cost but lower carbon
- Embodied carbon accounts on average for 48% of total $LCCO_{2eq}$

CONCLUSIONS

- Simulation based MOO is a suitable methodology for optimizing design.
- LCCO2 better indicator of environmental impact as it considers embodied carbon
- Need for clearer LCA methodology, especially for End of Life and Recycling stages

Resources

Hamdy, M., Hasan, A., & Siren, K. (2011). Applying a multi-objective optimization approach for Design of low-emission cost-effective dwellings. *Building and Environment*, 46(1)

Al-Obaidy, M., Courard, L., & Attia, S. (2022). A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles. *Sustainability*, 14(6)

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