POLITECNICO DI TORINO

Master's Degree in Building engineering

Master's Degree Thesis

Optimizing decarbonization in the EU building stock: a interoperable framework tailored to end users needs

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Abstract - English version

The global shift towards sustainability and energy efficiency has significantly influenced the building sector, which plays a critical role in energy consumption, greenhouse gas emissions, and the depletion of natural resources. This is a key driver behind the European Union's push for decarbonizing the building stock, through the introduction of concepts like Nearly Zero Energy Buildings (nZEBs) and Zero Emission Buildings (ZEBs), presented in the current version of the Energy Performance of Buildings Directive (EPBD). This thesis introduces a versatile and adaptable tool designed to optimize building energy performance and reduce carbon emissions. It integrates easy end-user access and results visualisation, compliance with current European Union regulations, while offering a practical and platform-interoperable application channeled towards a Building Information Model (BIM) environment. Through this approach, the tool addresses a range of issues spanning societal, technological, research, and policy-related challenges. By employing a multi-stage, multi-objective optimization process powered by the Non-dominated Sorting Genetic Algorithm II (NSGA-II), it efficiently tackles conflicting objectives related to heating and cooling needs, overall energy demand, and carbon emissions.

The first stage of the process optimizes the building envelope parameters represented by the thermal transmittance, in order to reduce thermal energy need. The second stage focuses on minimizing CO_2 emissions by optimizing the efficiency of the building technical systems, with the addition of renewable energy sources. The integration of a two-stage process ensures that the optimization reflects both energy and environmental performance, while maintaining flexibility in addressing user-specific needs. Compliance with the current European standard framework is guaranteed by the implementation of an Excel file that performs the energy simulation in accordance with EN ISO 52016-1, adhering to the most recent update of the EPBD, dated May 2024. A key feature of this research is its adaptability to different legislations, while guaranteeing straightforward implementation for the end users, such as engineers, architects and technicians. Automation and interoperability between different platforms are fundamental for this purpose. The tool's design allows easy modifications, making it adaptable for evolving energy standards across Europe.

The algorithm was tested and validated through a case study, represented by Manifattura Tabacchi in Turin, Italy. This application demonstrates how the tool can be applied in real-life settings, offering practical solutions that balance energy performance with environmental impact. In the future, the tool can be further developed, with the objective of providing even more information and adapting it to include thermal comfort, cost-optimality, Life Cycle Assessment (LCA) and other building-related central aspects. By providing a range of near-optimal solutions, this approach provides support for design decision-making, particularly in the context for building retrofits, thus promoting long-term sustainability.

This thesis contributes to the development of an adaptable, regulation-compliant and interoperable tool that is designed to assist building professionals in achieving decarbonisation aiming at a nZEB or a ZEB, as outlined in the last version of the EPBD.

Abstract - versione italiana

Il crescente impegno globale per la sostenibilità e l'efficienza energetica ha un impatto significativo anche sul settore edilizio, che contribuisce in modo critico al consumo di energia, alle emissioni di gas serra e allo sfurttamento delle risorse naturali. La decarbonizzazione è un elemento centrale delle nuove politiche dell'Unione Europea, la quale punta a portare tutti gli edifici del patrimonio edilizio ad un livello zero emissioni, nominato Zero Emission Buildings (ZEB), come delienato nell'ultima versione dell'Energy Performance of Buildings Directive (EPBD), Questa tesi intende presentare uno strumento flessibile e adattabile per ottimizzare le prestazioni energetiche degli edifici e ridurre le emissioni di carbonio associate, integrando una facile interfaccia per l'utente finale, un'applicazione pratica e semplificata dall'interoperabilità fra i software utilizzati e il rispetto degli attuali standard e normative dell'Unione Europea. Utilizzando un algoritmo di ottimizzazione multi-fase e multi-obiettivo gestito dal Non-dominated Sorting Genetic Algorithm II (NSGA-II), è stato possibile affrontare obiettivi contrastanti relativi al fabbisogno di riscaldamento e raffrescamento, alla domanda energetica e alle emissioni di carbonio.

La prima fase del processo ottimizza i parametri di trasmittanza termica dell'involucro edilizio, affinché venga ridotto il fabbisogno di energia termica per riscaldamento e per raffrescamento. La seconda fase si concentra sulla minimizzazione delle emissioni di CO_2 ottimizzando l'efficienza degli impianti dell'edificio, con l'aggiunta di fonti di energia rinnovabile. Il processo composto da due fasi garantisce che l'ottimizzazione rifletta sia le prestazioni energetiche che ambientali, mantenendo al contempo la flessibilità nell'affrontare le esigenze specifiche degli utenti finali. La conformità al quadro legislativo europeo attuale è garantita dall'implementazione di un file Excel che esegue la simulazione energetica secondo la EN ISO 52016-1, aderendo all'aggiornamento più recente dell'EPBD, datata a maggio 2024.

Una caratteristica innovativa di questa ricerca è la sua adattabilità a diverse normative, garantendo al contempo un'implementazione semplice per gli utenti finali, quali ingegneri, architetti e tecnici. L'automazione e l'interoperabilità con software come il BIM sono fondamentali a questo scopo. L'algoritmo implementato nello strumento consente di apportare modifiche facilmente, rendendolo adattabile agli standard energetici costantemente in evoluzione nel territorio europeo. L'algoritmo è stato testato e validato attraverso un caso studio, rappresentato dalla Manifattura Tabacchi di Torino. Questa applicazione dimostra come lo strumento possa essere utilizzato in contesti realmente esistenti, offrendo soluzioni pratiche che bilanciano le prestazioni energetiche con l'impatto ambientale dell'edificio. In futuro, lo strumento potrà essere ulteriormente sviluppato, con l'obiettivo di fornire ulteriori informazioni e di adattarlo per includere il comfort termico, l'ottimizzazione dei costi, la Life Cycle Assessment (LCA) e altri aspetti centrali nel settore edilizio. Fornendo una gamma di soluzioni quasi ottimali, questo approccio supporta il processo decisionale pro-

gettuale, particolarmente nel contesto dei retrofit edilizi, promuovendo così la sostenibilità a lungo termine, tema centrale delle nuove iniziative europee per la sostenibilità.

Questa tesi contribuisce allo sviluppo di uno strumento adattabile, conforme alle normative e interoperabile, progettato per assistere i professionisti del settore edilizio nel raggiungimento dei livelli di Nearly Zero Energy Building (nZEB) e di Zero Emission Building (ZEB), come delineato nell'ultima versione della EPBD.

1 Introduction

The global push for sustainability and energy efficiency has placed the building sector under intense investigation. Buildings are responsible for approximately 40% of global energy consumption and 33% of greenhouse gas emissions. As urbanization continues to accelerate worldwide, the importance of decarbonization of the building stock and consequent optimization of building energy performance becomes increasingly alarming in our fight against climate change and resource depletion. With this perspective, one of the most powerful strategies to consider for environmental sustainability is building energy retrofit for existing buildings. However, this still represents a complex issue involving two divergent points of view. On one hand, the public perspective aims at reducing energy consumption and polluting emissions, contributing to broader environmental objectives. On the other hand, the private sector's main goal is to achieve economical benefits and maximising profit, often prioritizing short-term gains over long-term sustainability.

The energy performance of a building is a complex interplay of various factors, including envelope characteristics, technical systems, occupant behavior, and local climate conditions. The building envelope, comprising elements such as walls, roofs, floors, and windows, plays a crucial role in regulating heat transfer between the interior and exterior environments. The thermal properties of these components, often expressed in terms of U-values (thermal transmittance), significantly influence a building's heating and cooling demands. Lower U-values indicate better insulation and less heat transfer, reducing the energy required to maintain comfortable indoor temperatures. Complementing the passive role of the building envelope, technical systems such as HVAC (Heating, Ventilation, and Air Conditioning), lighting, and renewable energy installations actively manage the indoor environment and energy use. Optimizing these systems can dramatically reduce a building's overall energy consumption and associated carbon emissions. Advanced HVAC systems, energy-efficient lighting solutions and the integration of renewable energy sources such as solar or photovoltaic panels contributes to shape sustainable buildings with reduced environmental footprints.

In recent years, the advent of computational optimization techniques has opened new avenues for enhancing building energy performance. These methods allow designers and engineers to navigate the vast solution space of possible design configurations, seeking optimal trade-offs between multiple, often conflicting objectives such as energy efficiency, thermal comfort, and cost-effectiveness. Optimization algorithms, such as genetic algorithms and multi-objective optimization frameworks, allow for systematic exploration and identification of the best possible solutions, balancing the various performance criteria. The adoption of optimization techniques in building design and retrofitting presents numerous benefits. By systematically evaluating different design alternatives, it is possible to identify configurations that minimize energy consumption while maintaining or improving the performance of the building. Nowadays, these techniques facilitate the integration of renewable energy systems, enabling buildings to become more self-sufficient and less reliant on fossil fuels. The ability to predict and quantify the impact of different design choices on energy performance enhances decision-making and supports the development of sustainable building practices.

As the urgency to address climate change intensifies, the building sector must embrace innovative solutions to enhance energy performance. The integration of computational optimization techniques, coupled with advancements in building materials and technologies, offers a promising pathway toward achieving energy-efficient and sustainable buildings. By aligning public and private interests, fostering collaboration among stakeholders, and leveraging cutting-edge tools, it is possible to create a built environment that meets the demands of a growing population while minimizing its ecological footprint.

2 Legislation Framework

The main EU key policy documents and directives emphasise the issues of energy efficiency and the use of renewable energy resources, focusing on a forward-looking approach to sustainable development. The main EU energy policy priorities are outlined in the European Commission's agenda and include: (1) minimizing the environmental impact of energy consumption; (2) promoting improvements in energy production and efficient energy use; (3) increasing the reliability and security of the energy supply; and (4) promoting renewable energy resources alongside climate change mitigation efforts to combat climate change [1].

The EU's first objective arises from its recognition of the urgent worldwide climate challenges. Actions involve mitigating adverse environmental effects associated with both energy production and use. Going towards innovation and clean energy technologies is the core of the second objective. By fostering energy efficiency, the EU aims to reduce overall energy demand, lower costs for costumers and decrease dependence on imported energy. For the third point, the EU recognizes the importance of a stable and secure energy supply for economic growth. In order to achieve this, the EU is working to diversify energy sources, strengthen the resilience of its energy infrastructure, and improve the functioning of energy markets. These initiatives are designed to safeguard the EU against potential disruptions in energy supply, whether due to geopolitical conflicts, natural disasters, or other unforeseen events. Finally, the fourth key objective highlights the EU's commitment to promoting renewable energy resources as a vital strategy for reducing dependence on fossil fuels. By supporting the development and deployment of wind, solar, biomass, and other renewable energy technologies across Europe, the EU is making significant steps in its climate change mitigation efforts, while also fostering sustainable energy solutions for the future. Nowadays, a cornerstone of the EU's legislative approach to improve energy efficiency in the building sector is the Energy Performance of Buildings Directive (EPBD). This directive serves as the primary legislation tool for driving improvements in the energy performance of buildings, which accounts for a significant portion of the total EU's energy consumption.

2.1 Overview of current EU Directives

This paragraph will present the regulations that best fit the aim of this thesis, providing a broader introductory insight on EU actions. A brief overview on the most relevant European initiatives will be introduced as to offer a solid foundation and a more comprehensive background to the legislative landscape. A more detailed examination of the regulations representing the basis for this analysis will follow in subsequent sections. By establishing an harmonized approach across Member States, the seamless functioning of the single market is ensured. It creates larger markets for European suppliers, protects and boosts competition, and guarantees that consumers enjoy consistent rights and receive comparable information across the European Union. A coordinated Union action is essential to achieve policy objectives at the lowest possible cost. By creating a unified market, it sends a strong signal to investors and manufacturers, encouraging the development of energy-efficient products and services. This coordinated effort helps to alleviate energy poverty, especially after COVID-19, providing consumers with accurate, understandable information on energy use and related costs, and ensuring access to competitive markets for energy-efficient solutions. By acting at the Union level, the directives address barriers to public and private investments, enhances administrative capacity for cross-border projects, and supports schemes. It provides a stable framework that leaves flexibility for Member States in choosing specific measures while maintaining the overall structure needed to achieve collective goals.

The European Green Deal [2] provides an action plan that leads the EU towards a green transition with the ultimate goal to achieve climate neutrality across the whole continent by 2050. Such initiatives involve different sectors covering the climate, the environment, energy, transportation, industries, agriculture and sustainable finance. Particularly, among these initiatives, the Fit for 55 and the Renovation Wave stand out for their focus on energy efficiency in the building sector. The Fit for 55 [3] package is a core part of the European Green Deal and contains a set of legislative proposals and initiatives presented by the EU Commission in 2021. The main purpose of this package is to revise and strengthen existing European legislation to align with the EU's climate objectives. Central to this package is the target of reducing net greenhouse gas emissions by 55% by 2030, relative to 1990 levels. This ambitious target is designed to drive substantial environmental progress and is closely linked to the Energy Performance of Buildings Directive (EPBD Recast), which will be discussed in subsequent sections. In October 2020, the European Commission presented also the Renovation Wave [4] strategy as another component of the broader European Green Deal. The focus is set on the long-term building renovation strategy, on aspects of the Directive on Energy Performance of Buildings and on other building-related aspects of each EU country's National Energy and Climate Plans (NECPs). At its core, the Renovation Wave aims to double the annual rate of energy renovations in buildings by 2030 promoting a range of measures such as financial incentives and support mechanisms to facilitate and encourage building owners to upgrade their properties. By promoting deep renovation in this way, the Renovation Wave aims to transform the existing building stock in terms of energy efficiency focusing on what is already existing rather than to build *ex novo*.

2.2 Energy Performance of Buildings Directive (EPBD) and Nearly Zero Energy Buildings (nZEBs)

The Energy Performance of Buildings Directive (EPBD) is a Union-level directive aiming to improve energy efficiency of buildings across all MS. As buildings are significantly contributing to energy consumption and carbon emissions, the primary objective of the EPBD is to improve their energy performance, which is essential for achieving EU's climate goals for a fully decarbonised building stock by 2050. The background of this directive lies in the fact that 85% of EU buildings were built before 2000 and 75% of those have poor energy performance. The following data are provided by the Eurostat Energy Balances and the EEA Greenhouse Gas Inventory (from the year 2023) [5] to give some insight on the impact of buildings across Europe: they are using around 40% of the energy consumed in the EU, they release over 1/3 of the EU's energy related greenhouse gases (GHG) emissions and, finally, more or less 80% of the energy used in EU homes is for heating, cooling and domestic hot water (DHW). The first version of the EPBD was adopted in 2002 with the directive 2002/91/CE [6] and it aimed to develop a common framework for the MS to promote energy performance certification and encouraging the implementation of energy efficiency methods in new and existing buildings. By 2007, the requirements were implemented, and the Energy Performance Certificates (EPCs) became mandatory.

In 2010, the Directive was revised into the 2010/31/UE (EPBD II), also defined as the EPBD Recast. In this revision, the methodology of calculation of the EP of buildings is defined. Additionally, the EPBD states that all MS "*must ensure that minimum energy performance requirements are set with a view of achieving at least cost-optimal levels*", also providing actions to promote "*the cost-effective transformation of existing buildings into nZEB*" [7]. The Nearly Zero-Energy Buildings (nZEBs) define buildings with a very high energy performance. It is required that the nZEBs energy demands are covered significantly by renewable resources, either produced on-site or nearby. MS were required to ensure that all buildings constructed after the 31st December 2020 had to be nZEBs. To coherently assess a Nearly Zero-Energy Building means considering not just a specific requirement but the combination of different ones such as the indoor environmental conditions, the thermal characteristics of the building, the technical building systems (such as HVAC, DHW and lighting), the energy systems based on renewable resources and the district or block heating and cooling systems. No general quantification regarding the assessment of a nZEB building is provided in the regulations; as a consequence, it is responsibility of every MS to set their own benchmark to achieve this goal. This is one of the reasons why the cost-optimal analysis has been implemented: encouraging MS to set their own EP requirements related to the cost-optimal level helps implement policies that should lead to a neary zero energy demand.

The further integration and revision of the EPBD (also referred to the Amended EPBD Recast or the EPBD III) was reached with the 2018/844 Directive [8] which raised the bar on energy efficiency standards for buildings. This revision focused on strengthening the EP requirements for new buildings to approach better nZEB standards improving also the provisions on technical building systems and on Building Automation and Control Systems (BACS). For existing buildings, new measures were introduced such as long-term renovation strategies and financing projects aspiring to support energy renovation works.

2.2.1 Current EPBD version (updated May 2024)

On May 8, 2024, the updated version of the EPBD was published [9], following its adoption in April. The revised Directive enhances the regulatory framework already established in 2018 to better align targets and expectations with the EU climate ambitions. Under the modified version, residential and non-residential buildings are treated differently. Regarding the first typology, each MS will autonomously reduce their primary energy use by 16% by 2030 and by 20-22% by 2035; both values are compared to the levels of the year 2020. The measures adopted have to establish that at least 55% of the reduction of primary energy use is accomplished with the refurbishment of what are defined the "worst-performing buildings", which represent the most inefficient ones in the building stock. Concerning non-residential buildings, the Directive sets the gradual introduction of Minimum Energy Performance Standards (MEPS) according to which 16% of the worst-performing buildings have to be renovated by 2030 and 26% by 2033. MEPS are only compulsorily defined for non-residential buildings; they are based on maximum energy performance thresholds. Each MS will have the flexibility to target the residential and non-residential buildings subjected to renovation to achieve this goal. Exemptions can be made individually, for example for historical buildings or holiday homes.

In the new version of the Directive, it also has been introduced the Zero-Emission Buildings (ZEBs), substituting the former nZEBs, as the new standard for newly constructed buildings. Similarly to the definition of nZEB, a ZEB is *"a building with a very high energy performance, requiring zero or a very low amount of energy"* [9]. Additionally, a ZEB should also offer flexibility in its energy grid integration as it shall *"where economically and technically feasible, offer the capacity to react to external signals to adopt its energy use, generation or storage"* [9]. The last EPBD recast marks a significant shift in how it conceptualizes energy supply for new buildings. Moving away from the explicit focus on renewable energy that characterized the nZEB definition, the new directive embraces a broader, more holistic concept of "zero emissions." Under this new framework, a ZEB is defined by two key criteria. Firstly, it must not cause any on-site carbon emissions from fossil fuels. This requirement directly addresses the need to phase out fossil fuel use in buildings, a crucial step in the fight against climate change. Secondly, a ZEB should produce either zero or a very low amount of operational greenhouse gas emissions. To ensure this standard is met, Member States are required to establish maximum thresholds for these emissions in their National Building Renovation Plans (NBRPs). This approach allows for some flexibility while maintaining a high standard of environmental performance. In this regard, the Directive includes two safeguards: first, the thresholds should be set with a view to achieve at least the most recent cost-optimal levels, which should be updated every five years to improve progressively the buildings' performance. The second safeguard establishes that the ZEB threshold must be at least 10% lower than the national nZEB threshold for total primary energy use in place in 2024.

When it comes to the energy sources that can be adopted to supply a ZEB, the Directive provides a list of options that include on-site or nearby renewable energy sources. Other options are renewable energy from a renewable energy community or energy distributed from efficient district heating and cooling (DHC) systems. Additionally, energy from "carbon-free sources" is permitted by the Directive, however, it does not provide a specific definition for these terms. Out of these four options, the two first exposed should have the priority towards a zero-emission goal, since both the DHC systems and the "carbon-free sources" do not ensure that a ZEB sources its energy from renewables only. By specifying the list of sources of energy eligible for a ZEB, the Directive addresses the need for buildings that are fully decarbonized, though not exclusively reliant on renewable energy. Recognizing that these preferred options may not always be feasible, the directive includes a provision for exceptional cases. Where it is not technically or economically viable to use the above options, a ZEB may cover its total annual primary energy use with other energy from the grid. However, this grid energy must comply with criteria established at the national level, ensuring that even in these cases, there is a push towards cleaner energy sources. [9]

As of January 1, 2028, for publicly-owned buildings and January 1, 2030, for all other new constructions - both residential and non-residential buildings - must be free of on-site emissions from fossil fuels. This requirement is closely linked to cost-optimality and the goal of achieving ZEB, which are major considerations for both public and private investors evaluating the financial viability of renovation projects. The timeline of requirements linked to cost-optimality and ZEB is shown in Figure 1. Additionally, the updated EPBD introduces also the "Building Renovation Passport" which provides a tailored road-map in the case of deep renovation. The document outlines how to act to improve the energy performance of a specific building helping owners and investors in the renovation process. Although the concept of "deep renovation" has not been properly outlined, the general definition refers to the renovation works that aim to transform the building into a ZEB. Finally, for expressing the energy performance of a building, all MS have to quantitatively define indicators of total, non-renewable and renewable primary energy use and, additionally, of operational greenhouse gas emissions produced in $kgCO_2eq/(m^2y)$. [9]

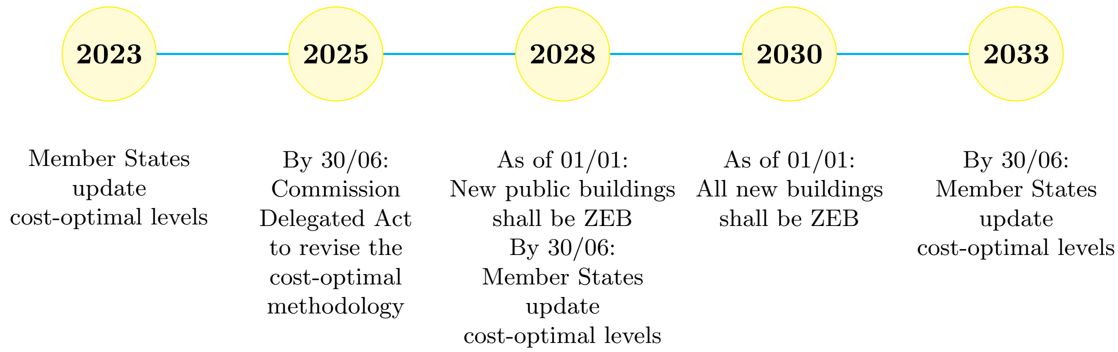


Figure 1: Requirements timeline for cost-optimality and ZEB

2.3 The adoption of the EPBD in Italy

The EU's legislative framework places a lot of emphasis on sustainability, energy efficiency and decarbonization, which are all topics reflected in the requirements of the EPBD. However, the transposition of EU directives into national law is not automatic, but every MS is required to individually adopt the provisions of such directives into domestic legislation. This process requires regular updates to national laws in order to remain aligned with the evolving targets, especially as the EU strongly aims to climate neutrality by 2050. As seen in Section 2.2.1, the EPBD IV builds upon the previous versions, introducing even more stringent requirements. As the directive was published officially in May 2024, at the time of writing, Italy has not yet adopted the necessary decrees to formally adopt EPBD IV into national law. The adoption of the third version of the EPBD, introduced in 2018, has also faced considerable delays and challenges due to the concurrent COVID-19 pandemic. Consequently, certain aspects of the EPBD remain unfulfilled within Italy's national framework. In response to the pandemic-induced delay, the Italian government introduced Legislative Decree 76/2020 [10], which set forth urgent measures regarding the digital simplification and innovation, two key elements also emphasized in the EPBD III and IV. However, the decree's focus left gaps in Italy's specific implementation of the EPBD III requirements. The current legal reference to the EPBD is currently outdated, as it continues to refer to the EPBD II, despite the introduction of the subsequent version of the directives by the EU. The Ministerial Decree 26/06/2015 [11], represents the implementing decree of Law 90/2013 [12], and establishes the minimal requirements for the energy performance of buildings. Figure 2 provides a schematic representation of the legislative timeline, indicating the relevant implementing decrees.

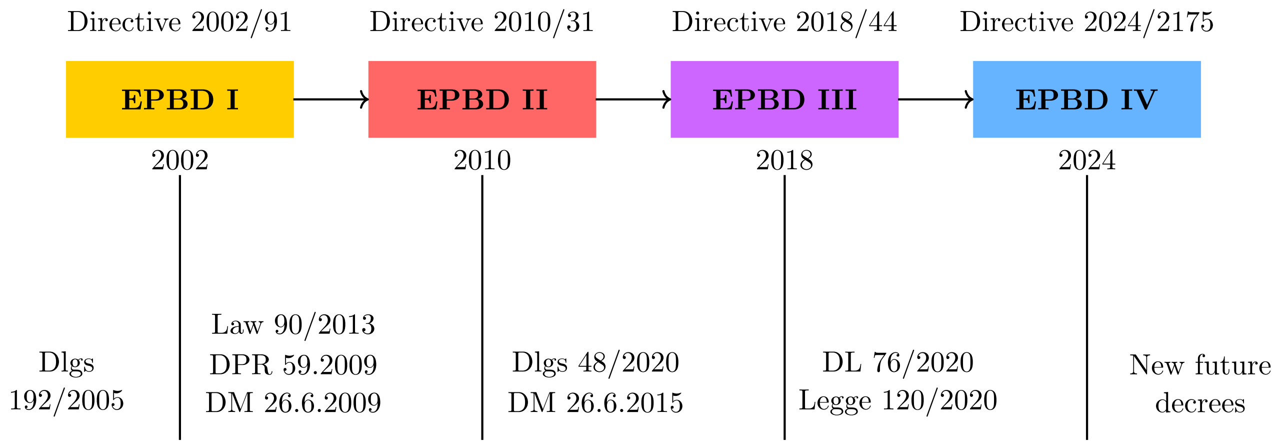


Figure 2: Timeline of the adoption of EPBD in Italy

2.3.1 Italian Ministerial Decree 26/06/2015

The Italian Ministerial Decree of the Ministry of Economic Development dated 26 June 2015 [11] represents a significant legislative milestone in promoting energy efficiency and renewable energy resources in buildings across the Italian territory. The decree aligns with the 2010 version of the EPBD, further analysed in Section 2.2. It involves the application of the calculation methodologies for energy performance and definition of the requirements and minimum standards for buildings, including also renewable resources. These requirements apply to both public and private buildings, including new constructions and existing buildings undergoing renovations. The implementation of this decree is expected to have a significant impact on energy consumption in buildings across Italy in the future years. A central aspect of the 2015 Ministerial Decree is the introduction of the "reference building". This standard model serves as a benchmark for assessing the energy efficiency of actual buildings by comparing them to an hypothetical structure designer with the same dimensions. This approach establishes a reference framework that allows for the comparison of energy characteristics between new or renovated buildings and existing ones. By doing so, it helps set achievable energy efficiency targets and promotes sustainability in the built environment. Ultimately, this contributes to the reduction of CO_2 emissions, aligning with broader environmental goals.

In Appendix B of the decree, the thermal transmittance values presented are minimum requirements that buildings should meet to ensure satisfactory energy performance. While these values are intended as benchmarks to guide the design and renovation of buildings, they are not mandatory. The primary objective is to encourage real buildings to match or exceed the performance levels of the reference buildings. It is important to note that the U-values for actual values may differ from those of the reference building, since the key is to ensure that overall energy efficiency is maintained. Given the geographical diversity of Italy, the decree defines distinct U-values for each climatic zone, from Zone A (warmest regions) to Zone F (coldest regions), thus ensuring that energy efficiency standards are appropriately tailored to local weather conditions. For the scope of this analysis, the reference U-values for the building envelope are those applicable to Zone E, given that Turin is located within this geographical area. Table 1 shows the U-values adopted for the reference building for the city of Turin.

Table 1: Reference building thermal transmittance values for zone E for different envelope elements, referring to building renovations (M.D. 26/06/2015, Appendix B)

Element	U **[W/m^{2}K]**
Opaque vertical components	0,28
Opaque horizontal components - roofs/ceilings	0,24
Opaque horizontal components - bottom floors	0,29
Transparent components	1,40

2.4 Energy Performance assessment methods

In order to ensure compliance with the current building regulations, the procedures that perform the calculation of the energy performance of a building not only have to be accurate, but also robust. The robustness requirement is achieved when the results obtained show a restricted loss of accuracy. Scalability is an additional key property, in the sense that the method should be suitable for a wide range of scenarios, regardless of the specific choices of the users. Moreover, transparency, applicability and verifiability are essential attributes as to allow the municipalities to check the compliance with minimum EP requirements. Beyond calculations, the accuracy of such models depends firstly on input data quality and the related uncertainties. Thus, the related accuracy must always be balanced with the limitations and uncertainties inherent in the input data, as well as with the robustness of the model itself. This concept of "balanced accuracy" is essential, as the most accurate and comprehensive method may not necessarily be the best fit for the model [13].

The main aim of the calculation procedures is to obtain the annual primary energy needs in terms of heating, cooling, ventilation, DHW and lighting. As a consequence, the overall annual value is calculated for each energy end-use on a monthly basis. The phases of the procedure comprehend the calculation of:

1. Thermal energy need in order to satisfy the users

2. Subtraction of the thermal energy derived from renewable and on site resources (e.g. solar panels)

3. Energy consumption for every final use (heating, cooling, ventilation, DHW, lighting) for every energy vector (electricity, fuel)

4. Subtraction of the electric energy derived from renewable and on-site resources (e.g. photovoltaic panels)

5. Delivered energy for every energy vector

6. Primary energy associated with the delivered energy, using appropriate correction factors

The classification of the three calculation methods is summarized in Table 2. Nevertheless, the methods prescribed in the Guidelines supporting the Commission Delegated Regulation No. 244/2012 [14] are connected to the time range considered in the calculation and on the complexity of the procedure itself. The simplified dynamic hourly is being introduced as the most efficient method for obtaining accurate results in a simpler way. The fully dynamic one will not be treated thoroughly in this analysis as it is the most complex one to implement, for it requires a lot of choices, details and complexities. For its implementation, it is required to use some specific softwares that are able to simultaneously solve a long list of equations. Additionally, this method cannot be used in the calculations aiming at verifying the compliance with the regulations for its complexity in the reproduction and the lack of transparency. The quasi-steady state monthly method and the simplified hourly method are the improved versions of the corresponding methods presented in the former EN ISO 13790 [15]. Nevertheless, the best reference to assess the energy performance of a building should involve the evaluation of the real energy consumption related to each case study. However, data are very hard to collect and the time required to acknowledge the result is not feasible.

Table 2: EP standard calculation methods

Calculation method	**Dynamic effects**	**Implementation**
Steady state	Not accounted	Not used
Quasi-steady state	Partially accounted with utilization factors	In legislative verifications
Dynamic	Accounted fully	In simulation tools

2.4.1 Simplified dynamic method (EN ISO 52016-1)

As already mentioned, calculation models need to meet the requirements of accuracy, simplicity, robustness, and transparency. Among them, the EN ISO 52016-1 is the result of a technical standard that challenges the complexities of the input data typical of dynamic calculation methods and the simplifying assumptions in order to maintain a "balanced accuracy". The leading objective of the simplified hourly method is to also consider the dynamic interactions and fluctuations occurring on an hourly and daily basis that are referring to various factors such as the weather conditions and the operational-focused aspects (including solar shading, thermostats, occupancy profiles, thermal inertia values, mechanical ventilation, weekend operation, heat pump, solar panels, etc.), particularly in relation to heating and cooling requirements. In order to meet today's low energy performance requirements, the majority of the technologies used involve such dynamic fluctuations and that is the reason why it is essential to consider them. In the past, the dynamic effects were less frequent, however nowadays in nZEBs and ZEBs those effects can have a large impact on overall energy performance.

In the EN ISO 52016-1 [16] standard the calculations cover on an hourly basis three main components: energy need, internal temperatures and design heating and cooling load; more specifically, there are considered:

- Sensible energy need for heating and cooling (also possible to calculate for a monthly basis)
- Latent energy need for humidification and de-humidification (also possible to calculate for a monthly basis)
- Internal temperatures: air temperature, mean radiant temperature of the surfaces, radiant temperature and operative temperature
- Sensible heating and cooling load
- Moisture and latent load for humidification and de-humidification
- Design sensible heating and cooling load
- Design latent heat load
- Supply air to provide the necessary humidification or de-humidification

Such method can be implemented both for residential and non-residential buildings. Additionally, its application can be involved either in the design stage, in the use phase both for new buildings and existing buildings. As per usual, the process starts from the definition of the thermal zones the building is subdivided into. Since they were developed together, both the hourly and the monthly methods use as much as possible the same input data and assumptions for an easier implementation. In the case the specifications of the technical system are known, the heating and cooling loads and needs are calculated according to the system specifics and controls (for e.g.: limited heating or cooling power, recoverable heat losses, different temperature set-points in the time schedule, etc.); in the opposite situation, the calculations will be performed according to basic needs and loads that are not influenced by a specific choice of a technical system. In the last case, standard indoor environment conditions are assumed and the system is considered to operating continuously [17, 18].

2.4.2 Italian National Annex

The thermal resistance (or transmittance) and the areal heat capacity are the only parameters required by the standard to correctly describe the opaque component. Therefore, the simplification compared to the fully dynamic methods is evident, especially when considering that no layering information nor other specific thermophysical properties are required. These simplifications are extremely important when assessing the energy performance of an existing building, where little or no information regarding the envelope is provided: this will not be true for the Italian National Annex [19].

The calculation workflow involves the simultaneous resolutions of different heat balance equations. Naturally, the equations will depend on the position of the node considered: if the node is an indoor surface one, the heat balance equations will take into account the convective heat transfer with indoor air, the longwave radiation exchanged with the indoor surface nodes of other components, the radiative part of both the internal gains and the solar gains and the radiative component of sensible heating or cooling load. Alternatively, if the node is on the outside surface, the balance equations consider the convective heat transfer with the outdoor air, the longwave radiation exchanged both with the sky vault and with other external surfaces and the absorption of the shortwave solar radiation.

Different modelling options are presented by the Italian National Annex linked to the EN ISO 52016-1: the method is improved taking into account the characteristics and the mass distribution of the component layer for the determination of the resistive-capacitive nodes. The main objective is to improve the opaque component discretization, as to aligning it better with the physical characteristics of the component itself. The improved National Annex adds a more specific procedure for determining the number of R-C nodes and their position inside the component. Each layer is now discretized in at least one node; the number of nodes in each layer is now defined based on a comparison between the Fourier number for the layer itself, and a reference value (assumed 0,5). The higher level of detail required by the Italian National Annex mirrors Italy's diverse climate zones (e.g., Alpine and Mediterranean regions) and diverse traditional architectural elements. Such level of detail helps to ensure that the calculations are tailored to the specific area [20].

2.4.3 Monthly method (EN ISO 52016-1)

The monthly quasi-steady state is the most implemented method nowadays due to the its prominent presence in the Guidelines [14]. It consists in a simplified approach aimed to be transparent, robust and reproducible. The calculation period is based on a full year and the procedure considers intervals of a month at a time. This method allows only to calculate sensible and latent monthly energy needs; hourly thermal loads or temperature profiles cannot be acquired. It is defined as quasi-steady-state because it operates under the assumption that the building's thermal state can be considered quasi-steady over the course of a month, thus simplifying the calculation of the energy needs.

The monthly heat balance is easy to implement, to follow and to test. On the other hand, as mentioned in the assumptions, it does not consider the influence of time variations in weather, during operation and their dynamic interactions lacking in transparency. The dynamic effects of the building's thermal mass are only considered with the gain utilization factor for heating and the heat transfer utilization factor for cooling. The overall calculation procedure is divided in different steps that help defining:

- Sensible energy need for heating and cooling
- Latent energy need for humidification and de-humidification
- Total heat transfer by transmission for heating and cooling
- Gain and transfer utilization factor, zone time constant
- Heat transfer by transmission and ventilation
- Internal heat gains and solar heat gains

2.4.4 Differences between the Monthly and Hourly methods

The selection of the appropriate method depends on the requirements of the single projects, as well as on the complexity of the building systems and the level of detail needed for the energy performance assessment. Nowadays, the monthly method is the most employed approach as it offers the optimal balance of precision and accuracy in accordance with the aforementioned "balanced accuracy" criteria [13]. On the other hand, the hourly method uses a more complex resistive-capacitive model requiring more computational time and resources, but providing more granular results. In addition to the final objective, the two methods share a few similarities, such as the input data, which include external air temperatures, wind speed, solar irradiance, occupancy patterns, and building features. The only difference in the input data is the time step each method adopts: the hourly method requires hourly weather data, whereas the monthly method uses average monthly ones. The principal distinctions between the two methods are specified in Table 3.

Table 3: Summary of the differences between the Monthly and the Hourly methods

	Monthly method	**Hourly method**
Time scale	Calculation of energy needs on a monthly basis	Calculation of energy needs on an hourly basis
Calculation model	Steady-state with correlation factors	Dynamic using RC (resistive-capacitive) model
Thermal mass consideration	Simplified, using utilization factor	Detailed, using the capacitance
Dynamic effects	Approximated through correlation factors	Directly calculated at each time step
Temperature fluctuations	Not directly considered within each month	Calculated for each hour
Computational time	Faster	Slower, requires more computational resources

3 Literature review

In this section, the main objective is to explore the key methodologies and strategies employed for optimize building energy efficiency, with a particular focus on multi-objective optimization techniques, Energy Efficiency Measures (EEMs) and the reduction of carbon emissions during the operational stage of the buildings' life-cycle. This literature review serves for introducing the basis of the tool modelled later in this thesis.

3.1 Building Energy Performance

Assessing the Energy Performance (EP) of a building means to determine the total annual primary energy demand to fulfill the users' needs including heating, cooling, domestic hot water and lighting. The assessment is nowadays performed at building level, employing a holistic or systemic approach. In the past, EP requirements were set at component level like, for example, setting a minimum thermal insulation level. However, this approach would now be an obstacle for the necessary technological transition. Any combination of these technologies can be now useful for reaching the EP target at the lowest cost. The EN ISO 52000-1:2017, titled "*Energy performance of buildings - Overarching EPB assessment - Part 1: General framework and procedures*" [21] is helpful for provide energy ratings based on primary energy, carbon dioxide emission and other parameters. The primary energy demand is evaluated by aggregating the energy demands per final use and per energy carrier or vector (e.g. electricity, fuel) also considering energy generated on site from renewable resources.

Overall, the energy performance of a building depends on two key components: the operational energy and the embodied energy. The first one refers to the energy related to the day-to-day consumption of a building, so the energy strictly connected to heating, cooling, ventilation (HVAC), lighting, domestic hot water and powering appliances. Basically, it is the energy needed to run the building during its service life. It largely depends on the level of indoor comfort, the climatic conditions and the occupancy and operating schedules. In this analysis, only the operational energy will be explored. On the other hand, the embodied energy represents the one related to the production and the transportation of materials and the elements which the building is composed of. It is the energy content used during the manufacturing, the renovation and the demolition phases. Studies performed by Venkatraj et al. [22] have proven that the OE is much more energy-demanding, accounting for 60-90% of the life cycle energy of a building, whilst the EE demands around 10-20%. Incorporating passive and active energy strategies in the building design can largely influence the OE, thus increasing the EE. As a result, both components need to be properly balanced to achieve high levels of energy performance and overall sustainability.

3.2 Multi-objective optimization techniques in building design

Multi-objective optimization (MOO) is a research area applied in various field of science, such as engineering, economics and logistics that applies a multi-criteria decision making in mathematical optimization problems. It can involve many objectives to be optimized at the same time or, on the contrary, can involve a single function (called mono-objective). In MOO, optimal decisions are taken by balancing trade-offs between more conflicting objectives. The problem formulation in mathematical terms aims to optimize a set of functions $f_1(x)$, $f_2(x)$,..., $f_k(x)$, where each $f_i(x)$ represents a fitness function representing a performance criterion:

$$\min_{x \in X} \quad (f_1(x), f_2(x), \ldots, f_k(x))$$

$$\bar{x} = [x_1, x_2, \ldots, x_m]$$

where $k \geq 2$ is the number of objectives for the multi-objective optimization. For mono-objective optimization, the number reduces to $k = 1$. The set x is the set of feasible decision vectors. Usually, the feasible set is limited to some constraint functions as to establish a minimum and a maximum value for each parameter.

The objective of the MOO is to identify the Pareto front, a set of non-dominated solutions where no objective can be improved without worsening the other. As shown in Figure 3, the Pareto front manifests as a curve composed of all the non-dominated solutions. Solutions that fall within the curve are categorized as "dominated" solutions. These options are not viable for inclusion in the Pareto front because they do not offer an optimal trade-off balance between the objectives. The "ideal" point on the graph represents the theoretical optimal solution, where both f_1 and f_2 are minimized. However, this point is often not achievable and merely serves as a reference for assessing the proximity of actual solutions. It needs to be noted that the two-dimensional representation of the Pareto front is only feasible for two objectives optimization algorithms. In scenarios where three objectives are involved, a three-dimensional representation is necessary to accurately depict the relationships among the objectives. To approximate the Pareto optimal set, various Multi-Objective Evolutionary Algorithms (MOEAs) are utilized, including the Non-dominated Sorting Genetic Algorithm (NSGA) and Multi-Objective Particle Swarm Optimization (MOPSO). These algorithms are designed to generate a diverse array of solutions, by allowing informed trade-offs during the design phase, which can significantly impact the entire life-cycle of a project, such as a building [23, 24].

In the field of building energy retrofit and optimization, multi-objective optimization (MOO) has been extensively applied to balance various competing objectives. Researchers have utilized MOO to achieve an optimal trade-off among different factors such as energy efficiency, cost, comfort, and environmental impact [25, 26]. Ascione et al. [27, 28, 29, 30, 31, 32] performed various multi-objective optimizations, mostly working on a cost-analysis of building energy retrofit by multi-stage multi-objective optimization using MATLAB coupled with EnergyPlus: the first stage was a bi-objective optimization of the energy retrofit measures for reducing the thermal energy demand; the second stage involved a tri-objective optimization of the entire energy retrofit and the final assessment of the cost-optimality for a developed hospital reference building set in Italy. This final stage ensures that the retrofit measures are also financially viable. In addition to this work, Ascione and colleagues have contributed significantly to the academic literature by exploring various MOO scenarios. They have conducted studies that focus on different objectives for optimizing the building envelope, the heating and cooling systems and the renewable energy resources. Hamdy et al. [33] explored the potential for achieving a nZEB energy performance levels while also finding cost-optimal solutions for a single-family house in Finland. The three-stage optimization involved different options for building envelope parameters, heat-recovery units, heating and cooling systems and the use of renewable energy resources as well. The objective was to find the optimal balance between energy performance and cost, thereby ensuring both sustainability and affordability. Carlucci et al. [34] took a different approach by utilizing the GenOpt optimization engine in combination with the Java Genetic Algorithm package, which interacted with EnergyPlus. Their study aimed to minimize thermal and visual discomfort in buildings, considering a total of four objective functions. By addressing these comfort-related aspects, the researchers provided a more holistic view of building optimization that goes beyond energy efficiency and cost. Similarly, Hyojoo et al. [35] used NSGA-III algorithm to perform a four-objective optimization that evaluated trade-offs among retrofit costs, CO_2 emissions, and thermal comfort. This study highlighted the importance of considering multiple criteria simultaneously to achieve a balanced and sustainable retrofit solution. Asl et al. [36] focused on multi-objective design optimization model to minimize life-cycle cost and life-cycle emission, while maximize at the same time occupant satisfaction level in a commercial building. By addressing these conflicting objectives, the researchers sought to identify the best trade-offs that could lead to more sustainable and occupant-friendly building designs.

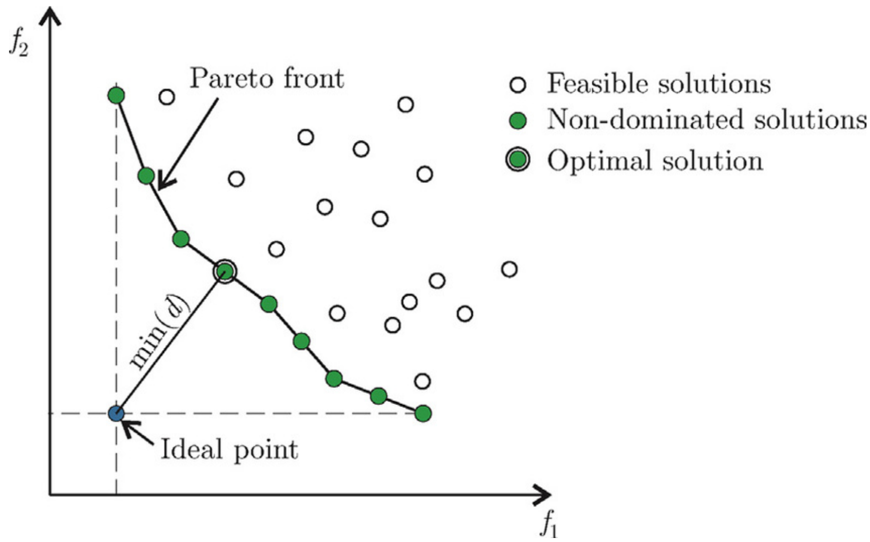


Figure 3: Example of generic Pareto front, courtesy of F. Bre and V. D. Fachinotti [23]

3.3 Energy Efficiency Measures (EEMs)

The life-cycle of a building, from the initial construction phase through its ongoing operation and the maintenance, is intrinsically energy-intensive. In response to this significant energy demand, Energy Efficiency Measures (EEMs) have been developed as strategic solutions aimed at reducing energy consumption. The application of EEMs is fundamental for improving overall sustainability of buildings by minimizing the energy need to provide essential services and maintain functionality over time. Given the variety of energy-related challenges across different stages of a building's life-cycle, several classifications of EEMs have been proposed in literature. These classifications specifically address the stage of the life-cycle considered and the needs and the characteristics of the building in question. However, as previously mentioned, this thesis only focuses on the operational stage of a building life-cycle. Consequently, it needs to rely on a classification approach that aligns with the objectives of this research. In this regard, Madushika et al. [37] proposed an EEMs framework based on three primary aspects (shown in Figure 4): building envelope, building technical systems and renewable energy integration.

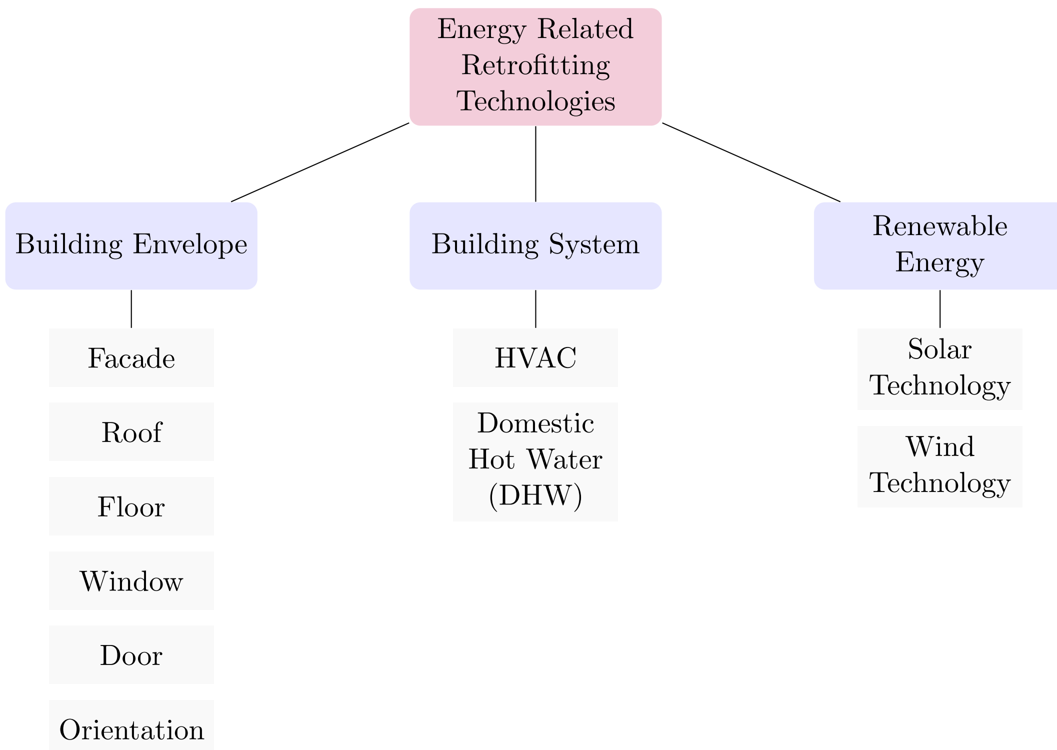


Figure 4: Classification of the EEMs relevant for this thesis

The building envelope includes every component that separates the building indoor environment with the outdoors, regulating the heat exchange between the two zones. It includes external walls, roof, windows and slab on ground. The composition of the building envelope directly affects the heating and cooling demand of the building thermal zones. Façade retrofitting stands as the most effective passive strategy for energy efficiency as the external walls represent the largest surface area exposed to direct solar radiation. Effective façade retrofitting can help in reducing energy demand by minimizing heat gain during summer and heat loss during winter. Among the most common façade retrofitting techniques, wall insulation and the installation of shading devices have proved beneficial contribution in energy savings. Insulation helps reducing the amount of energy required to maintain comfortable indoor conditions, while shading devices control the amount of direct solar radiation entering indoors. Similarly, roof and floor retrofitting with insulation layers or high-insulating materials has been a widely adopted strategy nowadays. Windows, on the other hand, are often considered as the weakest component in a building's envelope due to their lower thermal insulating properties and because of the presence of thermal bridges. Windows performance can be upgraded through the installation of double-pane or triple-plane glazing, low-emissivity coatings or the use of high-performance frame materials.

Beyond the building envelope passive strategies, the optimization of the building technical systems is fundamental for reducing operational energy demand. Technical systems act on a wide range of building services, including heating, ventilation and air conditioning (HVAC), lighting and domestic hot water systems. Among these, HVAC systems are the most energy-intensive, accounting for a substantial portion of a building's total energy use. Transitioning from inefficient to more advanced and energy-efficient HVAC technologies through retrofitting helps in reducing energy consumption. Modern technologies, such as heat recovery systems, are often included in new constructions and in retrofitting projects. Such systems capture and reuse waste heat from exhaust air, thereby reducing the need for additional heating or cooling energy. Additionally, the integration of automated controls, including time and occupancy sensors, allows for more precise regulation of indoor climate conditions. These controls can adjust HVAC and lighting systems based on real-time occupancy and usage patterns, further minimizing unnecessary energy use. The application of such advanced controls in lighting systems, for instance, ensures that artificial lighting is only used when and where it is needed, thereby reducing energy waste and improving overall efficiency [38].

Complementing the EEMs framework, the integration of Renewable Energy Sources (RES) offers a sustainable alternative to traditional energy supply methods. RES such as photovoltaic panels, solar water heaters, wind turbines, can be incorporated into the building design to supply a significant portion of the building's energy needs, reducing the reliance of the building on fossil fuels but also lowering its overall carbon footprint. The use of renewable energy technologies is increasingly being recognized as an integral component of building energy efficiency strategies. Solar energy, in particular, has gained widespread adoption due to its versatility and adaptability to transform energy on-site.

3.4 Carbon emissions in the operational stage of the building life-cycle

During its life-cycle, a building produces CO_2 emissions at varying levels across different stages. Firstly, the terms *energy* and *carbon* need to be properly distinguished, as they are often used interchangeably, which can lead to misunderstandings. Carbon emissions are linked to the type of energy used, with the amount of carbon produced depending on the source of the energy. Different energy sources carry varying carbon footprints, with fossil fuels resulting in significant carbon emissions when burned for energy. For instance, energy derived from coal, oil and natural gas, results in high carbon emissions due to the combustion process releasing significant amounts of CO_2. On the other hand, energy derived from on-site or near site renewable sources, like solar, wind or geothermal energy produces less carbon emissions. This clearly illustrates how the relationship between the type of energy used and the resulting carbon emissions related to technical systems is linear.

However, the same straightforward relationship can not be drawn for the embodied carbon. It represents the total amount of carbon emissions generated during the entire life-cycle of building materials. This includes the extraction of raw resources, the processing and manufacturing of materials, transportation to the construction site, the actual construction process as well as the deconstruction and the disposal phases. Each of these stages contributes to the total embodied carbon footprint of a building. Unlike operational carbon, which is primarily concerned with energy use during the building's functional phase, embodied carbon is spread across the various stages of a building's creation and disposal. While this topic is beyond the scope of the current thesis, it presents an intriguing area for future research in the field of building energy performance optimization, offering valuable insights for more sustainable construction practices. Operational carbon, on the other hand, is strictly associated with the emissions resulting from activities conducted during the building's operational phase, which begins once construction is complete. This phase includes processes such as heating, cooling, lighting, and the provision of domestic hot water, as well as the energy consumption of various appliances and other building-related energy uses. The operational phase is typically the most energy-intensive period in a building's life-cycle, and thus, it is crucial to address and optimize energy efficiency to minimize carbon emissions.

Several key factors influence a building's operational carbon emissions, each playing an important role in the overall energy performance. The building envelope that includes walls, roof, floor, and windows acts as the primary barrier between the indoor and outdoor environments. High-performance envelopes with proper insulation, high-quality windows, and excellent air tightness can dramatically reduce the energy needed for heating and cooling. The efficiency of the building's systems, particularly HVAC, also has a substantial impact. High-efficiency heating and cooling systems, coupled with heat recovery ventilation and smart building automation, can significantly reduce energy consumption. Similarly, the use of energy-efficient lighting, such as LEDs, can cut electricity use. For grid-supplied electricity, the carbon emissions depend on the energy mix used for feeding the local grid. The emissions can also vary from one country to another: areas with high proportion of renewable energy in their mix can have lower carbon intensity, while those who still rely heavily on coal or gas have higher emission rates. In Table 4, a list of Life Cycle Assessment (LCA) emission factors for consumed electricity across various EU countries illustrates these differences. France and Sweden stand out with the lowest emission factors, attributed to their substantial investments in nuclear and renewable energy. Conversely, Italy's carbon intensity is above the EU average of 0.578 tCO_2eq/MWh_e, reflecting its reliance on a more carbon-intensive energy mix. This unit of measure is commonly used to quantify the carbon intensity related to an energy source. CO_2 is not the only greenhouse gas considered as also methane (CH_4) and nitrous oxide (N_2O) are included converted to their CO_2 equivalent based on their global warming potential [39].

Additionally, occupants' behaviour can have a surprising impact on the energy use and, consequently, on the carbon emissions. Variables such as temperature set points, the exploitation of natural ventilation, the shading and the operation of equipment and appliances all contribute to the overall energy profile. The intended use of the building is one of the main factors influencing the occupancy rate: municipal, residential, tertiary buildings have different schedules that need to be evaluated accordingly. Even the building's geometry and orientation can influence its carbon footprint. The shape of a building affects its surface area to volume ratio, which in turn impacts heat gain and loss. The orientation can affect solar gains and daylight, both of which have implications for energy use.

Table 4: National emission factors for consumed electricity - example of some European countries. From: Technical annex to the SEAP template instructions document: the Emission Factors [39]

Country	**LCA emission factor (tCO_2eq/MWh_e)**
Austria	0.310
Belgium	0.402
Germany	0.706
Denmark	0.760
Spain	0.639
France	0.146
Greece	1.167
Italy	0.708
Netherlands	0.716
Sweden	0.079
Poland	1.185

4 Preliminary analysis

In the initial stages of this research, an exhaustive analysis of the current European Union legislation and academic insights in the field was carried on. As seen in the previous chapters, this examination unravelled some critical gaps and challenges within the building sector, specifically concerning the optimization of building energy performance and the definition of ZEB buildings. While the regulations do not set a specific carbon emission threshold, they require that every EU country takes the proper actions to refurbish buildings to have a very high energy performance. The driving force carrying this thesis is to address such challenges through innovative solutions that integrate advanced simulation tools and optimization algorithms.

4.1 Problem statement

The substantial environmental impact the building sector is responsible for underscores the critical need for innovative approaches to decarbonize the building stock and to optimize building energy performance. Despite the availability of advanced simulation tools and optimization algorithms, the goal of optimising building energy performance remains challenging due to several factors. Complexity associated with building systems is one of the main problems. Changes in one specific parameter can have cascading effects on other system variables it is interacting with, making it difficult to predict overall performance. Predicting building energy performance means to have a deep knowledge on building design involving the balance of multiple objectives, such as minimizing energy consumption, reducing carbon emissions, maintaining occupant comfort above a certain level and managing construction and operational costs. A detailed building energy simulation is computationally expensive and the tools that help in achieving that can only simulate for an extended period of time. One of the solutions for reducing the simulation time is to limit the number of design alternatives that can be evaluated in a reasonable time-frame. For doing this, a crucial step is to properly weight the balance between accuracy of the results and simplification of the model, referring to the concept of "balanced accuracy", as already mentioned in Section 2.4.4.

As buildings are dynamic systems, they respond to changing environmental conditions, occupancy patterns, and internal heat gains. This is the main reason why static or steady-state simulation models often fail to capture the multi-faceted energy flows and thermal behaviours that occur in real buildings over time. This is translated in the necessary use of dynamic simulation tools (i.e. EnergyPlus) which, while accurate, they are also computationally intensive and time-consuming to run, posing challenges for optimization process that require numerous interactions. Additionally, while dynamic energy simulation tools provide accurate results, they are not typically designed with an integrated optimization model. Another important aspect in evaluating overall building energy performance is to properly connect the envelope and the systems optimization. Many already existing approaches focus on the optimization of either the building envelope or the technical systems in isolation, potentially missing synergies between these interdependent aspects. Although important, these issues are also difficult to address given the complexity of the optimization algorithms that run the whole process. That is why professional figures need to have a proper knowledge background to be able to operate with an optimizer.

Moreover, while EU regulations, such as the Energy Performance of Buildings Directive aim to improve building energy efficiency and promote Nearly-Zero Emission Buildings, they do not provide clear thresholds or limits for carbon emissions. The lack of an exhaustive regulation regarding emissions complicates the standardization of energy optimization processes across the EU. These regulations also leave room for interpretation, meaning that while some buildings may meet the prescribed energy efficiency targets, they may still fall short of more aggressive carbon reduction goals.

4.2 Research objective

This thesis aims to address the aforementioned global and engineering challenges associated with energy consumption by developing and implementing a comprehensive multi-step, multi-optimization approach for improving building energy performance and reducing operational carbon emissions in the building stock. In doing so, the research addresses both global and engineering challenges, including the complex issues of end-user utilization, visualization, and compliance with European Union regulations. The core objective is to develop a robust two-stage optimization framework that sequentially optimizes building envelope parameters and technical systems, capturing the interdependencies between these two aspects. A significant advantage of this framework is its automation, user-friendliness and visualization capabilities. The implementation of traditional optimization algorithms can be a complex and challenging process. The objective of this research is to overcome these complexity barriers by providing an automated tool that simplifies the optimisation process and presents results in an interactive and intuitive manner. This approach addresses the critical need for a tool that is not only technically sound but also accessible and simple for end users, including architects, engineers, and building managers. The first optimization stage is focused on the evaluation of the best solutions regarding the envelope thermal parameters with fitness functions based on the calculation of energy consumed for heating and for cooling. The final optimised parameters will then be used for the second stage of the process, focused on the carbon emissions related to the technical systems during the operational phase of the building life cycle, contributing to a more sustainable long-term building operations.

In pursuing these objectives, an intrinsic goal is to bridge the gap between theoretical optimization and practical real-world application in the professional field. While the most energy-efficient solutions may be identified through simulation and optimization, they are often not practical or feasible when implemented in real-world scenarios due to several constraints such as complexity, costs, material availability, or site-specific conditions. For this reason, the optimization tool provides the best trade-off solution that can optimize at the same time two conflicting objectives, which are firstly the thermal energy need for heating and for cooling, and secondly the delivered energy and the assiociated carbon emissions. Finding proper solutions means not only to minimize overall energy consumption, but also to search for solutions that compromise between multiple, often conflicting criteria. The multi-objective optimization approach employed in this research allows for the consideration of these conflicting objectives and seeks to find compromises that result in the best possible outcomes. Ultimately, this research intends to contribute to the achievement of ZEB levels. The optimization tool developed in this thesis could also serve as a valuable starting point for building professionals during the design phase, providing insights into the most effective strategies for minimizing energy use and carbon emissions. Currently, there is no common range for acceptable carbon emissions for ZEBs, as each EU member state is supposed to set its own threshold value. With this tool, it could be possible to hypothesize a possible range of carbon emissions that allows to reach this level, considering the current building stock.

The final step in the optimization process is to present the results in a simplified, clear, and accessible format, ensuring that they can be easily understood by a wide range of users, including those without technical expertise. The challenge lies in translating complex analytical data into a format that is not only digestible but also meaningful, allowing stakeholders to make informed decisions. This is crucial, especially in fields like building performance optimization, where the technical nature of the data can create a barrier to broader comprehension. To bridge this gap, the results need to be communicated in a way that highlights key insights and actionable outcomes without overwhelming the end user with technical information or overly detailed metrics. Interactive visualizations, such as dynamic charts, graphs, and dashboards, are highly effective tools for achieving this. These visual aids allow users to engage with the data in an intuitive manner, exploring different facets of the results without needing an in-depth understanding of the underlying computational methods.By presenting the optimization results through custom-tailored visualizations, stakeholders from diverse backgrounds—whether they are engineers, architects, policymakers, or building owners—can engage with the data meaningfully. This ensures that the outcomes of the optimization process are not only accessible but also actionable, supporting better decision-making and promoting more sustainable building practices. Ultimately, this approach ensures that the complexity of the analytics is distilled into a format that drives understanding, fosters collaboration, and encourages informed action across all levels of project involvement.

As to provide a practical demonstration of the proposed optimization methodology, this thesis will use the case study of the Manifattura Tabacchi project, set in Turin, Italy. By applying the multi-step, multi-objective optimization framework to this real-world example, this study will not only illustrate the process in action but also allow for an in-depth analysis of the results. Manifattura Tabacchi, an iconic former industrial complex, represents a significant challenge and opportunity for energy optimization, as it is currently undergoing redevelopment and refurbishment. This setting offers an ideal platform for testing the effectiveness and robustness of the proposed optimization framework. By implementing the optimization method in this real-life scenario, the thesis aims to demonstrate not only the feasibility of the proposed approach but also its potential to deliver measurable improvements in energy efficiency and carbon emission reductions. Furthermore, the case study will serve as a testing ground to assess the resilience and adaptability of the optimization framework under various conditions. The visualization of the results of Manifattura Tabacchi will be a valid way to validate and determine the strengths and weaknesses of the approach, ensuring that the framework is refined and improved for future applications, while also empathizing with the end user. Effective visualization and interoperability are critical to ensuring that the optimization results are practical and actionable. This research culminates in the development of an interactive visualization platform that presents optimization results in a clear and user-friendly manner. By providing end-users with intuitive, interactive dashboards, the tool facilitates a deeper understanding of the optimization outcomes and supports informed decision-making. This aspect is particularly important for professionals who must interpret complex data and apply it in real-world scenarios.

5 Methodology

The following section presents the overall methodology employed in this thesis to achieve optimal building energy performance, addressing key challenges such as software interoperability, ease of employment from end users and compliance to EU standards and regulations. The chapter outlines each critical step, providing a clear understanding of the process from initial concept to final implementation. The initial intention was to integrate the NSGA-II algorithm within the Autodesk Revit environment, via Dynamo. Such integration was firstly considered because of the great potential the platform holds for parametric design and optimization. However, as the analysis progressed, it became evident that this integration was not feasible anymore due to issues with software interoperability and associated limitations.

Given these challenges, alternative methodologies were explored, in order to achieve the optimization objective defined. The research shifted focus towards a more flexible approach, leveraging multiple platforms, without excluding Revit. This included the use of Python for scripting and automation, and Microsoft Excel for managing data and running energy simulations, in order to bridge the gaps between design, simulation, and optimization processes, while ensuring compliance with current EU directives, such as the EPBD. This chapter also investigates the strategies employed to ensure these diverse tools interacted efficiently, highlighting the importance of data interoperability and the iterative nature of the optimization process. Each platform's role in the overall workflow is discussed in detail, illustrating how the tools were integrated to overcome the initial technical challenges and ultimately achieve the goal of optimizing building energy performance. Additionally, the visualization of results is effectively communicated at the end through an interactive dashboards in Microsoft PowerBI. Furthermore, this chapter clarifies how the algorithm was configured as a tool to meet the diverse needs of various stakeholders and end-users, detailing the conditions and user requirements that shaped its development, ensuring practical applicability in real-world scenarios. Figure 5 illustrates the procedural scheme employed in this thesis. Each step will be explained in detail in the subsequent sections.

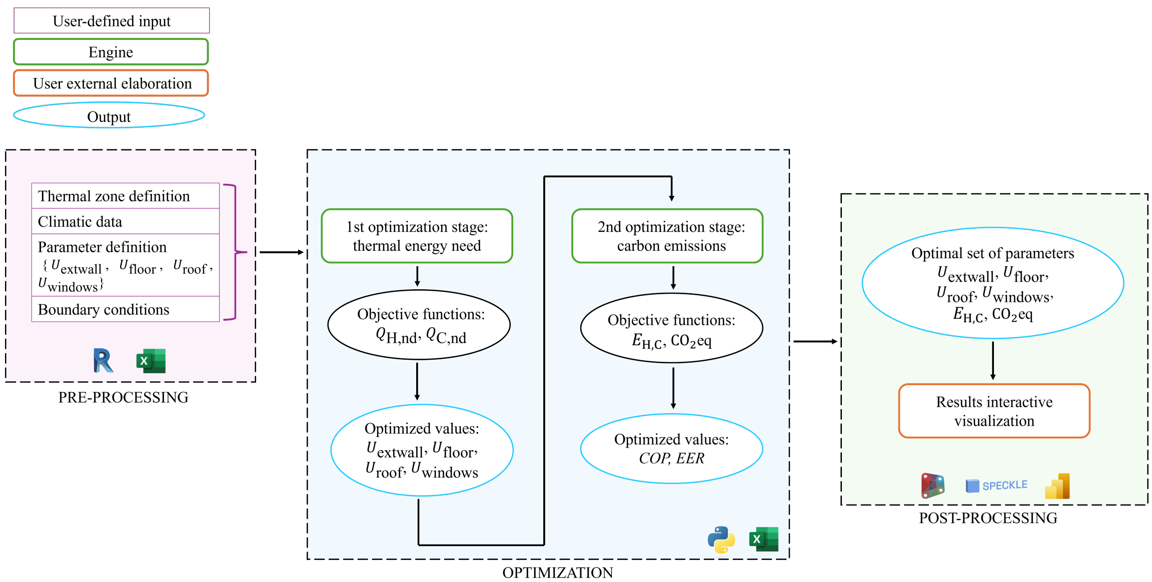


Figure 5: General procedural scheme

5.1 Integrated algorithm workflow tailored for end-user solutions

The procedural workflow presents a multi-stage framework that allows to minimize computational time required to identify reliable results for energy retrofit solutions for buildings. The different stages are the following:

1. Preliminary analysis and selection of the Energy Efficiency Measures (EEMs) for both stage 1 and stage 2

2. First optimization stage: two-objective optimization of thermal transmittance related to the building envelope for reducing the thermal energy demand for space heating and cooling

3. Second optimisation stage: technical system optimization according to the previously found envelope parameters for reducing carbon emissions

4. Transmission and graphical visualization of the results obtained

Dividing the optimization in different stages not only reduces the computational time but also allows to explore better and well-mixed sets of energy efficiency measures. Figure 6 presents a summary of the principal elements of this optimization problem, subdividing them depending on their purpose. The decision variables are including the EEMs chosen for this specific optimization method, while the objectives are employed as fitness functions in NSGA-II. Finally, the constraints are set at the beginning and they are limited by a lower and an upper threshold value.

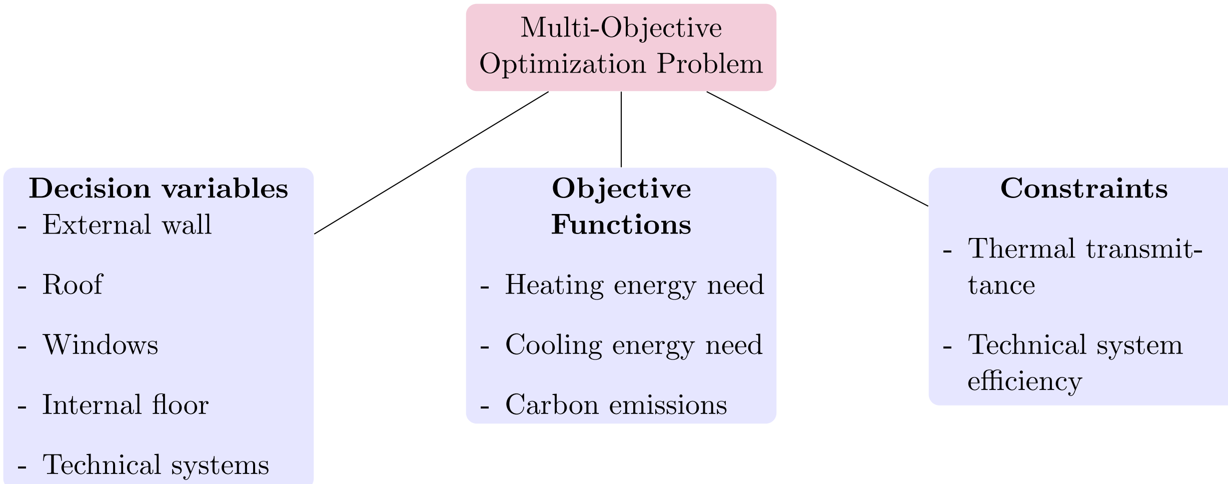


Figure 6: Summary diagram of the main components of the optimization problem

The composition of the algorithm presented in this thesis is the result of an extensive research, as already discussed in Section 3 - Literature Review. While the field of building energy performance optimization has been widely explored, it seems that no existing tool currently integrates all the necessary components required for assessing both energy efficiency as requested by EU standards and practical industry needs. For instance, the work of Ascione et al. contributed to the development of diverse algorithms, specifically focusing on the energy analysis, providing valuable tools for optimizing thermal energy demand coherently with current EU directives. However, these algorithms do not provide an integration with any BIM software. On the other hand, Asl et al. [36] proposed a solution that focuses on building optimization within BIM environments, particularly aimed at reducing the complexity of integrating multiple tools and just perform the optimization with one algorithm. Although this approach is effective in simplifying interoperability within the BIM environment, it does not address the wider spectrum of energy performance considerations, nor does it fully align with the rapidly evolving legislative landscape.

The tool developed as part of this thesis is distinguished by its capacity to bridge these gaps, offering a more integrated and flexible approach. Considering the current EU legislative framework, as explored in Section 2, the algorithm has been designed to adapt to the evolving regulatory framework that aims to unify energy performance standards across all Member States. EU's commitment to creating a consistent set of regulations that facilitate the transition towards nZEB and ZEB is a driving factor in the development of this tool.

By incorporating these legislative priorities into its core functionality, this tool can address both immediate and long-term regulatory energy-related needs for buildings. In addition to fulfilling the requirements of policy compliance, this tool has been designed with the end-users in mind, focusing on professionals who work in the building sector, such as engineers, technicians, designers and architects. In recognition of the operational challenges faced by these stakeholders, the tool has been developed to be almost fully automated, necessitating neither manual intervention nor modification to the fundamental parts of the code. Adjustments are only required when the files the algorithm is interacting with are changing. This ensures that users, regardless of their technical background, can implement the tool without concerns about complex software integration or the need for technical adjustments. The seamless interoperability between different software platforms, including BIM and energy simulation tools, is another key feature, simplifying the workflow for professionals linked to the building sector.

Moreover, one of the core strengths of this tool lies in its compliance with EU standards for calculating energy performance of buildings, particularly the EN ISO 52016-1. This ensures that the tool not only meets current regulatory requirements, but is also aligned with best practices in energy performance assessment. Nevertheless, the adaptability of the instrument is not limited to the mere fulfillment of static compliance. After recognizing the dynamic nature of the regulatory environment, the tool has been designed with adaptability in mind, as explained earlier in this thesis. As new directives or calculation methods keep emerging, the tool can be easily modified to reflect these changes. By simply updating the associated Excel sheets used for the calculation for both phases, users can tailor the tool according to their needs and the prevailing legislative context at the same time. Such adaptability allows the tool to remain a practical and relevant solution even in the context of evolving regulatory frameworks and requirements regarding energy performance.

As summarized in Table 5, the innovative tool presented in this thesis addresses a wide spectrum of issues spanning technological, social, political, and research-related domains. Each of these dimensions plays a fundamental role in the successful development and deployment of the tool, and their integration ensures an integrated approach to solving the challenges faced by the building sector today. From a technological perspective, the tool's operational functionality is bases on the synergy between various platforms and software components that allow its seamless execution. A key aspect of this functionality is the interoperability between these platforms, which ensures the tool's ability to ease communication between different software environments without compromising the accuracy or quality of the results. Interoperability, in this context, refers to the seamless integration and communication between distinct technological systems, which allows for the aggregation and analysis of data from diverse sources. Achieving this was possible through multiple attempts and testing phases, culminating in the selection of platforms and tools that support high-quality data exchange. Further technical details regarding the selection process and the integration of the platforms are better explained in Section 5.3 - Platforms, software applications and tools interoperability.

In addressing social considerations, the tool responds directly to the needs of its end users — primarily professionals in the building and construction sectors — by providing practical solutions to real-world challenges. The complexity of modern building projects often leads to inefficiencies in both time and cost. This tool offers a significant improvement in both areas, by streamlining the decision-making process during the design phase of construction and retrofit projects. By allowing stakeholders to visualize and interpret complex datasets more effectively, the tool intensifies understanding and fosters more informed decisions. The visualization of results is indispensable, as the ability to present complex analytical data in an accessible and user-friendly format influences the strategic decisions made during both the construction and retrofitting phases. To this end, the integration of a 3D model serves as a comprehensive representation of the project at both the initiation and conclusion of the process. Such 3D model ensures that professionals can easily understand the implications of various decisions, thereby aligning the data output with industry expectations and improving overall utilization. This capability not only optimizes workflow but also facilitates better communication between different stakeholders, particularly those less familiar with technical datasets, by presenting results in a familiar and intuitive format.

From a policy and regulatory standpoint, this tool offers substantial benefits in relation to European Union regulations governing the energy performance of buildings. One of the major challenges faced by stakeholders in the building sector is the necessity to remain compliant with constantly evolving regulatory framework. These policies, which are influenced by environmental and energy efficiency goals, impose strict requirements that stakeholders must adapt to. The tool mitigates this challenge by being designed to align with current EU directives, such as the EPBD, while maintaining the flexibility to accommodate future policy changes. By simplifying the process of regulatory adaptation, the tool allows users to easily modify the attached files for energy simulations to reflect updated regulations. This adaptability is particularly useful for ensuring compliance with energy efficiency targets set forth by the EU, and it positions the tool as an helpful asset for stakeholders seeking to navigate the complexities of building regulations without incurring significant delays or costs, while adhering to policy changes.

Research, as the prime driving force, serves as the foundation for the entire tool's development. In particular, research efforts focused on the identification the most effective methods for optimizing building energy performance. These efforts began with an investigation into the EEMs, which laid the groundwork for the subsequent stages of the process. The incorporation of the NSGA-II optimization algorithm constituted a further significant outcome of this research project. Additionally, the tool draws upon the EN ISO 52016-1 technical standard, which outlines the methodology for calculating the energy performance of buildings. While technical standards such as EN ISO 52016-1 provide valuable frameworks for conducting energy performance assessments, they are voluntary guidelines. In contrast, regulations like the EPBD are legally binding and compliance is mandatory for MS. Figure 7 represents a schematic circular workflow with the key words referring to the main parts of the methodology scheme.

Table 5: Summary methodology scheme

PROBLEM FORMULATION	
END USER NEEDS	POLICIES
• Easy access to an optimization tool • Easy use and implementation • Limited input • Simplifying compliance to current EU legislation	• nZEB and ZEB levels (EPBD) • Decarbonization of the building stock by 2050 • Long term and short-term goals • Adaptability to different EU requirements
RESOLUTION PROCESS	
RESEARCH	TECHNOLOGY
• Formulation of Energy Efficiency Methods (EEMs) • Optimization methods (NSGA-II) • EU technical standards for EP calculation (EN ISO 52016-1:2017)	• Application of the algorithms • Interoperability • Exchange data format (IFC) • Communicative dashboards
SOLUTIONS ANALYSIS	
END USER NEEDS	POLICIES
• Optimized solutions • Easy acknowledgement of final results • Integration inside BIM environment	• Confirmation of compliance with EU current directives

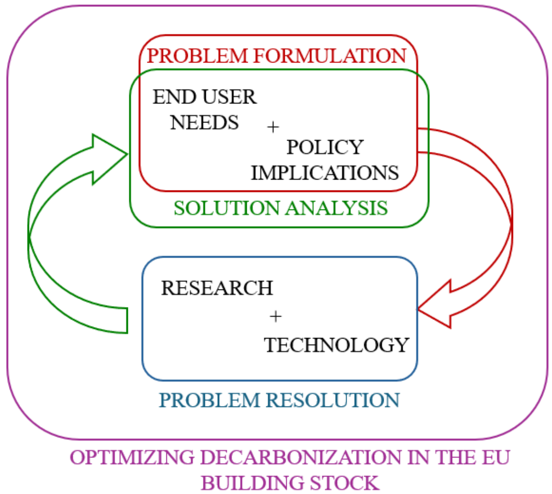


Figure 7: Graphical representation of the circular workflow and the actors involved

5.2 Initial attempt with Dynamo Revit: parametric optimization in BIM environment

Visual Programming Languages (VPL) have become increasingly essential in the field of Building Information Modelling (BIM), offering customizable and flexible form-generating algorithms that can significantly enhance the design process. Dynamo, an open-source VPL managed by Autodesk within the Revit environment, exemplifies this integration. VPLs like Dynamo empower users by providing a Graphical User Interface (GUI) that makes programming more accessible and intuitive, especially for non-programmers or those new to coding. This GUI-centric approach allows users to manipulate code graphically rather than textually, streamlining the process of parametric-BIM modeling and fostering a more user-friendly experience. BIM-VPL integration represents a powerful tool for automating numerous tasks within the BIM workflow. These tasks can range from simple data manipulation to complex form generation and optimization processes. The visual nature of VPLs, such as Dynamo, enables users to engage with and modify algorithms dynamically, fostering a more interactive and responsive design environment. Another popular VPL in the design industry is Grasshopper for McNeel Rhinoceros, which, like Dynamo, is based on the Python programming language. Both of these tools underscore the growing importance of VPLs in modern architectural and engineering practices. A key application of Dynamo within the BIM environment is the implementation of optimization algorithms, such as the Non-Dominated Sorting Genetic Algorithm (NSGA-I and NSGA-II). The Optimo package, developed by Mohammad Rahmani Asl and Dr. Wei Yan from Texas A&M University [36], facilitates this process. This package equips Dynamo with nodes that contain pre-built code, simplifying the optimization process to its essential components. Users need only to focus on defining the fitness functions, which are crucial for calibrating the model accurately, on the initial population and on the eventual initial constraints [40].

The workflow for implementing the NSGA-II algorithm in Dynamo, as illustrated in Figure 8, begins with the collection of upper and lower limits for each chosen parameter from a specific Excel sheet. These initial constraints form the foundation for the optimization process. After setting these constraints, users can define the population size and the number of objectives, which correspond to the number of fitness functions. These functions are created using customized nodes that incorporate Python code. The "AssignFitnessFuncResults" node evaluates the initial solution list by applying the fitness functions, and the NSGA-II algorithm iterates through this process until all specified iterations are completed. Finally, the results are exported to another Excel sheet within the same file used for the initial parameter limits.

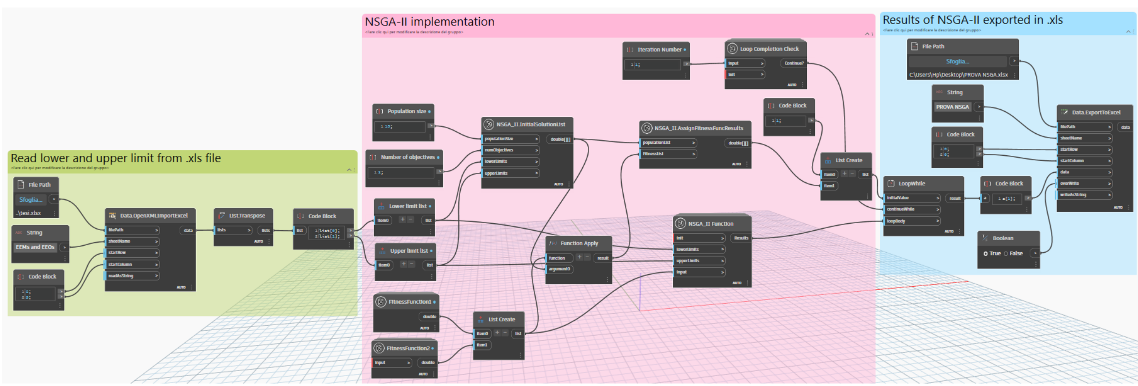


Figure 8: Dynamo workflow for NSGA-II implementation

Despite the robust capabilities of this workflow, a significant challenge was encountered during its implementation. Dynamo struggles to interact effectively with macros used in the Excel files that perform energy simulations according to EN ISO 52016-1. This limitation was a starting point for a deeper analysis within the scope of this thesis. Addressing this issue requires further development and refinement of the interaction between Dynamo and Excel macros, ensuring seamless integration and accurate energy simulation results. The issue encountered was a starting point for the modifications made in the tools and programs used for achieving the aim of this thesis. An alternative prototype of the optimization model involves substituting the tool dedicated to perform the energy simulation. Its workflow is visible in Figure 9. Instead of relying on the Excel sheets, an energy model can be generated in a gbXML format (Green Building eXtended Markup Language), as it retains all necessary information for energy simulation, using Revit's Application Programming Interface (API). "RunAnalysis.CreateProject" node is useful for creating a new project in Green Building Studio (GBS) that extracts all the useful information from the BIM model. The gbXML can be created either based on masses or zones, with dedicated nodes for each method that will be chosen by the user. Subsequently, the "RunEnergy-Analysis" node runs the energy analysis for each gbXML file if multiple files are present. Bypassing the macros in the Excel sheets and substituting them with a dedicated tool with another format like gbXML can be one of the solutions for working seamlessly with Dynamo. The approach here described necessitates careful consideration of the level of detail (LOD) adopted in the BIM model, as the energy simulation relies largely on the 3D model's accuracy. Achieving optimal results requires a careful balance, ensuring that the model's details are sufficient to provide as accurate simulations and results as necessary. This method not only improves the integration and functionality within Dynamo but also enhances the precision and reliability of the energy simulation outcomes.

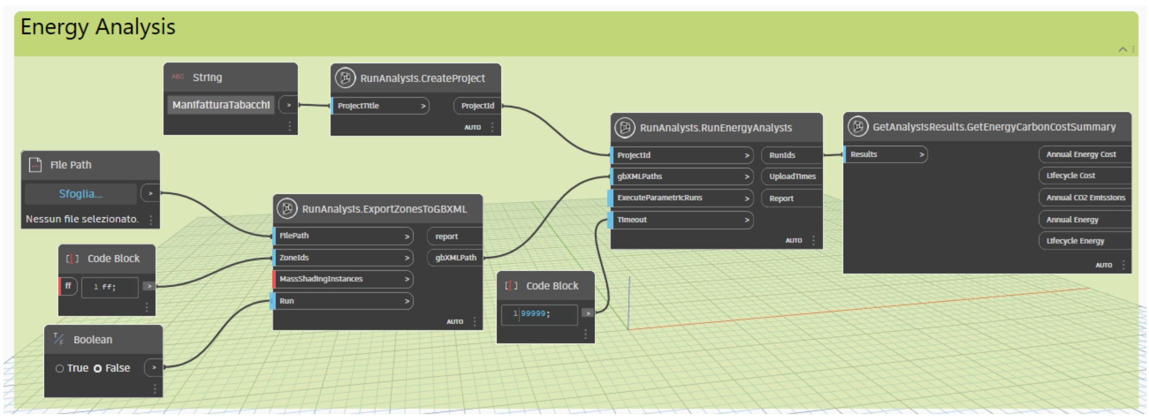


Figure 9: Modified workflow with automated energy analysis inside Revit

5.3 Platforms, software applications and tools interoperability

The successful implementation of this multi-stage optimization model relies on the seamless integration of various softwares, tools and platforms. Despite the challenges, such smooth integration was crucial for bridging the gaps between BIM, energy simulations and optimization algorithms. In order to achieve the objectives of this thesis, the following tools have been employed: Autodesk Revit, Python, Microsoft Excel, Microsoft PowerBI. The challenges encountered highlighted the importance of developing robust interfaces and data management strategies for working in a multi-tool environment. Figure 10 shows the workflow process that helped in achieving such objectives, alongside with the platforms employed for each stage.

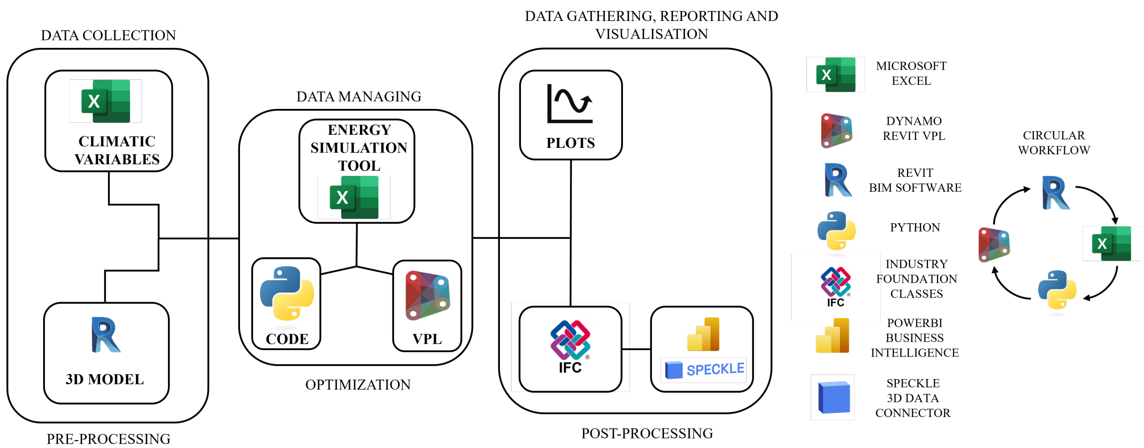


Figure 10: Workflow and interoperability scheme

5.3.1 3D Model in Autodesk Revit

The starting point for this analysis is an Autodesk Revit BIM model of a case study. A refined BIM model serves as both the foundation and the ultimate destination for the optimization process, creating a circular workflow, as already mentioned in Paragraph 5.1. As a starting point, it provides data about the hypothesised refurbished envelope build-up like the external and internal walls and the roof and floor structures. As new optimal solutions for envelope components are identified, these are finally re-integrated into the BIM model. Ultimately, the optimized data derived from the analysis will be fed back into the element properties of the 3D model. This creates a closed-loop process where the initial values to be optimized are extracted from the BIM model and the optimization results will then update again the 3D model. This closed loop ensures that every modification is fed back into the digital model, maintaining a dynamic link between simulation resutls and the building's virtual representation.

5.3.2 Python code

Python acts as the engine driving the optimization process, exploiting a combination of libraries to automate simulation and data processing. The optimization code is able to interact automatically with the macros present in the Excel file. The whole optimization algorithm is based on libraries and custom-built components that address the objectives of the optimization. At the core of the implementation lies the DEAP (Distributed Evolutionary Algorithms in Python) library, which allows evolutionary computations that are the basis for the genetic algorithm implementation. It provides robust methods for defining individuals, populations and evolutionary operations like mutation and crossover. Additionally, the win32com.client library is used to automate interactions with Microsoft Excel, allowing the code to establish the input parameters and execute macros for energy simulation. The matplotlib library is then added in order to visualize graphically the Pareto front and the results obtained. Timeout mechanisms, implemented using threading and custom decorators, ensure that operations do not hang indefinitely, making the system more reliable. The numpy library provides efficient array operations and statistical functions. It is used for calculating fitness statistics and managing large datasets of simulation results. Timeout mechanisms, implemented using threading and custom decorators, ensure that operations do not hang indefinitely, making the system more reliable. The code also includes comprehensive logging for tracking the process and debugging purposes.

5.3.3 Application of NSGA-II algorithm

The Non-Dominated Sorting Genetic Algorithm (also in short NSGA) is an optimisation algorithm designed as an extension of the genetic algorithm. Its objective is to find a set of optimal solutions for problems with either one or multiple, often conflicting objectives. The NSGA algorithm is derived from the genetic algorithm with some particular differences in terms of performance. It performs a faster, non-dominated sorting of individuals before the selection phase, increasing the probability that better individuals are retained. The rest of the structure remains the same as a basic genetic algorithm. The specific objective to be pursued will determine the type of NSGA that should be employed: NSGA-I, NSGA-II or NSGA-III. The present thesis analyses only NSGA-I and NSGA-II. The main difference between the two methods lies in the number of objectives: NSGA-I can only tolerate one, while NSGA-II can tolerate multiple. In the context of building energy performance optimisation, both methods have been used with different goals, however the Genetic Algorithms have mainly been implemented for optimizing shape, orientation, type of HVAC system, structural elements or even thermal comfort. This chapter will undertake a detailed examination of NSGA-II, given the greater complexity of the algorithm and its status as the successor to NSGA-I. Nevertheless, the discrepancies between the two genetic algorithms are outlined in Table 6 in order to provide a more comprehensive explanation of the rationale behind the selection of one algorithm over the other in this thesis.

Table 6: Main differences between the two Genetic Algorithms

NSGA-I	**NSGA-II**
Non-elitist approach	Elitist approach
Fitness based only on non-domination level, without crowding distnace	Fitness based on non-domination level and crowding distance
Single-step fitness assignment	Two-step fitness assignment (non-domination rank, then crowding distance)
Entire population replaced by offspring in each generation	Combines parent and offspring populations, selects best N individuals
Does not preserve diversity very well in solutions	More effective in maintaining a diverse Pareto front
Less suitable for many-objective optimization	More adaptable to many-objective problems

The three core principles of the NSGA-II optimisation method are (1) the non-dominated sorting, (2) the elitism and (3) the crowding distance. The first is a technique used to classify solutions based on Pareto dominance. A solution x_1 is said to dominate another solution x_2 if x_1 is no worse than x_2 in all objectives and x_1 is strictly better than x_2 in at least one objective. Solutions are sorted into different fronts based on their level of non-domination. The first front consists of non-dominated solutions, the second front consists of solutions dominated only by those in the first front, and so on. The elitism is incorporated into NSGA-II to ensure that the best solutions keep proceeding to the next generation. This is achieved by preserving the best solutions from both parent and offspring population in each generation. NSGA-I lacks an explicit elitism mechanism, which can lead to the loss of good solutions found in earlier generations. Finally, the crowding distance is a metric obtained for measuring how close a solution is to its neighbors. It is particularly useful to maintain diversity in the population by favouring solutions that reside in less crowded regions of the objective space. The distance is calculated by sorting the population according to each objective function value and computing the normalised distance between neighboring solutions. NSGA-II does not have a well-defined mechanism to ensure diversity in the population. The algorithm structure followed by the NSGA-II method involves several steps schematized in Figure 11.

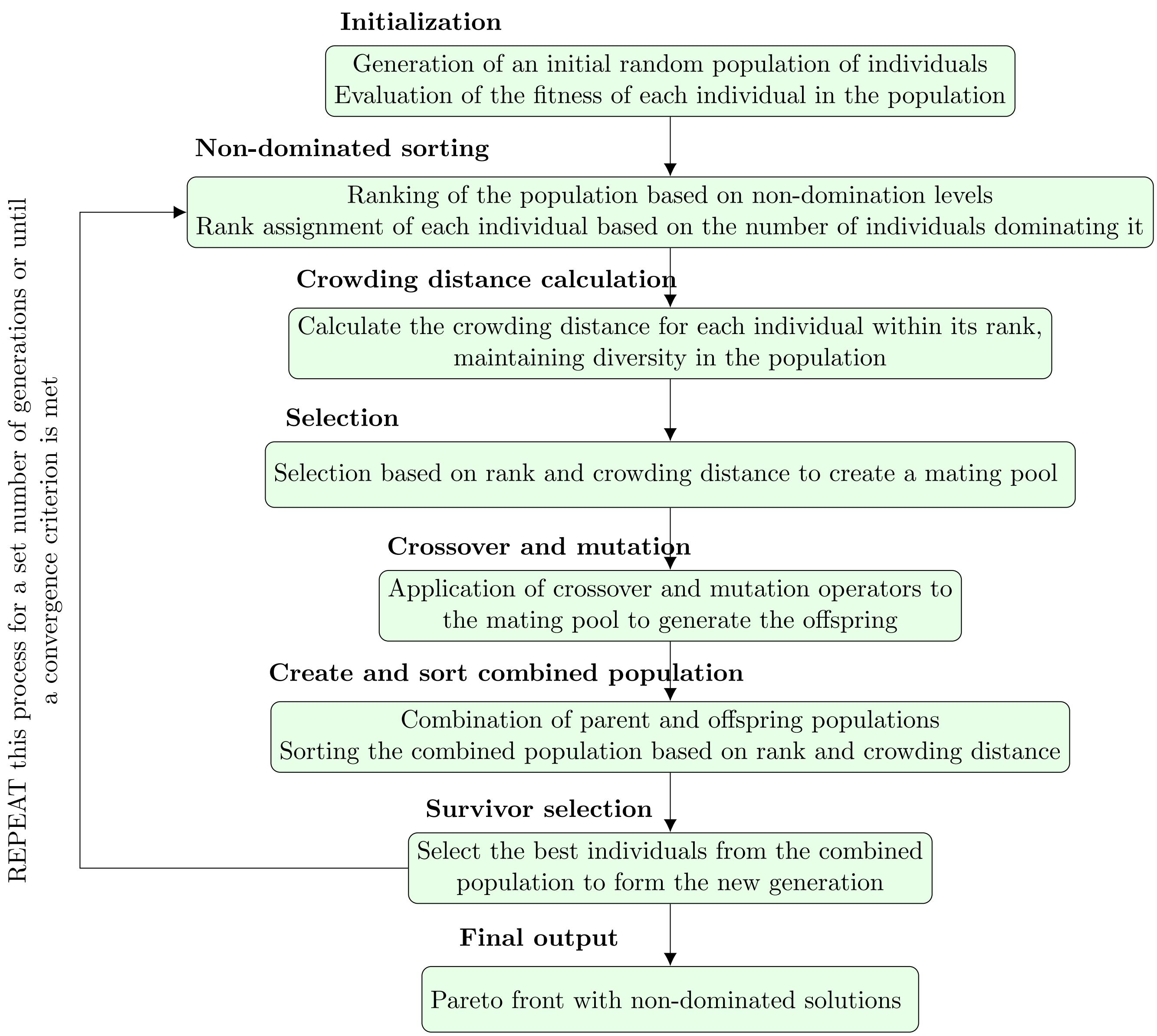


Figure 11: NSGA-II algorithm workflow summarized

The implementation of the algorithm starts with the initialisation phase, in which the multi or mono-objective problem is defined. For this analysis, the focus is set on the simultaneous minimization of the energy consumption related to heating and cooling and, finally, of the carbon emissions identified in the operational phase only, which corresponds to the one related to energy technical systems. The decision variables in the optimisation are the thermal transmittance values for walls, floors, roof and windows as they represent the key thermal properties of the building envelope. The algorithm starts by creating an initial population of potential solutions, each representing a unique combination of the U-values previously described. The initial population is generated randomly within specified upper and lower bounds to ensure both practical feasibility and compliance with the current benchmark values available for the reference building for zone E.

After the initialization, the algorithm starts an iterative process, beginning with the evaluation phase. Each solution in the population is assessed using an Excel-based building energy simulation model that simulates the hourly method of EN ISO 52016-1. The evaluation process is computationally intensive and it is the most time-consuming phase of the algorithm. That is the reason why it has been implemented a caching mechanism as to avoid redundant calculations. The evaluation function is designed to handle potential errors in the simulation process, assigning penalty fitness values when necessary to maintain the integrity of the optimisation process. The core of the NSGA-II algorithm lies in the phases of population sorting and selection. The population undergoes non-dominated sorting, which is a process that categorizes solutions into different Pareto fronts. As already mentioned, a solution is said to dominated another if it is no worse than the other solution in all objectives and better in at least one objective. Non-dominated sorting uses this concept to partition the population into different "fronts" or levels of non-domination. Non-dominated sorting is crucial because it allows the algorithm to handle multiple objectives simultaneously without having to combine them into a single objective function. It allows the algorithm to maintain a diverse set of good solutions, representing various trade-offs, throughout the optimization process. The sorting into the Pareto front is complemented by the calculation of the crowding distance for each solution. These two metrics - the non-domination rank and the crowding distance - form the basis of the selection process, driving the population towards optimal trade-offs while maintaining diversity.

The algorithm then applies genetic operators to create offspring solutions. A blend crossover operator combines characteristics of parent solutions, while the Gaussian mutation introduces small random changes to maintain genetic diversity. Both operators are carefully constrained to ensure that new solutions remain within the specified variable bounds. In each generation, the offspring population Q_t is merged with the parent population P_t, creating the combined population $R_t = P_t \cup Q_t$ and the best individuals are selected based on their non-domination rank and crowding distance to form the next generation P_{t+1}. This elitist approach ensures that the best solutions are always retained, driving continuous improvement over generations. The algorithm iterates this process for a specified number of generations chosen by the user, progressively refining the population towards the Pareto-optimal front. The final population represents a set of trade-off solutions, each offering different balances between heating and cooling efficiency and carbon emission impact. The user can also be able to change the starting population size, which is usually four times the number of parameters to be optimized. Additionally, post-optimisation analysis is a critical component for this type of implementation. The final population undergoes extensive analysis and visualization, including the extraction of the Pareto front and the creation of various plots to illustrate the trade-offs between objectives. A correlation analysis is also performed to uncover relationships between input variables and performance metrics, providing valuable insights. In order to clarify the workflow of the Genetic Algorithm, it is possible to schematize its steps in the following pseduo-code.

```
Initialize population P_0 of size N
Evaluate fitness of P_0
t = 0
while not termination_criterion:
    Q_t = Crossover_and_Mutation(P_t)   //creation of offspring
    Evaluate fitness of Q_t
    R_t = P_t U Q_t
    Perform non-dominated sorting on R_t
    Select N individuals based on rank and crowding distance
    P_{t+1} = selected individuals
    t = t + 1
Return final Pareto front
```

5.3.4 Excel-based Energy Performance Simulation according to EN ISO 52016-1:2017

For assessing the energy performance of a building, an Excel-based simulation tool adhering to the EN ISO 52016-1 has been employed. It allows to perform a full annual calculation of the heating and cooling needs, with both the hourly and monthly method provided by the standard. The workbook is subdivided into various sheets based on their function: input data, calculation processes and output results. Most input data are similar for both methods, while the calculations performed are exposed side-by-side in order to allow comparison between the two methods, and consequently choose the most suitable for one's needs. More specifically, the hourly method is also employed for developing or for validating the correlation factors for the monthly method, ensuring accuracy and reliability. However, one of the main limitations of this instrument is that the calculations are restricted to one single thermal zone at a time. This approach fails to account for adjacent thermally unconditioned zones in the calculations. Furthermore, solar shading is not adequately addressed yet. The computational processes within the tool are performed by macros. For example, the hourly calculation of the thermal balance in the zone involves complex matrix operations for each building element, broken down into layers according to EN ISO 52016-1. Another macro performs the calculation of the hourly heating and cooling needs. While these macros help automate the process and add precision, they significantly increase the computational time requested for each iteration, making the tool more time-consuming.

5.4 First stage: heating and cooling energy need optimization

In the first stage of the optimization algorithm, the goal is to minimize at the same time the energy need for heating ($Q_{\mathrm{H,nd}}$) and for cooling ($Q_{\mathrm{C,nd}}$), expressed both in kWh units. Trying to optimize two functions at the same time requires the use of the NSGA-II, as pointed out in Section 5.3.3. For such calculations, the method employed for obtaining the energy needs is the hourly one presented in EN ISO 52016-1. The calculation are performed by the Excel file for energy simulation. The parameters to be optimized are listed in Table 7.

Table 7: List of parameters to be optimized in the algorithm stage 1

Parameter	Nomenclature	Range	Unit
External wall thermal transmittance	U_{extwall}	0.10-0.32	$\mathrm{W/m^2K}$
Floor thermal transmittance	U_{floor}	0.15-0.31	$\mathrm{W/m^2K}$
Roof thermal transmittance	U_{roof}	0.20-0.33	$\mathrm{W/m^2K}$
Windows thermal transmittance	U_{windows}	1.0-1.6	$\mathrm{W/m^2K}$

The envelope thermal transmittance is the main concern as it involves the parts exposed to the external environment. In defining the ranges for these parameters, a particular approach has been applied, particularly regarding the U-values. The upper limits are set slightly higher than the characteristic values typically associated with existing high-performance buildings. These values refer to the Italian Ministerial Decree dated 25/06/2015, which is further analyzed in Section 2.4. Such values represent benchmark parameters for reference buildings undergoing major renovations and they are specific for climatic zone E, the one in which the case study later analysed is set.
This deliberate overestimation serves as a strategic purpose: it allows to explore a broad spectrum of possibilities and combinations, considering how various U-values interact and influence each other when combined. The rationale behind this expanded range is rooted for a more comprehensive, better-fit solution. By allowing this slightly higher upper limit, it is possible to create a scenario where the interplay between different thermal transmittance values can be fully explored. This approach acknowledges that the optimal solution might

not always align perfectly with predetermined standards for individual elements. Such methodology recognizes that in the complex system of a building's thermal performance, the whole can indeed be greater than the sum of its parts. A combination of U-values that might seem sub-optimal when viewed in isolation could, actually, yield superior overall performance when working in combination. The result of this first step is a 2D Pareto front that explores the best solutions that minimize the energy need for heating $Q_{\mathrm{H,nd}}$ and for cooling $Q_{\mathrm{C,nd}}$ at the same time. Furthermore, the best range of values for $Q_{\mathrm{H,nd}}$ and $Q_{\mathrm{C,nd}}$ is used as a starting point for the next stage of the optimization algorithm.

5.5 Second stage: carbon emissions optimization

Building upon the results of the first phase, the second stage focuses on optimizing both the overall energy efficiency and the carbon-related environmental impact of the building's HVAC system. This phase incorporates the best U-values obtained from the first stage and introduces a new set of parameters for optimization, centered around the technical system efficiencies. Specifically, the Energy Efficiency Ratio (EER) and the Coefficient of Performance (COP) are used as key indicators, representing the ratio respectively of cooling and heating provided by a unit relative to the amount linked to a specific energy vector required for its generation. COP and EER are specific for heat pumps, which are the systems this stage is focusing on.

Initially, the second-phase optimization problem was approached using NSGA-I method. However, after a comparative analysis between NSGA-I and NSGA-II (as explained in Section 5.3.3), and careful considerations of the challenges encountered with NSGA-I results, the decision was made to transition to NSGA-II for this phase as well. The reasons behind this decision lie in the nature of the optimization problem, which, although centered on efficiencies, involves multiple objectives, as EER and COP are evaluated independently. NSGA-II was then selected due to its superior capability in generating high-quality solutions with a well-distributed Pareto front, which is critical for multi-objective optimization problems. Sampling is the first step involved in this second optimization process: the optimal value obtained from the heating and cooling energy needs Pareto front is selected and used as a starting dataset for the second optimization process. This selection provides a robust foundation for the building envelope, allowing to focus on the efficiency of technical systems instead. The initial population is generated randomly within the specified ranges for each scenario.

After an initial implementation with a set up including also gas boilers and chillers, it became immediately evident that these solutions were not only outdated but also inefficient in the context of modern energy demands and building retrofitting practices. Gas boilers, while historically common, are highly resource-intensive and no longer align with current energy efficiency goals. Such systems are now considered obsolete, especially when compared to the advanced technologies in the market nowadays. The performance results derived from scenarios involving gas boilers were significantly below the expected standards for energy-efficient buildings. These outcomes did not meet the key objectives of this phase of the project, which is focused on minimizing energy use. Given the clear difference of performance between gas boilers and energy efficiency requirements, these scenarios were deleted for further analysis. After the modifications, the second phase finally revolves around the two scenarios involving heat pumps, as they represent one of the most effective technologies to be used in building retrofit. This shift in focus is consistent with the overarching goal of this thesis, which is to explore and identify the best solutions for minimizing energy use. The specific ranges of performance related to the two scenarios are detailed in Table 8.

Table 8: Solutions for the heat pump scenarios and their related efficiency

Scenario number	**Solutions**	**Heating/ Cooling**	**Range *EER* [-]**	**Range *COP* [-]**
1	Reversible electric air-to-air heat pump	Heating + Cooling	8-14	2-7
2	Reversible electric ground source heat pump	Heating + Cooling	9-25	2-7

The energy demand E (in kWh) related to heating and cooling is calculated as follows:

$$E_H = \frac{Q_{\mathrm{H,nd}}}{COP}; \qquad E_C = \frac{Q_{\mathrm{C,nd}}}{EER}$$

Considering the proper COP and EER values for each evaluated scenario. The energy demand obtained is then divided for an utilization coefficient f_u, equal to 0,81. This coefficient is linked to the losses related to the delivery systems, which are unable to provide 100% of the energy generated. The carbon emissions associated are then calculated according to a conversion factor f_c specific for each energy vector. In this analysis, the energy vector is the same for both scenarios. The general formula for calculating CO_2 emissions related to building technical systems is the following:

$$\mathrm{CO_2\ emissions} = E_{\mathrm{H,C}} \times f_{\mathrm{c,electricity}}$$

Where:

$E_{\mathrm{H,C}}$ is the delivered energy summed for heating and cooling; expressed in MWh

$f_{\mathrm{c,electricity}} = 0.708$ tCO_2eq/MWh is the conversion factor for electricity (see Table 4)

The impact of renewable resources is examined in a dedicated sheet of the same Excel file, where a calculation of the energy produced by the photovoltaic panels is performed. The orientation is to be considered the South-East one. The calculation is performed on an hourly basis and it uses the following parameters as input data:

$E_{\text{sol,pv}}$ is the solar energy input that a PV panel receives hourly, in Wh/m^2

K_{pv} is the the peak power, assumed here 0.15 W/m^2 for monocrystalline silicon

A_{pv} is the area covered by the panels in m^2

f_{pv} is the efficiency factor, here assumed 0.75 for PV modules partially ventilated

The electrical energy output, represented by the variable $E_{\text{el,PV,out}}$ in kWh, is calculated on an hourly basis over the course of the year. The values obtained for each hour are summed to obtain the yearly value. Subsequently, this value is then subtracted to the delivered energy for heating and for cooling $E_{\text{H,C}}$, as this quantity is covered by renewable resources that produce electricity in situ.

5.6 Results visualization in PowerBI via Dynamo Revit

Once every phase of the optimization algorithm is completed, the optimized values of all the evaluated parameters are gathered in a results sheet in the same Excel file. This sheet contains the values of thermal transmittance, thermal energy need for heating and for cooling, the scenarios with the related efficiencies and carbon emissions in form of lists. Subsequently, to seamlessly integrate the final optimized values into the Revit model, a custom Dynamo script (shown in Figures 12, 13 and 14) is implemented. This script is designed to extract the thermal transmittance values directly from the results sheet (Figure 13) and automatically assign them to the corresponding building elements within the Revit model (Figure 14). To achieve this, a custom project parameter, named "U_value" is created within the Revit environment. This parameter is then integrated into the properties of each relevant building element within the project. By establishing this parameter, the thermal transmittance value can be effectively attached to the specified elements within the model, ensuring that the information is instantly accessible.

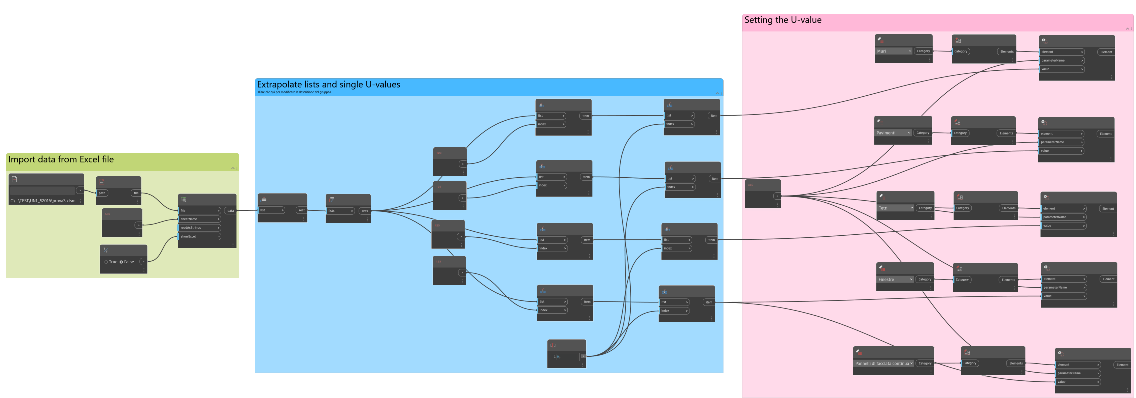


Figure 12: Transcription of the results - general workflow overview in Dynamo

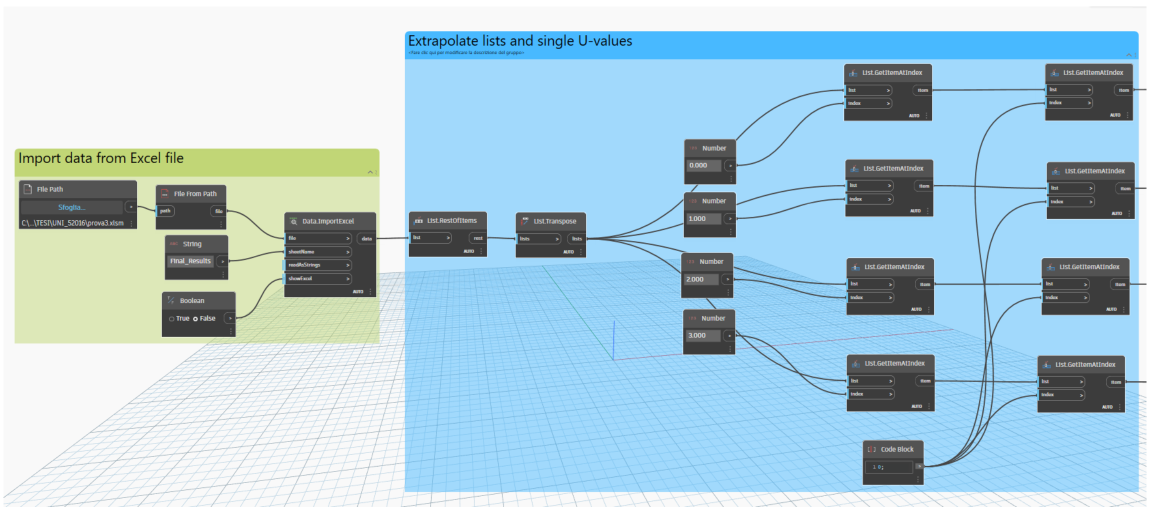


Figure 13: Detail of the first part of the transcription - data import and extrapolation

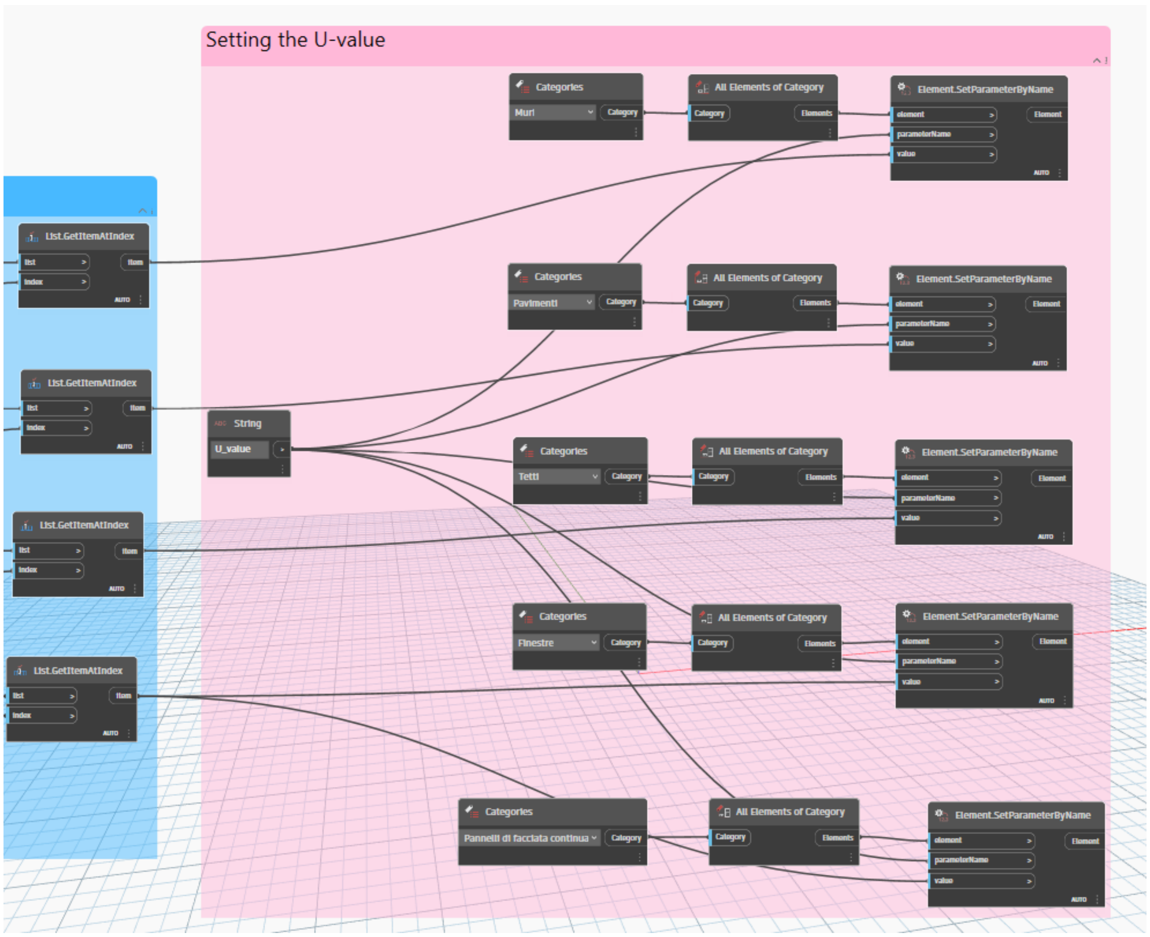


Figure 14: Detail of the second part of the transcription - setting data in the model

One of the challenges addressed by this approach is the intrinsic limitation within Revit's functionality, where the U-value of an element is automatically calculated as the sum of the thermal resistances of its constituent layers. This default calculation method requires all sub-elements, such as individual material layers, to be predefined and known in advance. However, this constraint can significantly reduce design flexibility, as it necessitates a fixed material composition early in the design process, which is not ideal during this iterative optimization. To circumvent this limitation and provide greater flexibility to the designer, the U-value is instead associated with a "dummy" project parameter rather than being directly imposed through Revit's built-in thermal properties. By using this custom parameter, enables designers to retain the autonomy to investigate and modify the configuration of building components without being bound by the predefined U-value calculation. The incorporation of the custom project parameter into the "Other" properties facilitates the accurate exportation of all pertinent data for this analysis.

The process of visualization of the results begin with the export of the Revit model into an Industry Foundation Classes (IFC) file. IFC is an open data format widely adopted in the Architecture, Engineering and Construction (AEC) sector. Its primary function is to ease the seamless exchange of information between different software applications, highlighting again the importance of the interoperability between different platforms, addressing the issues already pointed in Section 5.1. Once the BIM model is exported into the IFC file, it is imported into the Speckle platform, which provides tailored connectors to various widely-used software applications. Using Speckle as a bridge, the visualization of the results conveys in PowerBI, a business analytics service developed by Microsoft. The integration of the IFC model into PowerBI via Speckle simplifies the visualisation of complex data from this research's algorithmic workflows. PowerBI was selected for its robust capabilities in interactive data visualization, allowing stakeholders to intuitively explore the intricate results generated by the algorithm. PowerBI's dashboarding capabilities enable users to view the 3D BIM model alongside data-driven insights, all in one environment. This setup offers a high level of customization in how data is presented, ensuring that various layers of information can be filtered, manipulated, and viewed in a well-organized, user-friendly manner. One of the critical challenges identified in Section 5.1 is the need for clear and accessible visualization for end users who may not be familiar with technical aspects of the data or the model. By presenting the data in a clear, visually engaging way, Power BI helps bridge the gap between complex analytics and user understanding. Whether it's through interactive graphs, custom visualizations, or real-time data streaming, the tool is designed to communicate results effectively. This feature highlights collaboration across teams and stakeholders, as it allows non-technical users to easily interpret and act on the insights generated. In essence, Power BI turns intricate data analysis into an approachable, powerful tool for decision-making, while driving efficiency.

5.7 Model limitations

This methodology, while comprehensive in its approach, presents several limitations important to be acknowledged. These constraints primarily stem from the tools adopted, computational resources available, and the scope of analysis within the complex field of building energy simulation. The primary focus of the optimization process in this study is on building envelope parameters and technical systems. While these are crucial aspects of building energy performance, this narrow focus necessarily excludes other influential factors. Occupant behavior, as mentioned earlier in this thesis, can significantly impact energy consumption patterns but is challenging to model accurately and is thus not directly addressed in this optimization framework. Similarly, the integration of advanced lighting systems, which can play a substantial role in energy efficiency, falls outside the immediate scope of this study.

The genetic algorithms employed in this study were constrained by the available computational resources and time. This limitation potentially restricted the full exploration of the solution space, as a more extensive search with larger populations and more generations could potentially yield further improved results. It is also worth noting that the carbon cost optimization evaluated in the second stage considers only operational carbon emissions. The embodied carbon from materials and construction processes, which is becoming an increasingly important consideration in sustainable building design, is not included in the current scope of this study. Nevertheless, these limitations do not diminish the value of the research, but rather provide clear pathways for future improvements and expansions of the model. The framework developed in this thesis is designed with flexibility in mind, allowing for relatively straightforward adaptation and expansion to incorporate additional parameters and objectives as needed. For instance, the model could be extended to include other factors useful for designers and engineers. However, expanding the capability of the model to include these additional factors would necessarily increase the computational complexity, potentially requiring more sophisticated optimization algorithms, more powerful computational resources, and longer execution times. This trade-off between model complexity and computational efficiency is a common challenge in optimization studies and presents an opportunity for future research to explore more efficient algorithms or parallel computing strategies.

The interoperability part proposed some challenges as well. The first was linked to the creation of a "dummy" parameter for attaching the U-value, even though this thermal characteristic is already automatically calculated in Revit according to the different build-up composition of the elements. Although Revit automatically calculates the U-value based on the specific build-up of materials within the element, employing this pre-existing parameter directly in the export process presented significant challenges. The complexity of accessing and defining this automatic parameter through code made it difficult to seamlessly integrate into the design workflow. In order to bypass this problem, the optimized U-value obtained was attached to an independent project parameter, outside of the thermal characteristics of the element, as also explained in Section 5.6. By storing the optimized U-value in an external parameter, it became possible to bypass the constraints of the automatic calculation while ensuring the data remained accessible for further design and analysis. Moreover this approach facilitates the proper export of the IFC file without losing critical information related to the project parameters.

Despite these limitations, the current model provides a solid foundation for multi-objective optimization in building energy performance. It offers valuable insights into the interplay between building envelope characteristics and technical systems, and demonstrates the potential for significant energy savings through targeted optimizations. As such, it serves as both a practical tool for current use and a springboard for future research and development in the field of sustainable building design and retrofit.

5.8 Future applications and areas of improvement

Despite the few limitations listed in the previous paragraph, the current model provides a solid foundation for multi-objective optimization in building energy performance. It offers valuable insights into the interplay between building envelope characteristics and technical systems, and demonstrates the potential for significant energy savings through targeted optimizations. This model is not only a practical tool for immediate application but also a promising starting point for future research and development in sustainable building design and retrofit. Looking ahead, several areas present opportunities for further enhancement of the model's capabilities. Although the calculations and the weather data set for this optimization problem are based on an hourly scale, incorporating hourly or sub-hourly energy simulation results as well as seasonal variations would help designers to better understand the dynamic changes related to building energy performance. Another promising path can involve the integration of occupancy prediction models. By accounting for variable internal heat gains and usage patterns, these models can better replicate real-life building conditions, thus improving the accuracy of the optimization process. This enhancement would allow the model to more effectively address the complexities associated with fluctuating occupancy rates and diverse usage scenarios.

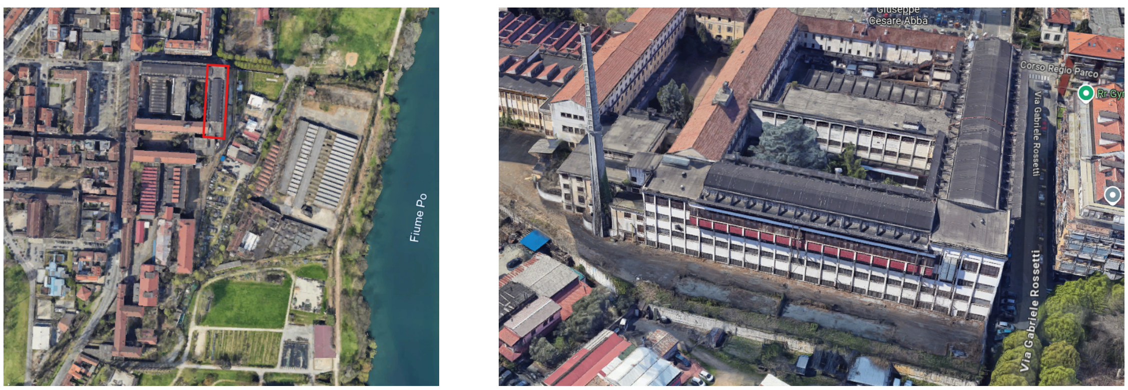
Expanding the range of HVAC system scenarios is also crucial for reflecting the diversity of the existing building stock and emerging technologies. For instance, analysing energy storage systems and district heating/cooling options would better reflect real-world diversity and potential energy-saving strategies. Similarly, applying advanced models to incorporate time-dependent and location-specific carbon intensity factors would improve the accuracy of the carbon emissions calculations. The current model uses fixed carbon intensity factors for electricity and gas across five specific scenarios, which, while common, do not account for the significant variability in carbon intensity over time and by location. Moving towards a more dynamic approach could lead to a better understanding of the environmental impacts of different energy sources. Moreover, integrating LCA within the model could provide a more holistic view of a building's carbon footprint. LCA would enable the analysis of both embodied and operational carbon emissions, considering the impacts of technical systems and materials across all phases of a building's life — production, construction, operation, and end-of-life. This comprehensive approach would support more informed decision-making in the context of sustainable building design.

Extending the application of the model beyond individual buildings to groups of buildings or entire urban districts is another valuable direction for future research. Such an extension would allow for the exploration of interactions between buildings, such as shading effects and the urban heat island phenomenon. The scalability of the model in this context involves not just applying the optimization algorithm to different types of buildings, but also addressing the complexities of mixed-use and diverse building groups. This would enable a more integrated approach to urban sustainability. Additionally, addressing the impacts of climate change within the model could provide essential insights into the resilience of buildings. By incorporating climate change projections, the model could evaluate building performance under various future scenarios, ensuring that designs remain effective in the face of changing environmental conditions. This approach could be particularly valuable for assessing the resilience of different HVAC configurations under extreme weather events, thereby supporting the development of buildings that are both sustainable and resilient. Incorporating thermal comfort models (e.g., Predicted Mean Vote (PMV), adaptive comfort models) and indoor air quality parameters (e.g., CO_2 levels, humidity, pollutant concentrations) could further enhance the model's utility. By optimizing for both energy efficiency and occupant well-being, these additions would ensure that sustainability goals do not compromise users' comfort and health.

Furthermore, another critical area for future development is the inclusion of economic analysis within the model. Currently, the economic implications of various design choices are not considered. Adding an economic dimension—such as calculating the actual refurbishment costs or the payback period for different energy efficiency measures — could significantly enhance the model's practical relevance. This would provide a powerful tool for balancing environmental performance with financial feasibility, considering factors like energy prices, construction costs, and available incentives.

6 Case study: Manifattura Tabacchi in Turin

Manifattura Tabacchi is a historic tobacco factory located in the northern part of Turin, in the neighbourhood known as Regio Parco. Historically, Manifattura Tabacchi was part of a larger network of tobacco manufacturing facilities that spanned across Italy, with branches in major cities such as Florence, Modena, and Milan. The scale of Manifattura Tabacchi, both in terms of land coverage and the dimensions of its structures, presents a vast and complex subject for any thorough analysis. Consequently, this analysis only concentrates on a specific, restricted area within the Manifattura Tabacchi site, which is highlighted in Figure 15a.



(a) Location of the case study; in red is highlighted the interested building.

(b) Focus on the current state of the building subject of this analysis

Figure 15: *@Google Maps* views of the location and the interested building

The scope of this analysis is further refined by focusing on a single standard floor plan out of the four floors that comprise the building in question. This decision to limit the study to one floor is driven by the necessity to reduce the computational complexity associated with the iterative energy simulation processes. Expanding the analysis to include multiple floors would exponentially increase the computational time required for each iteration, thereby posing practical constraints on the feasibility of the study. Moreover, another critical simplification employed in this study involves the evaluation of a singular thermal zone, gathering all internal spaces of all the floors into one theoretical or 'fictitious' zone. This approach allows for a concise assessment of the building's thermal performance, while simultaneously reducing the computational load and providing meaningful insights on energy performance. By concentrating on a single building, the analysis seeks to provide a more detailed and manageable examination of the site's features and energy impact, providing deeper insights into the methodology itself rather than a whole comprehensive analysis of the area. The data relevant to the whole site, along with the characteristics of the thermal zone under consideration are presented in Table 9.

Table 9: List of details pertaining the whole site and the specific thermal zone considered

Whole site details	
Location	Corso Regio Parco 134, Turin (TO), Italy
Latitude	45”05’25” N
Longitude	07”42’55” E
Altitude	250 m
Land area (A_l)	46.000 m^2

Thermal zone details	
Area floor (A_f)	1411 m^2
Interfloor height (h)	3 m, except 4 m for the 3rd floor
Volume (V_n)	16.932 m^3
Area windows (A_w)	1.319 m^2
Area envelope (A_e)	6.365 m^2

The details concerning the thermal zone are used as input data for the simulation performed in the Excel file. The floor area A_f, the interfloor height h, and the volume V_n are considered as net dimensions. The area envelope includes all the surfaces enclosing the thermal zone, such as ceiling, floor and external walls, excluding the windows, which have are included in the area windows A_w. As already outlined in Section 5.3.1, the BIM model represents the starting point for this analysis. The 3D model for Manifattura Tabacchi was obtained using an advanced Scan-to-BIM process, which translates the data obtained from an high-resolution point cloud survey into a 3D digital representation. However, as it often happens with point clouds, there are some areas where the scan data is incomplete or lacks sufficient details for the process to work. Such limitations are not uncommon, particularly in areas that are difficult to access or where the scanning equipment’s line of sight is obstructed. In order to address these issues, a manual refinement of the initial model to ensure its completeness and accuracy is necessary. The adoption of a 3D model provides significant advantages in the management of data and the efficiency of the process. Collecting data from a 3D model allows for a more optimized and less resource-intensive process, facilitated by the schedules and other data-driven tools available in Autodesk Revit that can be leveraged to automate various calculations and analyses. For instance, the determination of thermal zones, including the calculation of critical parameters such as volume and surface areas, can be performed automatically by the software. This automation not only reduces the potential for human error but also accelerates the overall process, allowing for more timely and accurate decision-making.

6.1 Climatic data: Turin-Bauducchi weather station

For ensuring the accuracy of the energy performance simulation implemented in this analysis, reliable climatic data are essential. The simulations performed employ the simplified hourly method as outlined in EN ISO 52016-1, which requires the acquisition of hourly data for external air temperature, solar irradiation, and wind speed for every hour of the year. However, the complexity and volume of such data is impractical for the purposes of visualisation and interpretation. As a consequence, this section presents the data aggregated into monthly averages, which nevertheless preserve the necessary detail for accurate data visualization while simplifying interpretation. This approach provides a clear overview of the climatic trends in Turin throughout the year. In order to guarantee that the climatic input data is representative for the specific conditions of the case study location, the standard monthly averages provided by UNI 10349-1 [41] were adjusted accordingly. This standard contains monthly averages for over 110 locations across Italy; however, specific modifications were applied to the weather station Turin-Bauducchi, the closest one to the site. The adjustments are necessary for representing the environmental conditions of the case study, which is about 17 km from the weather station, since they may differ significantly from those at the station itself. Such variations are neeeded to ensure that the climatic data accurately represents the conditions at the Manifattura Tabacchi. The hourly values employed in the simulation Excel sheets were provided by the Comitato Tecnico Italiano (CTI) [42], which collects the data for a specified reference year for every Italian region and province. The calculation of the meteorological characteristic year are performed according to UNI EN ISO 15927-4 [43]. In the following sections, the input data for the optimization algorith have been gathered in monthly ranges for sake of simplicity and visualization.

6.1.1 External air temperature

The external monthly air temperature for this case study can be properly calculated using the following formula:

$$t_e = t_{\mathrm{e,ref}} - (h - h_{\mathrm{ref}}) \cdot d \tag{1}$$

where:

$t_{\mathrm{e,ref}}$ refers to the average monthly temperatures of the reference location (Turin-Bauducchi weather station),

h is the altitude of Manifattura Tabacchi,

h_{ref} is the altitude of Turin-Bauducchi station,

d is the correction factor for North Italy equal to $d = 1/178$ [°C/m]

The reference monthly average temperatures $t_{e,ref}$ for Turin-Bauducchi, as provided by UNI 10349-1, are shown alongside the adjusted values for the reference site location of Manifattura Tabacchi (Table 10).

Table 10: Average monthly external air temperature and adjusted external air temperature values for the case study location

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\boldsymbol{t}_{\text{e,ref}}$ **[°C]**	1,3	3,2	8,4	12,0	18,1	22,2	23,7	22,7	19,2	12,4	6,9	2,7
$\boldsymbol{t}_{\text{e}}$ **[°C]**	1,34	3,24	8,44	12,04	18,14	22,24	23,74	22,74	19,24	12,44	6,94	2,74

6.1.2 Direct, diffuse and total solar irradiation

Similarly to the external air temperature, also the solar radiation needs to be adjusted starting from the values of the reference station Turin-Bauducchi. Those values refer to the monthly average values of the average daily solar radiation on the horizontal plane, in the direct H_{bh} and diffuse H_{dh} components (see Table 11). The solar irradiation on a tilted and for an oriented surface, for every month, can be established with the sum of the two:

$$H = H_{\text{bh}} + H_{\text{dh}} \tag{2}$$

Table 11: Direct, diffuse and total values of solar radiation

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H_{bh} [MJ/m^2]	2,4	3,8	4,9	6,1	8,3	9,1	8,8	7,6	6	4,3	2,8	2
H_{dh} [MJ/m^2]	2,2	3,9	6,8	9,9	11,4	13,7	15,2	12,6	8,6	4,7	2	1,9
H [MJ/m^2]	4,6	7,7	11,7	16,0	19,7	22,8	24,0	20,2	14,6	9,0	4,8	3,9

6.1.3 Wind speed

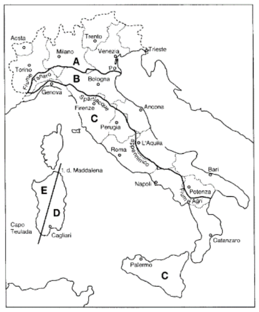
The calculation of the wind speed requires first the identification of the wind region and the wind zone of the area of the case study. From Figure 16, it is possible to see that Turin falls into wind region A. After evaluating the altitude of the site, which is lower than 300 meters above sea level, it is possible to find the wind zone, which in this case is the first one. The wind speed specific for this case study can be calculated with the following formula:

$$v = v_{\text{ref}} \cdot c \tag{3}$$

where:

v_{ref} is the wind speed of the reference location

c is the correction coefficient from Figure 17, based on the wind zones



Regione di vento	Fascia Costiera ⩽ 20 km	Fascia Subcostiera ⩽ 40 km	Entroterra > 20 km* Altitudine (m)						
			300	500	800	1 200	1 500	2 000	>2 000
A	3	2	1	1	2	2	3	3	4
B	2		1	2	2	3	3	4	4
C	3		2	2	3	3	3	4	4
D	3		3	3	3	4	4	4	4
E	4		3	3	3	4	4	4	4

* Ad eccezione della regione A per cui l'entroterra è > 40 km.

Figure 16: Reference tables for wind zones and region (UNI 10349-1)

Zona di vento della località di riferimento	Zona di vento			
	1	2	3	4
1	1	1,780	2,780	4,000
2	0,562	1	1,560	2,250
3	0,360	0,640	1	1,440
4	0,250	0,445	0,694	1

Figure 17: Correction coefficients based on the wind zones (UNI 10349-1)

The main direction of the wind in this zone is the North-East, with an annual average of 1,4 m/s. Applying the formula, it is possible to obtain the values adapted for the case study zone, listed in Table 12, alongside the reference values.

Table 12: Mean monthly values of the wind speed for the reference station and the adapted values for the specific location

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$v_{e,ref}$ [m/s]	1,3	1,3	1,6	1,9	1,9	1,6	1,6	1,4	1,1	1,2	1,5	0,9
v [m/s]	1,3	1,3	1,6	1,9	1,9	1,6	1,6	1,4	1,1	1,2	1,5	0,9

6.1.4 Partial vapour pressure

The partial vapour pressure p_{v} is calculated using the following formula:

$$p_{\text{v}} = \phi_{\text{staz}} \cdot p_{\text{vs}} \tag{4}$$

where

ϕ_{staz} is the relative humidity, represented by a dimensionless number

p_{vs} is the saturation pressure in Pascal

For determining the relative humidity ϕ_{staz} it is possible to rely to this formula:

$$\phi_{\text{staz}} = p_{\text{v,staz}} \cdot p_{\text{vs}(\text{t}_{\text{staz}})} \tag{5}$$

where

$p_{\text{v,staz}}$ is the partial vapour pressure of the reference location

$p_{\text{vs}(\text{t}_{\text{staz}})}$ depends on the value of t_{staz} and in this case it is calculated as follows:

$$p_{\text{vs}(\text{t}_{\text{staz}})} = 610.5 \cdot \exp\left(\frac{17.269 \cdot t_{\text{staz}}}{t_{\text{staz}} + 273.3}\right) \tag{6}$$

Tables 13 and 14 present the values obtained from the calculations.

Table 13: Mean monthly values of the partial vapour pressure for the station Turin-Bauducchi

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$p_{v,staz}$ [Pa]	558	618	888	934	1355	1616	1584	2003	1659	1180	925	654

Table 14: Mean monthly values of the relative humidity and the other variables needed for the calculations

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$t_{e,ref}$ [°C]	1,3	3,2	8,4	12	18,1	22,2	23,7	22,7	19,2	12,4	6,9	2,7
$p_{v,staz}$ [Pa]	558	618	888	934	1355	1616	1584	2003	1659	1180	925	654
$p_{vs(t_{staz})}$ [Pa]	670.73	768.20	1101.77	1401.81	2075.84	2674.79	2928.27	2757.26	2223.70	1439.21	994.48	741.41
ϕ_{staz} [-]	0.832	0.804	0.806	0.666	0.653	0.604	0.541	0.726	0.746	0.820	0.930	0.882

6.2 Envelope baseline building details: project proposal and current state

In this section, a detailed overview of the key build-up elements for this analysis will be provided. This examination will include both the current state of the building and the proposed refurbishment plans, which hypothetically aim to host a university department in the area considered. Nowadays, the building is in a state of disuse, exhibiting clear signs of degradation as the structure, originally designed for industrial purposes, has not been maintained in recent years. Due to the challenges associated with obtaining precise data on the existing building envelope, the layering and the related thermal transmittance have been hypothesized based on comparable data provided by TABULA WebTool [44]. While this platform primarily focuses on the residential building stock, the data has been adapted to account for the industrial nature and historical significance of the Manifattura Tabacchi building. The refurbishment project has been designed to improve the building's performance, with a particular focus on optimizing its thermal efficiency and functionality to meet the requirements of modern academic facilities. By analyzing the proposed design and comparing it to the outcomes generated by the optimization process, it will be possible to evaluate whether the refurbishment plan aligns with the most effective strategies for enhancing energy efficiency and sustainability, serving as a benchmark. The proposed refurbishment includes substantial modifications to all components of the building envelope: these upgrades are outlined in Tables from 15 to 17. A comparison of the pre- and post-refurbishment conditions of each building element's thermal transmittance is listed in Tables 18 and 19.

Table 15: External wall layering and composition for the baseline-refurbishment case

Layer number	**Material**	**Thickness [cm]**
1	Plaster	2
2	Solid bricks	8
3	Air gap	15
4	Solid bricks	12
5	Water vapour barrier	0.1
6	Thermal insulation in hemp	10
7	Waterproof membrane	0.5
8	Air gap	5
9	External cladding in stone panel	3

Table 16: Floor layering and composition for the baseline-refurbishment case

Layer number	**Material**	**Thickness [cm]**
1	Plaster	2
2	Hollow-core bricks	16
3	Screed in concrete	4
4	Self-levelling screed in cement mortar	2
5	LVT Vinyl Tile	0.6

Table 17: Roof layering and composition for the baseline-refurbishment case

Layer number	**Material**	**Thickness [cm]**
1	Plaster	2
2	Hollow-core bricks	16
3	Screed in concrete	4
4	Water vapour barrier	0.1
5	Thermal insulation in hemp	12
6	Waterproof membrane	0.5
7	Wooden slats	2.5
8	Roof covering in corrugated metal sheet	2

Table 18: Project proposal U-values

Envelope element	**Thermal transmittance W/m^2K**
External wall	0.257
Roof	0.253
Floor	0.231
DGU	1.100

Table 19: Current state U-values

Envelope element	**Thermal transmittance W/m^2K**
External wall	1.150
Roof	1.100
Floor	1.170
Windows	4.900

7 Application to the case study and results

This section shows the results obtained specifically for the Manifattura Tabacchi case study, according to the methodology previously described in Section 5. For each stage of the analysis, detailed specifications have been delineated to ensure that the methodology is adapted to the particular characteristics of this case. The Manifattura Tabacchi building is treated as a single, unified thermal zone, an assumption that simplifies the thermal analysis but also introduces some limitations. These limitations, thoroughly discussed earlier in this thesis, pertain to the nature of the optimization algorithm itself and the inherent trade-offs that arise when balancing accuracy with computational efficiency. In this case study, the building is treated as a standard building type, which allows for the application of a generalized approach to optimization. However, it is important to note that the simplifications made during the analysis are based on a thorough understanding of the model's complexity. These simplifications — while necessary for achieving a functional and efficient workflow — inevitably sacrifice certain details that would be decisive in a more in-depth, granular analysis. For example, dividing the building into multiple thermal zones could have provided more precise results, but doing so would have required more detailed input data and significantly increased the computational load. The decision to model the building as a single thermal zone reflects a careful balance between complexity and practicality, making the process more manageable while still providing valuable insights into the overall thermal behavior of the structure. All the calculations for this case study were performed in a laptop with the following system specifics: operating system Microsoft Windows 11 Home, 12th Gen Intel(R) Core(TM) i7-1255U, 1700 Mhz, 10 core, 12 logic processors and 16.0 GB of RAM.

7.1 First methodology stage results

The first stage of the optimization process focuses on determining the optimal thermal transmittance values by balancing the trade-off between heating and cooling energy needs. This stage begins with the careful selection and preparation of the input parameters required to run the genetic algorithm, as outlined in Table 20. To start the optimization, an initial population of potential solutions is generated randomly within pre-defined ranges for each parameter. The process of defining the population and the number of generations was not arbitrary but they were carefully selected after numerous trials. The objective was to strike a balance between generating a sufficiently large spectrum of output results while maintaining computational efficiency. Larger populations provide a more comprehensive search across the solution space, allowing the algorithm to identify a greater variety of potential solutions. However, larger populations and more generations also demand greater computational resources and time. Considering that performing the energy simulation took about one or two minutes each set of U-values, the iteration had to be weighted accordingly to reach the "balanced accuracy" already mentioned in this thesis. Through iterative testing, an optimal balance was achieved where the population size and number of generations allowed the algorithm to produce robust and diverse results without compromising the practicality of the process. The purpose of these adjustments was to ensure that the algorithm could effectively explore the entire solution space and avoid converging prematurely on sub-optimal solutions. Through several iterations, a configuration was established that allowed the algorithm to explore a broad spectrum of potential solutions, ensuring a wide variety of outcomes for further analysis.

Table 20: Configuration of the GA for Phase 1

Parameters	**Value**
Initial population size	16
Maximum number of generations	18
Crossover	0.7
Mutation probability	0.2

Figure 18 gives an overview of the Pareto front, the evaluated solutions, the current state and project proposal conditions from the initial optimization stage, with the heating energy need per square metre $Q_{\mathrm{H,nd}}$ on the x-axis and the cooling energy need per square metre $Q_{\mathrm{C,nd}}$ on the y-axis. Each blue dot represents a solution evaluated by NSGA-II. This graph includes two key reference points: the first one is the yellow dot on the graph, which represents the current state of the Manifattura Tabacchi building. This point is far removed from the Pareto front and lies in the upper-right corner, signifying both high heating and cooling energy demands. This indicates substantial inefficiencies in the building's current energy performance, consistent with the energy profile observed in older or poorly-maintained buildings. The discrepancy between the current state and the Pareto-optimal solutions underscores the opportunity for significant energy savings through strategic renovation and optimization strategies. Secondly, the project proposal for the Manifattura Tabacchi building is represented by the red dot (best identifiable in Figure 19). While this proposal shows improvement compared to the current state, it remains just outside the Pareto front, indicating that the proposed design is sub-optimal. Though it reduces the building's energy need compared to the current state, it does not fully capitalize on the possible trade-offs that would push it onto the Pareto front. This suggests that further optimization is possible, particularly by exploring solutions that could bring the project closer to the optimal balance between heating and cooling needs. The orange curve on the graph (better viewed in Figure 20) represents the Pareto front, which signifies a set of trade-offs between heating and cooling energy needs. In other words, as previously stated in Section 5.3.3, for any solution on this front, it is not possible to reduce the heating energy need without increasing the cooling energy need, and vice versa. A clear trend can be observed along the Pareto front: as one progresses from left to right along the x-axis, indicating a reduction in heating energy need, there is a corresponding increase in cooling energy need; vice versa, this occurs when moving from right to left. This pattern reflects the critical challenge in achieving energy efficiency in buildings: optimizing one aspect often requires sacrificing performance in another, especially in climates like that of Turin, where heating energy need typically outweighs cooling energy need. The first dot from the left on the graph highlights the solution with the lowest heating energy need. Although this solution minimizes heating energy consumption, it does so at the expense of increased cooling energy need, making it a less favorable option in climates where cooling loads are also significant. In contrast, the last dot on the right represents the best solution for minimizing cooling energy need. This solution achieves low cooling energy need but requires a considerably higher heating energy need, as is evident by its position further to the right on the Pareto front. Given the nature of the optimization process, a balanced solution has been selected based on proximity to the origin, representing the optimal trade-off between heating and cooling energy needs. This solution, often referred to as the "knee" of the Pareto front, balances the two conflicting objectives by minimizing the combined energy needs for both heating and cooling. It offers a practical approach where neither energy need is excessively high, aiming at the most efficient compromise for the building's thermal energy performance.

In the context of Turin's climate, which is classified as Zone E, the predominance of heating energy demand is well-reflected in the results obtained. Zone E is characterized by prolonged and cold winters, making heating a critical concern for building energy performance. The trade-off between heating and cooling seen in the Pareto front is consistent with this climatic reality, as reducing heating energy often comes at the cost of higher cooling energy need, even if cooling is less critical overall in such regions. For this reason, it can be interesting to consider the best heating solution or the ones next to it, in order to optimise the energy consumption related to heating, which is the most resource consuming in this area of Italy. However, one notable observation is the relatively narrow range of cooling energy demands among the evaluated solutions. The cooling demand values range tightly between approximately 9,5 and 13,5 kWh/m^2, which suggests that the variation in cooling requirements between different solutions is minimal. This restricted range is likely due to the input air temperatures employed are based on a typical reference year, which may not fully reflect the summer current climatic conditions. Given the increasing frequency and intensity of heatwaves in recent years due to climate change, it is possible that the cooling energy demand has been underestimated. If more up-to-date or extreme summer temperature data were used, it is likely that the cooling energy need would be higher, leading to a broader distribution of solutions along the Pareto front. Finally, Table 21 shows the values that are most significant to this study. The best solution is going to determine the initial configuration for the second optimization stage. Upon analysis, three out of four best solutions obtained exceed the reference U-values adopted for a reference building; the U-values of the latter are listed in Table 1. These reference values serve as a standard for high energy performance and are useful for comparative purposes. The only element that does not exceed the specified value is the external wall. This observation highlights the fact that, even when the specified values are exceeded, the performance is not compromised. Those values are provided for the purpose of comparing the case study with a benchmark that has proven good energy performance.

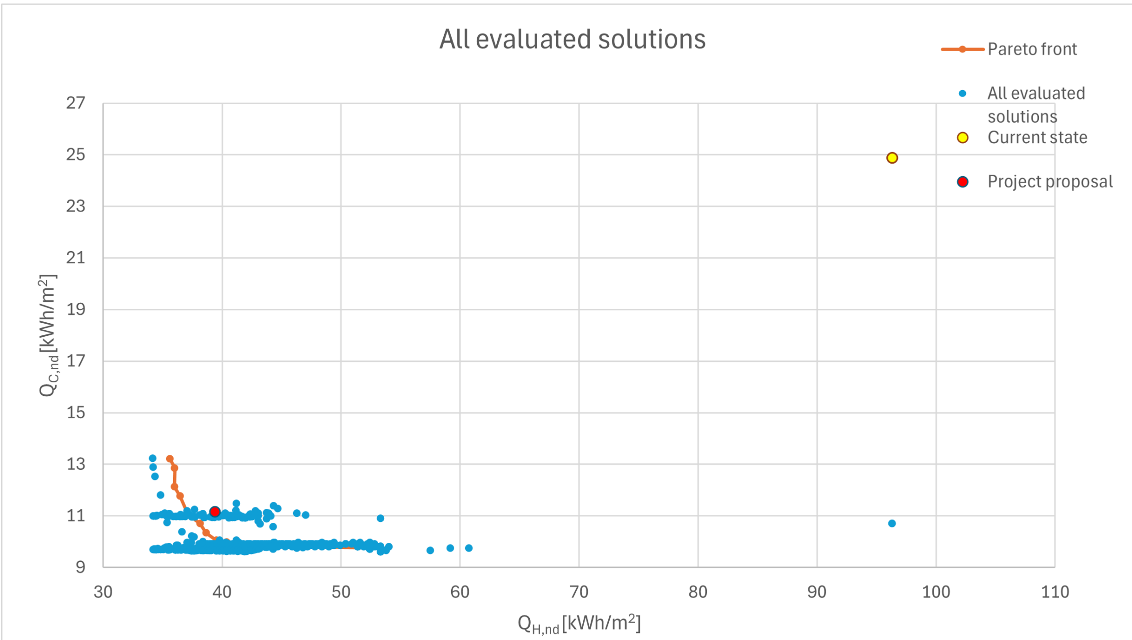


Figure 18: All evaluated solutions compared with the current state

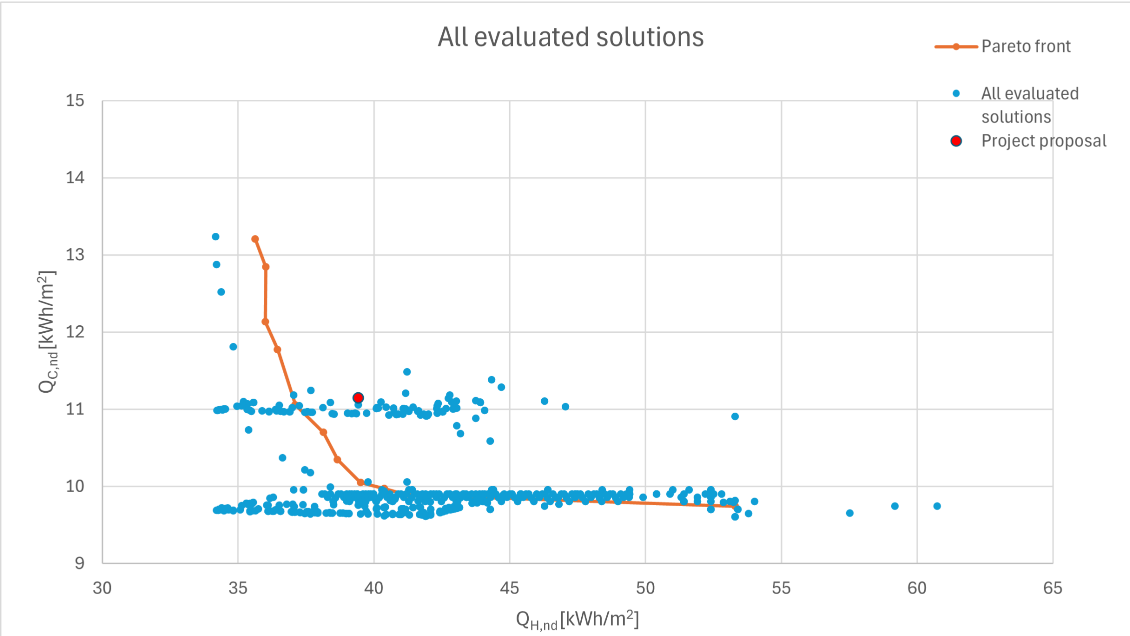


Figure 19: All evaluated solutions and indication of the project refurbishment proposal

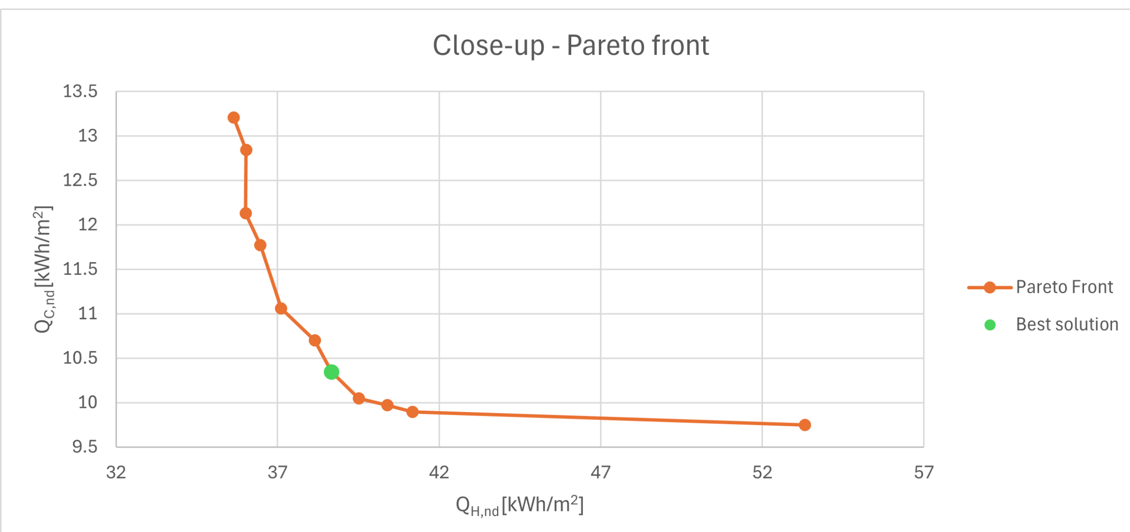


Figure 20: Pareto front close-up

Table 21: Results from the first stage of the optimization

	$\mathbf{U}_{extwall}$ [W/m²K]	$\boldsymbol{U}_{\text{floor}}$ [W/m²K]	$\boldsymbol{U}_{\text{roof}}$ [W/m²K]	$\boldsymbol{U}_{\text{windows}}$ [W/m²K]	$\mathbf{Q}_{H,nd}$ [kWh/m²]	$\mathbf{Q}_{C,nd}$ [kWh/m²]
Best solution	0,154	0,310	0,315	1,397	38,667	10,345
Project Proposal	0,257	0,531	0,252	1,100	39,428	11,144
Current State	1,150	1,170	1,100	4,900	96,324	24,878
Best heating solution	0,100	0,305	0,200	1,137	35,637	13,206
Best cooling solution	0,109	0,310	0,330	1,560	53,310	9,745

7.2 Second methodology stage results

The second stage results focus on the relationship between delivered energy for heating and cooling $E_{\mathrm{H,C}}$ and the equivalent carbon emissions associated with these energy demands. As outlined in the methodology, the calculations for this stage are performed by maintaining the optimal set of thermal transmittance values obtained during the first stage of the study. Such approach ensures that the analysis focuses only in the best-case scenario in terms of $E_{\mathrm{H,C}}$ and CO_2. To illustrate the outcomes, three key graphs have been generated: the first depicts a scenario with a reversible electric air-to-air heat pump (Figure 21), the second presents a scenario with a reversible electric ground-source heat pump (Figure 22), and the third graph compares the two systems (Figure 23). The plots include in the x-axis the delivered energy $E_{\mathrm{H,C}}$ per square meter and, in the y-axis the amount of emitted CO_2 in tonnes of CO_2 equivalent per square meter. These graphs not only highlight the performance differences between the two heat pump technologies but also incorporate the contribution of photovoltaic panels, which play a significant role in offsetting some of the energy demands. As visible from the graphs, the evaluated points shift to a lower value both for the emissions and the delivered energy.

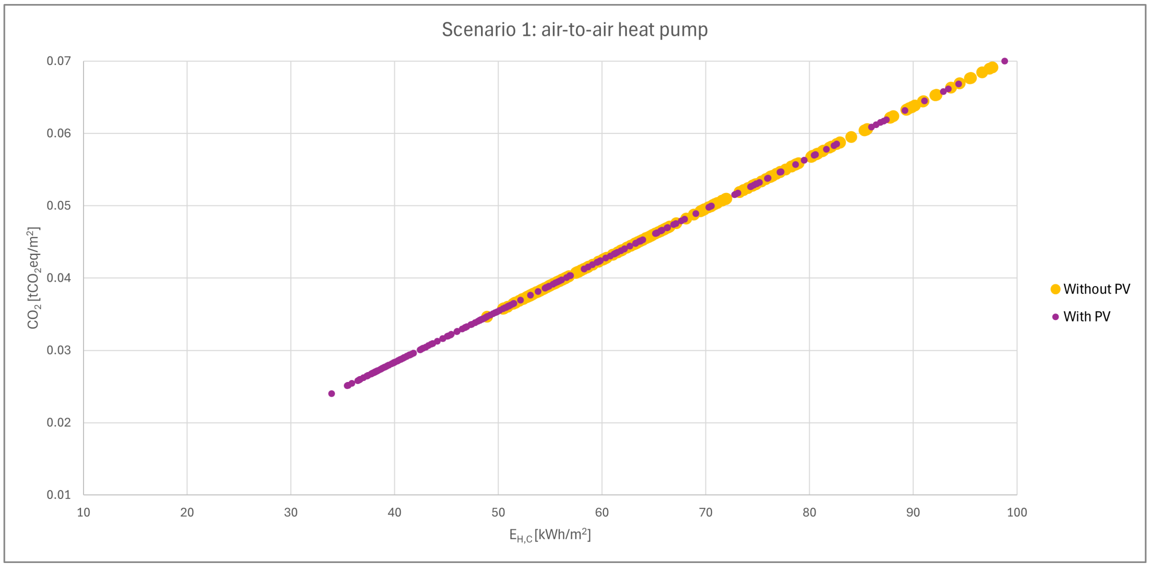


Figure 21: Scenario 1 results, with and without PV

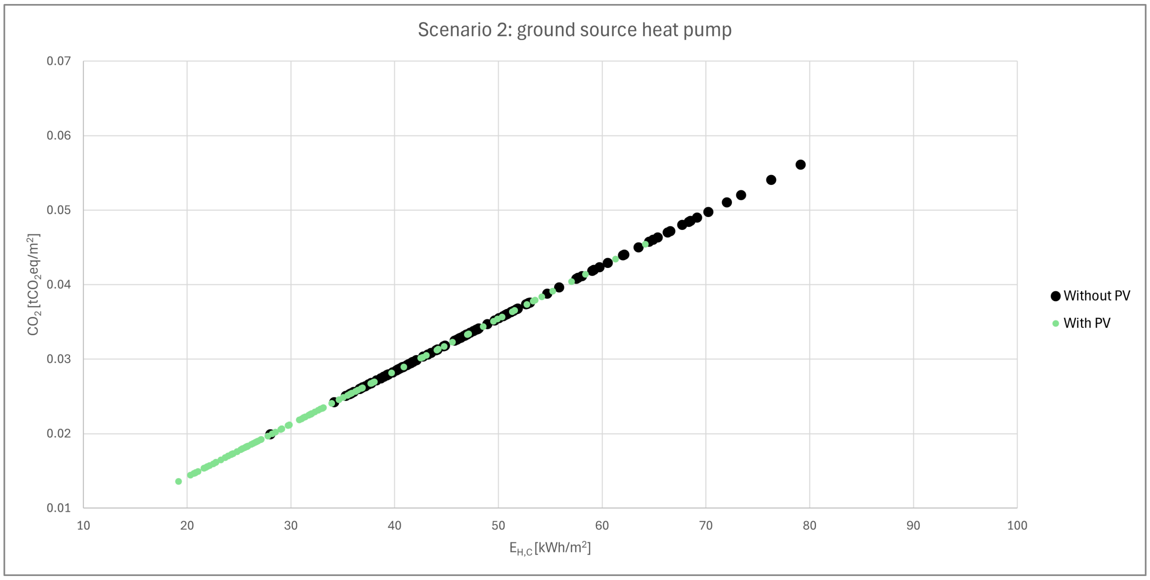


Figure 22: Scenario 2 results, with and without PV

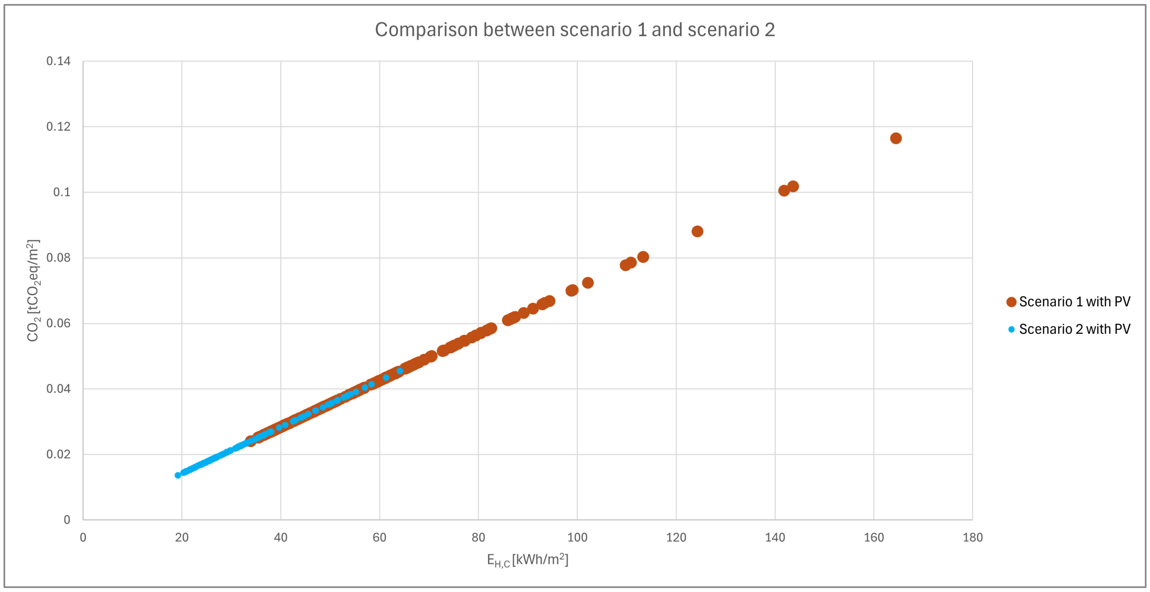


Figure 23: Combination of the two scenarios, with PV

However, one of the most immediate observations from the graphs is that the ground source heat pump has a better performance in terms of energy efficiency than the air-to-air technology. In scenario two, the heat pump requires significantly less electrical energy to deliver the same level of heating and cooling energy need, leading to a better overall performance. As expected, the relationship between delivered energy and carbon emissions follows a linear trend. This linearity indicates that as delivered energy increases, so too does the amount of carbon-equivalent emissions, making it clear that minimizing $E_{\mathrm{H,C}}$ also directly reduces the associated environmental impact, as one should expect. This correlation simplifies the decision-making process, as any solution that effectively reduces the energy demands for heating and cooling will simultaneously lower carbon emissions. In addition, the graphs also demonstrate the influence of photovoltaic panels on energy consumption. PV panels, by generating renewable electricity on-site, contribute to a reduction in the amount of delivered energy required from the grid by generating an average of 15 kWh/m^2. The conclusion from this phase is clear: the ground-source heat pump, supported by photovoltaic energy generation, represents the optimal solution in terms of minimizing both delivered energy and carbon emissions. This outcome is aligned with the broader goal of achieving energy-efficient building systems that contribute to long-term sustainability. Of course, the minimized delivered energy without renewable sources is obtained when the system is most efficient: this is evident in Figures 24 and 25 where, for the values of COP and EER evaluated by the genetic algorithm exclusively for scenario 2, it is represented the respective delivered energy $E_{\mathrm{H,C}}$. The graphs show scattered values of EER and COP which are the evaluated combinations of the two parameters for the same delivered energy.

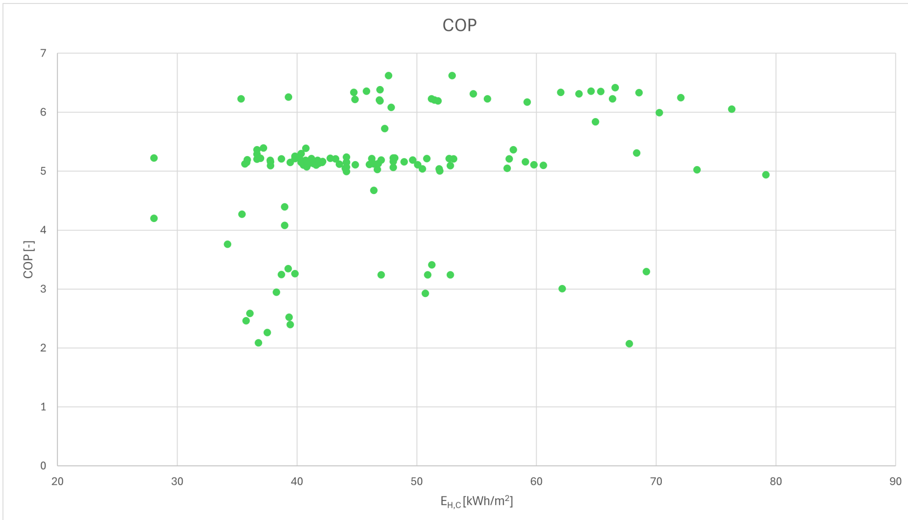


Figure 24: Evaluated *COP* values during the second phase of the optimization (scenario 2)

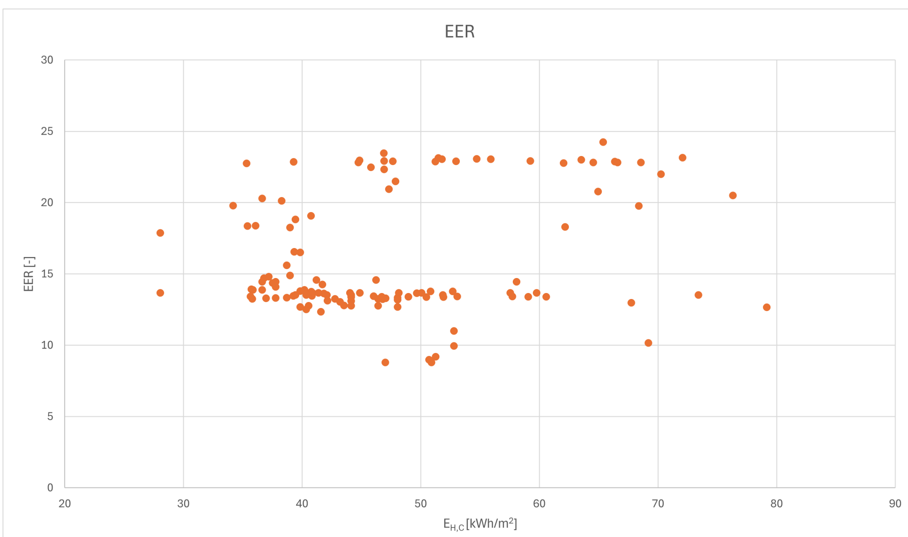


Figure 25: Evaluated *EER* values during the second phase of the optimization (scenario 2)

For a more detailed comparison of the performance of these systems, Table 22 presents the solutions that minimize both fitness functions — delivered energy and carbon-equivalent emissions. This table includes the total annual values for each scenario, offering a clearer view of the overall impact in terms of energy savings and CO_2 emissions. In green, it is highlighted the row that contains the specifics of the best result obtained at the end of the whole optimization process. Clearly, the evaluated set of solutions that minimizes the two objectives with PV integration for both scenarios, will also represent the best solution without the employment of renewable resources in situ. When evaluating the results in detail, the best-performing solution achieves an annual carbon-equivalent emission of 19,17 tCO_2eq. While this figure is still a considerable distance from the goal of achieving net-zero emissions, which is expected from a ZEB, it nevertheless represents a substantial advancement towards the decarbonization of the building related emissions. The result underscores that although the pathway to net-zero emissions is challenging, incremental steps, such as the adoption of these optimized solutions, can lead to significant reductions in carbon output and energy consumption. It is important to acknowledge that this outcome represents just one part of the larger optimization process that can be implemented. The initial parameters employed in the first phase provide a strong foundation, but there is still room for improvement. For example, a more detailed examination of the building's thermal envelope could help in reducing the thermal energy need. Currently, the analysis primarily focuses on the U-values of major building components such as external walls, floors, roofs and windows. However, a more complete approach that includes all building elements such as internal walls, slab on ground, and the evaluation of the thermal bridges, could increase the accuracy of the energy simulation, probably at the expense of a larger computational complexity. By improving the thermal performance of the entire building envelope, it may be possible to reduce the energy demand even further, thus bringing the building closer to its nZEB or ZEB targets. In the context of nZEB, the achieved carbon emissions level of 19,17 tCO_2eq, can be considered as a promising result when compared with similar building renovations that serve as benchmarks. The EU has set ambitious goals towards decarbonization of the building sector, yet it has not imposed rigid thresholds on carbon emissions when it comes to defining nZEB or ZEB standard. Therefore, while the obtained solution may not fully meet the ultimate objective of achieving net-zero carbon emissions, it can still be considered as a significant step forward in improving energy efficiency and reducing the carbon footprint of buildings.

Table 22: Results from the second stage of the optimization

	$\boldsymbol{E}_{\mathrm{H,C}}$ [kWh/m^2]	$\boldsymbol{E}_{\mathrm{H,C}}$ [kWh]	$\mathbf{tCO_2eq/m^2}$	$\mathbf{CO_2eq}$	***COP***	***EER***
Best solution scenario 1 (with PV)	33,92	47.865,02	0,024	33,89	6,62	22,91
Best solution scenario 2 (with PV)	13,04	18.406,17	0,013	19,17	6,62	22,91
Best solution scenario 1 (without PV)	48,92	69.030,02	0,034	48,87	6,62	22,91
Best solution scenario 2 (without PV)	28,04	39.571,18	0,019	28,01	6,62	22,91

7.3 Interactive dashboard for results visualization

The methodology explained in the dedicated chapter involves the final visualization in PowerBI, offering an interactive dashboard that functions as a comprehensive tool for infographic design. This dashboard not only visualizes data but also facilitates an engaging and intuitive user experience. It enables stakeholders to explore various aspects of the building model by leveraging interactive features that promote a deeper understanding of the technical information. The PowerBI dashboard serves as a crucial communication tool, aimed at delivering key insights derived from the optimization algorithms in a way that is both visually compelling and functionally informative. One of the primary objectives of this tool is to facilitate a dialogue between various stakeholders—ranging from technical professionals like architects and engineers to non-technical individuals such as clients, decision-makers, and the general public. The ability to adapt the information display depending on the user's needs ensures that the dashboard remains versatile, offering different levels of detail and complexity. This allows for a broad range of understanding while not sacrificing the precision of the technical details that may be critical for informed decision-making. Sections 5.6 and 5.7 discuss the various assumptions and simplifications made during the development of the optimization algorithms. These sections provide essential context for understanding the limitations and boundaries of the model, which must be considered when interpreting the results presented in the dashboard. The simplifications, while necessary to streamline the analysis and to allow usability, inevitably impose certain constraints on the accuracy and completeness of the outcomes. It is crucial to acknowledge these limitations to ensure the data is used appropriately and the findings are not over-interpreted.

One of the key functionalities of the dashboard is the comparison feature, which allows users to evaluate the building's current state, the project proposal, and the best solution generated by the optimization algorithm. This comparative analysis acts as a benchmark-ing tool, providing clear insights into the potential performance improvements achievable through the use of more advanced technologies or materials. Typically, the "best solution" proposed by the algorithm will include the highest-performing—often the most expensive—elements and construction technologies. While this may showcase the ideal scenario for maximizing energy efficiency and building performance, it might not always be the most practical solution from a cost perspective. The project proposal serves as an important feasibility benchmark in this context. By using the proposal as a comparative base, stakeholders can assess the trade-offs between performance and cost. This approach allows users to explore scenarios where similar performance levels can be achieved using more cost-effective alternatives. In this way, the dashboard helps guide decisions that balance technical excellence with financial feasibility, ensuring that the final design is not only optimized in terms of energy performance but also practical and affordable for implementation. Ultimately, the interactive dashboard is designed to be a powerful tool for conveying essential data obtained from advanced optimization processes. By speaking effectively to a diverse audience—both professional and non-professional—the dashboard highlights collaborative decision-making and contributes to more informed, data-driven choices throughout the design and implementation phases of the project.

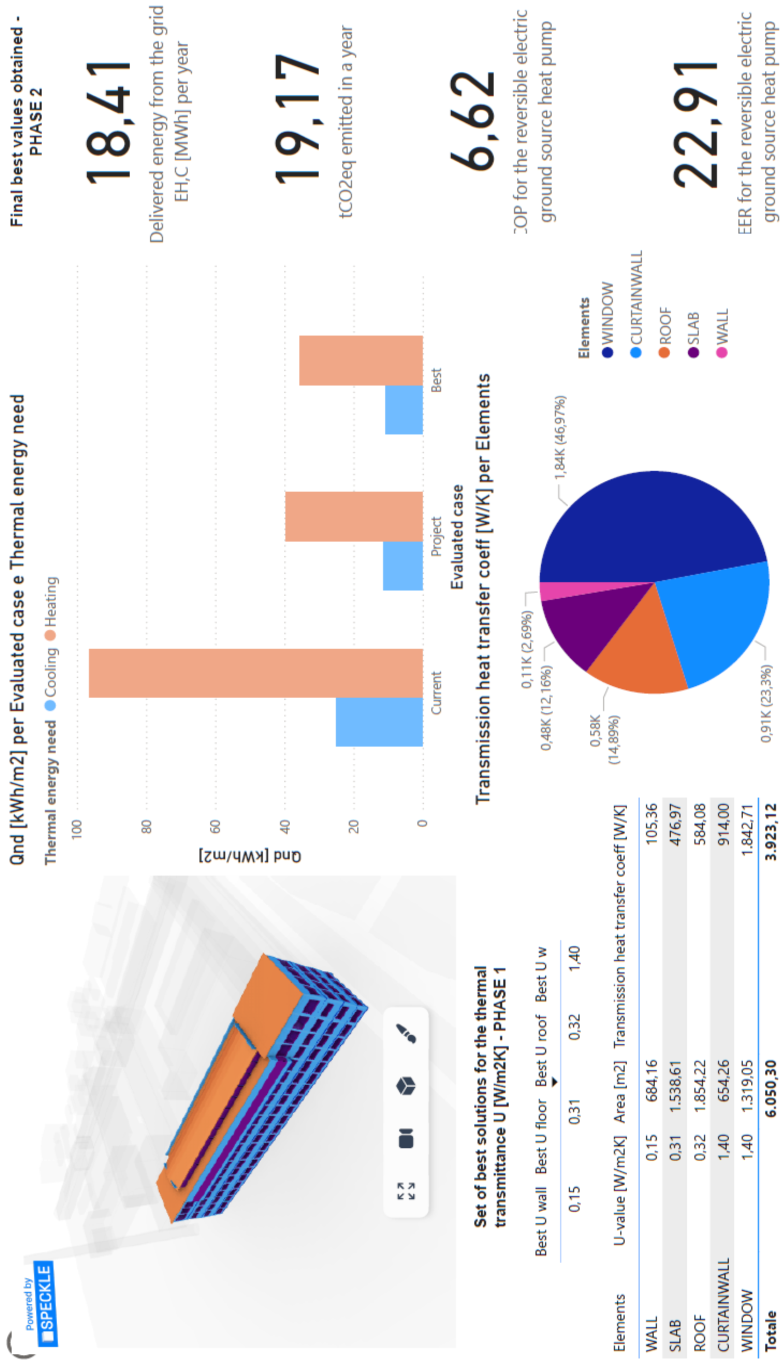


Figure 26: Final dashboard in PowerBI

8 Conclusions

This study has presented an integrated approach that helps in the decarbonization of the building stock by optimizing building energy performance through the application of a multi-stage optimization framework. The case study of Manifattura Tabacchi in Turin highlights the potential of this methodology to achieve significant improvements in both energy efficiency and carbon emissions reduction. By optimizing the thermal transmittance values of the building envelope and integrating advanced technical systems, the building's energy performance was substantially improved. The results of the study indicate that the ground-source heat pump, integrated with a PV system, offers the best solution for minimizing energy consumption and reducing the amount of CO_2 emissions. This combination not only meets modern energy efficiency standards but also aligns with the broader sustainability goals of reducing reliance on fossil fuels and promoting renewable energy integration.

Despite the success of the methodology, the study also acknowledges certain limitations. Firstly, the restricted number of parameters evaluated in the optimization and the limited fitness functions serve both as a simplification, in order to lower the computational time associated with the iterations that the genetic algorithm performs. Addressing a larger range of issues in the future could provide an even more holistic approach to sustainable building design. The analysis of the results conveyed in a best-performing solution that does not yet achieve the net-zero carbon goal, however it presents a remarkable advancement in the effort to decarbonize the building sector. The potential for further improvement, particularly through a more detailed optimization of the building elements, suggests that even greater reductions in thermal energy need and emissions could be achieved in the future. As such, this solution not only demonstrates the feasibility of significant reduction in emissions but also highlights the importance of continued innovation and optimization in the pursuit of nZEB and ZEB levels.

The dashboard has proven to be an invaluable tool for summarizing and simplifying complex analytical data. Its ability to distill intricate calculations and optimization results into visually engaging, easy-to-understand formats allows users from various backgrounds to grasp the key outcomes without being overwhelmed by the technical details. The dashboard provides a clear and concise overview of critical metrics, making it an essential component in the decision-making process, especially in fields where complex data plays a pivotal role, such as building performance and energy optimization. Despite its strengths, there remains significant potential for improvement, particularly in enhancing the interoperability between the different platforms involved. For example, the communication between Revit and PowerBI, while functional, could be streamlined further to improve workflow efficiency. Currently, exporting data from Revit into PowerBI requires additional steps that could be optimized to ensure a smoother, more seamless integration. Automating these processes would reduce the manual workload - bringing it almost to zero human intervention - allowing users to focus more on analyzing the results rather than managing data transfers between platforms. Improvements in this area could also reduce the likelihood of errors during data migration, thus enhancing the reliability of the final visualizations. Despite these areas for enhancement, the effective communication of the optimization results through the dashboard already significantly reduces the workload for end-users. By presenting data in a simplified yet comprehensive manner, it empowers stakeholders to quickly interpret the outcomes and make informed decisions. This not only saves time but also fosters more efficient workflows, as users can easily identify key trends and insights from the data.

In summary, this research highlights the feasibility of achieving significant reductions in thermal energy need, delivered energy and carbon emissions through targeted optimizations. The algorithm and the framework implemented here offer a solid foundation for future improvements and applications. Such methodology presents a promising pathway towards the decarbonization of the built environment.

Nomenclature

COP Coefficient of Performance

EER Energy Efficiency Ratio

AEC Architecture, Engineering and Construction

BACS Building Automation and Control Systems

BIM Building Information Modelling

DHC District Heating and Cooling

DHW Domestic Hot Water

EE Embodied Energy

EP Energy Performance

EPBD Energy Performance of Buildings Directive

gbXML Green Building eXtended Markup Language

GHG Greenhouse Gases

GUI Graphical User Interface

HVAC Heating, Ventilation, Air Conditioning

IFC Industry Foundation Classes

LCA Life Cycle Assessment

LOD Level Of Detail

MOO Multi-Objective Optimization

nZEB Nearly Zero-Energy Buildings

OE Operational Energy

RES Renewable Energy Sources

VPL Visual Programming Languages

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