UNIVERSITÀ
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An intelligent building from an existing building: integrated redevelopment, innovative storage system for energy from renewable sources

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International Doctorate in Civil and Environmental Engineering – XXXVI Cycle

ABSTRACT

Italy's industrial building stock is largely outdated and highly energy-intensive, forming a significant portion of the country's current built environment. Addressing these buildings to reduce energy demand and environmental impact is critical within the international and European objectives for sustainable development and a carbon-free economy. Due to the age of many manufacturing buildings, they present complex, multidisciplinary issues. These deficiencies not only affect their thermal and environmental performance but also compromise structural integrity and architectural quality, stemming from outdated regulations and inadequate technological solutions implemented during their construction.

In recent years, awareness around environmental sustainability and the role of industrial buildings has increased, shifting focus from pure production efficiency to worker well-being and corporate image. However, these aspects remain underestimated and often neglected in both national regulations and scientific literature, creating a significant knowledge gap. Standardized, systematic intervention protocols for the integrated redevelopment of existing manufacturing facilities are lacking.

This research aims to define guidelines for the effective enhancement of industrial buildings, emphasizing features unique to the Italian context. Extensive territorial analyses were conducted to collect and analyse the main distinguishing characteristics, the most frequently recurring typological solutions and the main criticalities to be tackled. Given the complexity of these buildings and the needs connected with production activities, a range of solutions was explored including both the redevelopment of outdoor areas in industrial districts and building-scale interventions. These encompass both renovating building envelope components, to improve the thermal properties of the facilities and to ameliorate comfort conditions for workers, and upgrading systems to increase the energy efficiency of the equipment and promote the integration of on-site renewable energy production.

ABSTRAKT

Zasób budynków przemysłowych we Włoszech jest w dużej mierze przestarzały i charakteryzuje się wysoką energochłonnością, stanowiąc znaczącą część obecnego zasobu budowlanego kraju. W kontekście międzynarodowych i europejskich celów zrównoważonego rozwoju i gospodarki neutralnej pod względem emisji dwutlenku węgla, modernizacja tych obiektów w celu zmniejszenia zapotrzebowania na energię oraz wpływu na środowisko jest dziś kluczowym wyzwaniem. Ze względu na wiek wielu budynków produkcyjnych, zmagają się one z wieloaspektowymi problemami, które wpływają nie tylko na ich efektywność cieplną i środowiskową, ale także na integralność konstrukcyjną oraz jakość architektoniczną. Problemy te wynikają z nieaktualnych przepisów oraz niewystarczających rozwiązań technologicznych zastosowanych podczas budowy.

W ostatnich latach wzrosła świadomość na temat zrównoważonego rozwoju oraz roli budynków przemysłowych, a podejście przesunęło się z samej wydajności produkcyjnej na dobrostan pracowników i wizerunek korporacyjny. Jednakże, te aspekty nadal są niedoceniane i często pomijane zarówno w przepisach krajowych, jak i literaturze naukowej, co tworzy znaczącą lukę wiedzy. Brakuje znormalizowanych, systematycznych protokołów interwencyjnych dotyczących zintegrowanej modernizacji istniejących obiektów produkcyjnych.

Celem niniejszych badań jest opracowanie wytycznych dla efektywnej modernizacji budynków przemysłowych, z uwzględnieniem cech charakterystycznych dla kontekstu włoskiego. Biorąc pod uwagę złożoność tych struktur, przeanalizowano szeroki zakres rozwiązań, w tym rewitalizację terenów zewnętrznych w strefach przemysłowych oraz interwencje na poziomie budynków. Obejmują one modernizację przegród budowlanych, systemów oraz silne nacisk na integrację produkcji energii odnawialnej na miejscu.

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1 INTRODUCTION, AIM AND MOTIVATION, METHODOLOGY OF THE RESEARCH

This introductory section is meant to provide the general framework of the research, to point out the main goals of the study and to highlight the distinguishing methodological features. The chapter will be organized in paragraphs, according to scheme reported below:

- 1.1 Introduction
- 1.2 Aim and motivation
- 1.3 Methodology of the research
- 1.4 References

1.1 Introduction

In the last decades, the need for a sustainable development of our planet appeared as one of the most relevant themes to be addressed at both international and national scales when outlining future growth scenarios. Consequently, effective energy management and reduction in energy demand became crucial challenges to be faced. The most accredited international institutions and the annual extensive reports available agree that Industry and Buildings are nowadays the most impactful sectors on the global energy balance since they cover about 33% each of the total final energy consumption (TFEC) [1], as illustrated in Figure 1.1.

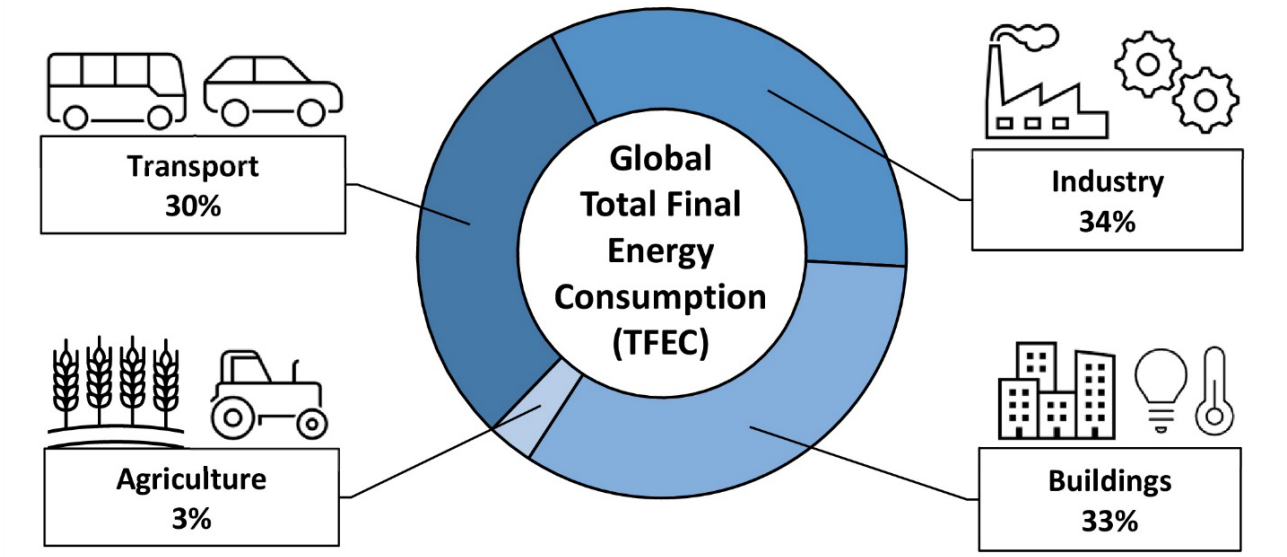

Figure 1.1 Share in TFEC according to the data provided by the Global Status Report 2023. *Source: elaboration of the author.*

At the same time, the Global Status Report for Buildings and Construction released in 2022 certifies that these economic sectors are also responsible for the highest amount of greenhouse gas (GHG) emissions [2]. In this regard, the building sector is the most critical one covering up to 37% of global CO_2 production including both the operational phase of residential and non-residential facilities and construction-related industries. Emissions can be tackled enhancing electrification and implementing energy production from renewables, but nowadays only a limited share of the total energy demand is covered by these sources. In building sector, they nearly account for 15% of final energy use, while industry exploited the highest share of renewables in 2020 (about 16.8 %) even if with different percentages depending on the various production sectors. Notably, both energy consumption and emissions have been constantly increasing in recent years: focusing on the decade 2011-2021 TFEC and CO_2 release in the atmosphere grew up by 16% and 15% respectively [3].

Given this context, the international community has drawn up a roadmap aimed at limiting the impact of human activities on the planet's resources to ensure a fully sustainable development. In 2015, the 193 United Nations members subscribed the Agenda 2030 that included 17 Sustainable Development Goals (SDGs) to be addressed by 2030 [4]. These targets encompass social, environmental and economic challenges to be faced within an integrated perspective. In 2015 another pivotal deal, globally known as the Paris Agreement [5], was reached during the 21st Conference of the Parties (COP21). Specifically focusing on climate change issues, it set a limit for global warming threshold of 1.5 °C above pre-industrialization levels was to avoid the environmental collapse. Efforts were needed at each contractor Nation to provide clear commitments and strategies, including also active support for developing countries. However, as stressed by the last Report on Climate Change and illustrated in Figure 1.2, an immediate change of pace is required because the currently implemented policies are estimate to result in a rise of global temperature of about 3°C, definitely not in line with the desired goals [5].

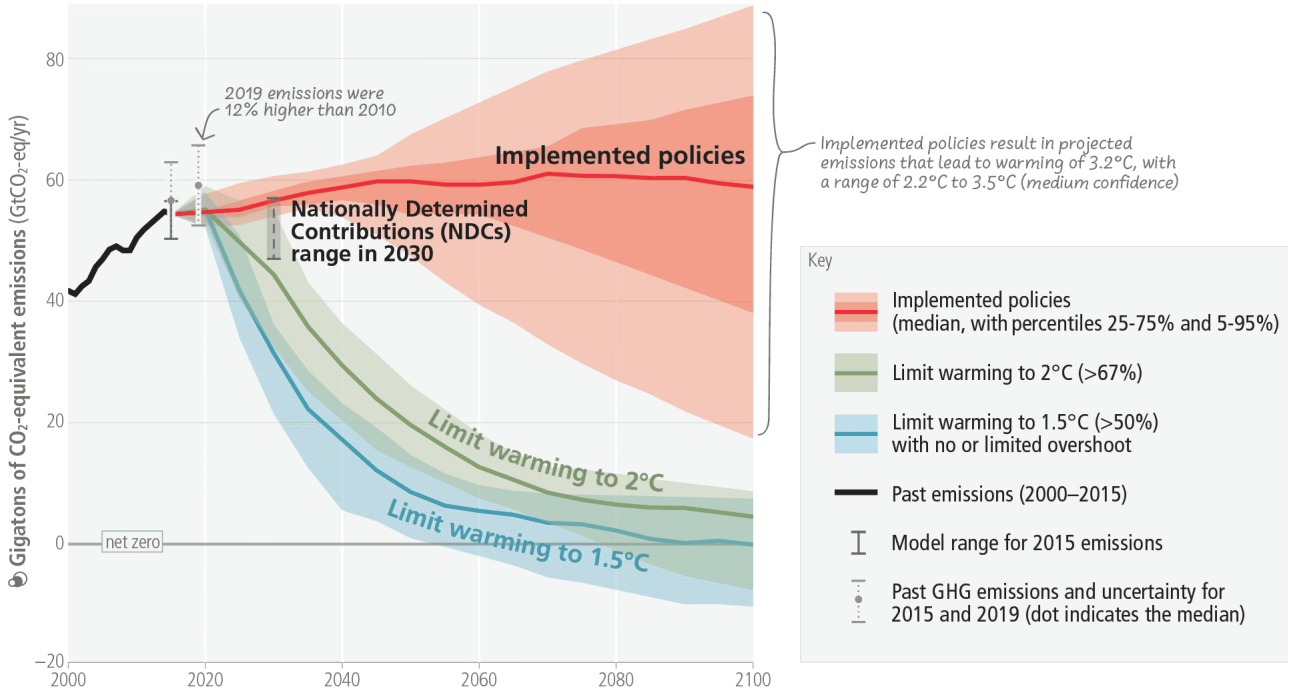

Figure 1.2 Projected scenarios for CO2 emissions and comparison with the threshold to be reached. *Source: Elaboration of the author from: IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647.*

Moreover, in recent years, the global COVID-19 pandemic and the changeable geo-political scenario as well, exasperated the need for concrete measures capable of mitigating the economic effects of the unpredictable fluctuations of the energy market, enhancing self-sufficiency and tackling energy-poverty.

Based on these premises, the European Union progressively strengthened its reglementary framework to adhere to the ambitious environmental goals previously introduced and to face these unexpected circumstances. In 2019 the European Commission promoted the European Green Deal [6], a comprehensive series of initiatives aimed at reshaping its economy to achieve carbon-neutrality by 2050. The enhancement of energy efficiency, the exploitation of renewable sources as well as the promotion of circular economy mechanisms were pointed out as key measures. Some mid-term goals were set for 2030: energy demand is expected to be reduced by 40% with respect to 2007 levels and be satisfied by renewable sources in a share equal to 32%. The expected reduction of GHG emissions, originally set at 40%, was furtherly scaled up to reach 55% following the adoption of the “Fit for 55” legislation package in 2021[7].

Following these initiatives at European level, each EU member state enhanced its energy and development plans and so did Italy with the definition in 2019 of the *Piano Nazionale Integrato per*

l'Energia e il Clima 2030 (PNIEC) that set for 2030 the target of decarbonisation to 43.7% with respect to 2005. Anyway according to the last available data, renewables only cover 18.5% of the National total energy demand, largely satisfied by fossil fuels [8]. Focusing on the Italian context, transport is currently the most energy-intensive sector (33.6% of TFEC), followed by residential utilities (26.8%), industry (21.8%), and services (14.8%). The same report also highlighted the variability of energy production from renewables: in 2022 hydroelectric generation in Italy suffered from unfavourable climatic conditions (-7.7%) while photovoltaic production set up the new record of 28 TWh. These highlights are particularly relevant as they underline the impact that unprecedented climate changes can have also on the strategies currently deployed to avoid them by transitioning to renewable energy sources.

Given the considerable relevance of buildings-related energy consumptions and GHGs emissions, environmental certification protocols started to be implemented following the growing awareness towards sustainability promoted by the new regulation schemes mentioned before. These voluntary protocols (e.g. LEED, BREEAM, Green Star, ITACA, etc.) provide guidelines and standards to be met for sustainable buildings promoting energy efficiency, natural resource management, and carbon emissions reduction acting at the same time as distinguishing features to enhance the market image of the entity or the company adopting them. The cited certification protocols are tailored on the characteristics of different building types, encompassing residential, education, healthcare, office and, in some cases, also manufacturing facilities.

1.2 Aim and motivation

On these premises, the research was developed with the final goal of defining guidelines for the integrated redevelopment of existing industrial buildings focusing on the Italian context. The protocol of interventions proposed is meant to cover a wide series of measures ranging from the redevelopment of external areas at district level to several strategies at building level. The latter will encompass the enhancement of buildings' external envelope components, the upgrade of system installations for both air conditioning and lighting, and the implementation of on-site energy generation from renewables and storage solutions. Each of the measures proposed will be specifically detailed and the expected results or impacts discussed.

The existing industrial buildings currently in use in Italy present a series of challenges to be tackled connected to both architectural, structural, and environmental performance. This type of facilities has been neglected by scientific research also because of the peculiarities of this buildings in terms of use

conditions and the widespread unawareness about sustainability topics among private industrial and manufacturing companies.

Addressing the challenges connected with industrial buildings requires a multifactorial approach that integrates several aspects and disciplines and. In this context scientific research is essential to drive innovation, disseminate best practices, and ease the adoption of sustainable solutions within the industrial sector. The key points to substantiate the aims and motivations of the research are graphically illustrated in Figure 1.3 and later diffusely discussed in this paragraph.

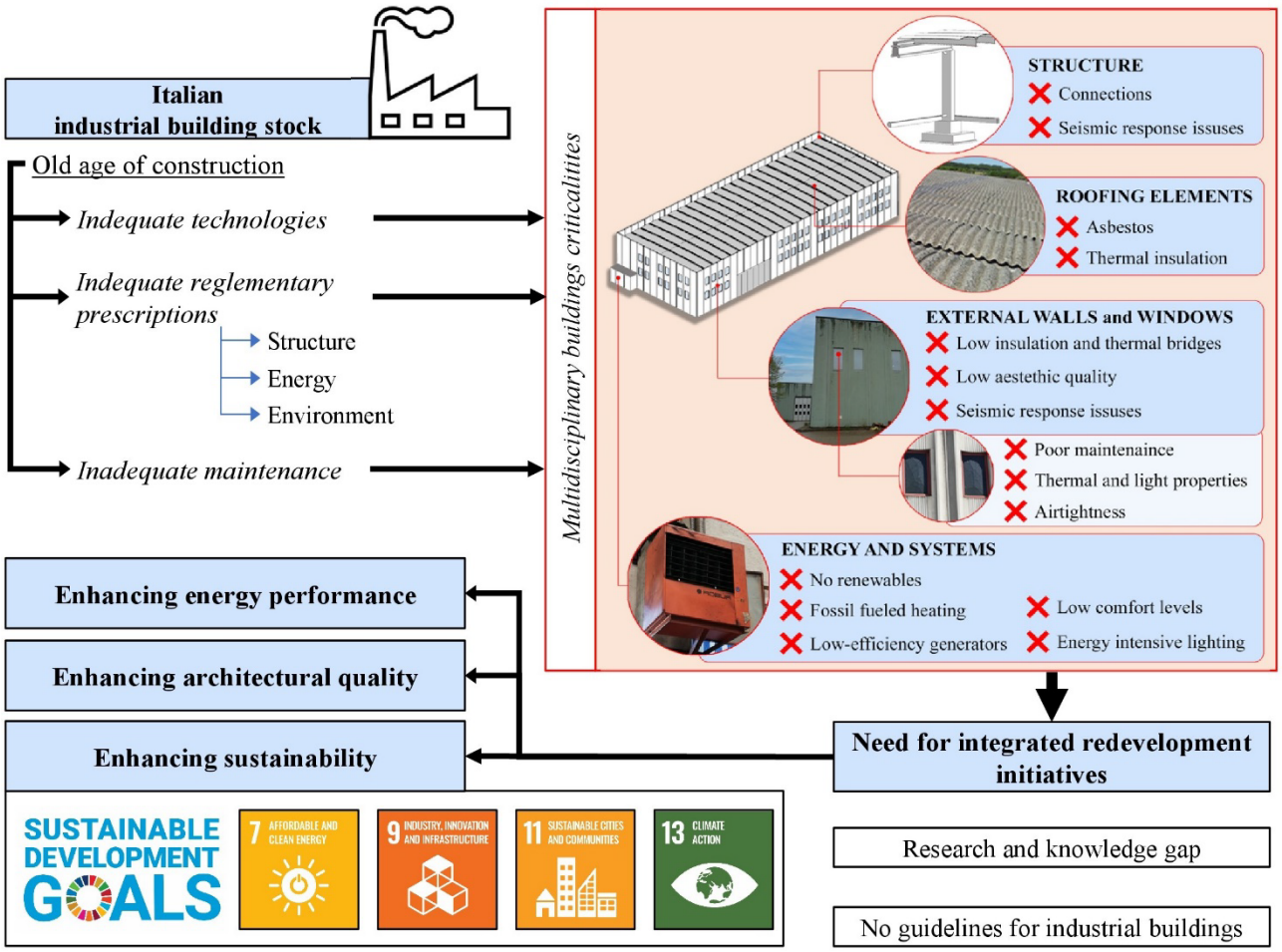

Figure 1.3 Aims and motivations of the research. In the figure, the SDGs addressed are reported along with a synthesis of the key issues affecting the industrial building stock. *Source: elaboration of the author.*

Considering the Italian scenario, the industrial building stock is substantially outdated. According to the ANCE-CRESEM report, 66% of the 325427 buildings for productive activities retraceable over the National territory in 2011 were built between the 50s and the 90s [9]. Most of these facilities were built to satisfy the increasing demand induced by the economic growth that Italy experienced in the decades after WWII. To achieve cost-effective and streamlined construction timelines, prefabricated solutions capable of covering long spans have been diffusely adopted in several buildings, also

supported by the simultaneous development of the prefabrication industry. The use of various structural solutions by different companies, regional distinctions, and evolutions of constructive technologies occurred over time have contributed to make the current industrial building heritage diverse and heterogeneous. However, the technological systems available in that periods were significantly affected by low architectural and overall performance standards. As a result, several buildings are currently suffering from structural deficiencies and from inadequate properties of the external envelopes in terms of thermal insulation, watertightness, and airtightness levels.

In addition to construction and technological limitations of construction system available in that period, at the time the reglementary framework about energy performance and environmental requirements for buildings was very loose compared to current standards, not mandatory or even non-existent. After a first attempt to limit energy consumption in buildings following the energy crisis of the early 70s through the implementation of the law 373/1976, the first systematic and structural Italian regulation is dating back only to 1991 (Legge 10/91). Starting from 2005, the development of similar prescriptions at National level adhere to the deliberation of the European Parliament. The last updates of the Energy Performance of Buildings Directive (EPDB), constantly reviewed over time after its first promulgation in 2002, are promoting the transition toward NZEB building stocks for the member states. To achieve this ambitious goal, wide scale retrofit and redevelopment initiatives should be implemented on a wide scale since the 80% of the existing built is expected to be still used within 2050 [10].

Despite these challenging scenario, industrial buildings are often not addressed by retrofit and regulations supporting these initiatives. Considering the Italian legislation for instance, some of the prescriptions of the Ministerial Decree of the 26$^{th\ of}$ June 2015 do not, or only partially, apply to buildings hosting industrial or manufacturing activities. As later expressed, the theme is under-explored also in the scientific literature as researchers mainly focused on buildings with several different intended uses, primarily addressing residential ones [11][12][13], but substantially neglecting the possible enhancement of the existing industrial facilities. Comprehensive retrofit guidelines or extensive interventions protocols suitable for the peculiarities of buildings for production activities are not available, neither regulatory prescriptions nor scientific contributions. Existing studies focus on specific case studies or on singular aspects of building performance, missing a multidisciplinary approach required by the peculiarities of the building stock considered.

Industrial buildings were examined in the last decade mostly considering their structural behaviour and seismic response, following tragic events occurred in the Mediterranean area. Earthquakes in Central (L'Aquila, 2009) and Northern (Emilia Romagna, 2012) Italy dramatically highlighted structural deficiencies with localized failures or even global collapses of the load-bearing elements. Precast concrete structures have suffered in these cases severe damages, due to the considerable seismic masses of their components and the inadequacy of connections between them, resulting in human losses and interruptions in production activities. As tragically proved, most of the existing buildings are not in line with the structural prescriptions introduced by latest regulations because outdated or, in some cases, because built in areas not yet pointed out as seismic. In Italy, it has been estimated that 29% of existing industrial facilities are located in highly seismic regions and 10% are subjected to severe hydro-geological hazards [9]. Following the dramatic consequences of the cited seismic events, research were conducted focusing on the structural deficiencies of industrial buildings producing some indications for retrofit interventions but generally only targeting the seismic response of these facilities [14] and the design of the most influential elements [15].

Conversely, the energy performance of industrial buildings has not been deepened adequately. When dealing with the energy demand of the production sector, attention is prevalently paid to industrial or manufacturing processes. Energy efficiency policies or sustainability related interventions have priorly targeted production-related aspects, often applying also Life Cycle Assessment methods in the analyses [16]. Only a few authors underscored the significant environmental impact of industrial facilities during their life cycle, considering both construction and operational phase [14]. At this regard, studies in the literature proved that the energy demand connected with heating, cooling, and lighting can even equal the energy consumption of the production machinery installed.

Industrial buildings are highly energy intensive because of the considerable volume to be conditioned, the low exploitation of natural lighting, usage conditions, and the poor thermal transmittance and tightness of the envelope. As previously mentioned, the construction technologies adopted were not adequate to satisfy energy and environmental requirements; moreover, the lack of maintenance over time has compounded these criticalities, resulting in a progressive and pervasive deterioration of the building's integrity and properties. Similar issues not only involve external walls but also roofing components where elements containing asbestos were often implemented and widely still in place, requiring urgent disposal in view of health and environmental risks.

External envelope related issues not only affect the energy performance of buildings but also negatively influence the architectural and aesthetical quality of the buildings. The extensive recurse to precast building systems and the deterioration of concrete surfaces over time result in the nondescript and low-quality built environment of manufacturing or industrial districts. These urban portions extensively built and paved, are characterized by a significative lack of green areas and can be also frequently affected by air-pollution. Despite of this, it has to be remarked that the visual appeal of manufacturing buildings has been re-evaluated in recent years by companies and entrepreneurs because it can positively contribute to the corporate image.

Similarly, by implementing environmentally friendly solutions in the redevelopment initiatives, companies can not only enhance their corporate image in the market but also show their commitment to sustainability. If implemented, this proactive approach also allows to reduce the operational running costs in the long-term fostering a sustainable and economically viable business model as envisaged by the United Nations Sustainable Development Goals.

To pursue the goal of sustainable industrial buildings, focusing on system equipment and integration of renewables is crucial to define cost-optimal solutions, as stressed out in the literature. Several inadequacies in lighting and HVAC conditioning systems can be assessed, relating to both low efficiency and fossil-fuel dependency. During the winter months, heating solutions typically deployed, relying on gas-fuelled fan air-heaters or traditional gas boilers with punctual terminals, are often energy-inefficient because outdated and not adequate for large internal spaces with high ceilings that induce air stratification phenomena and ineffective hot-air distribution. On the other hand, air conditioning systems for cooling during summer months are often not installed despite the growing incidence of overheating conditions. For these reason, thermal comfort for workers is often not guaranteed, exposing them to potential health issues and reducing their productivity [17].

The revitalization of industrial buildings should incorporate system retrofits to facilitate compatibility with smart control solutions and the integration of renewable energy sources, thereby promoting on-site energy production. Surveys performed in different areas of Tuscany let to assess that photovoltaic systems are usually implemented only in recently constructed facilities despite the wide roofing surface available [18][19]. Exploiting the considerable solar potential of these buildings is crucial for enhancing energy efficiency and simultaneously advancing the gradual electrification of the industrial sector [20]. Addressing the intermittent nature of renewable energy production, the adoption of storage systems should be encouraged. Furthermore, exploring economic incentive schemes or shared

consumption models is essential to evaluate financial feasibility for similar interventions and enhance business competitiveness in this context.

1.3 Methodology of the research

The method adopted in developing the research is briefly illustrated in Figure 1.4 in its main procedural stages and later detailed specifically in this paragraph and in the following section of this document.

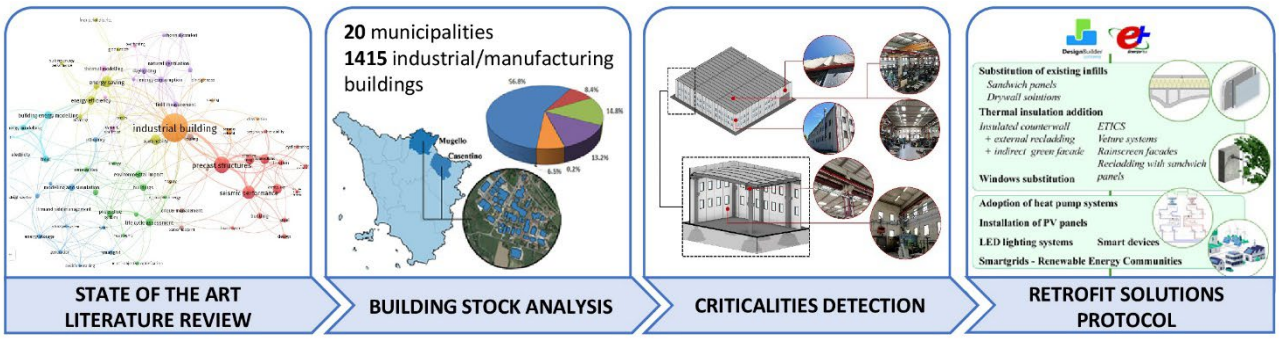

Figure 1.4 Methodological workflow of the research. *Source: elaboration of the author.*

As illustrated in the diagram above, the initial phase of the research was dedicated to an extensive review of the state of the art, by examining the studies currently available in the scientific literature. The primary objective of this review was to conduct a thorough assessment of the existing literature pertaining to industrial buildings, with a focus on identifying gaps and trends within this field of study. As lately described in Chapter 2.1., a methodology integrating the PRISMA framework and computer-assisted bibliometric analysis tools was applied. One of the key findings of this analysis is the conspicuous absence of systematic reviews specifically dedicated to industrial facilities, underscoring the knowledge gaps in this area. By critically evaluating prevailing research trajectories, the emerging themes were identified as well as critical shortcomings that need more accurate analyses. This first comprehensive review thus served as a robust knowledge repository, providing a solid reference for the following formulation of redevelopment strategies for the industrial building stock.

The research was later developed specifically addressing the real existing industrial building stock. Extensive surveys were conducted on different area of the Tuscany territory. This stage was meant to investigate the consistency of the industrial built heritage in both quantitative and qualitative terms and was conceived as a propaedeutic analysis to identify the main criticalities affecting industrial facilities. A typological classification was proposed to classify the existing facilities on the regional territory, highlighting features and peculiarities.

A series of retrofit interventions at district and building level were hence proposed and guidelines for the redevelopment were defined.

The three operative stages introduced before, will be described in detail as they represent the core of the research activity. In Figure 1.5, the workflow diagram specifically targeting these aspects is reported.

An extensive analysis of industrial building stock was performed addressing 8 municipalities of Mugello and 12 of Casentino areas, for a total of over 1000 manufacturing or industrial facilities analysed. Mugello was chosen because of its the geographical location close to the regional border that may have influenced the built context in terms of technological solutions and construction systems. Casentino was selected because of the presence of several precast producers active over time, whose activities led to a widespread diffusion of prefabricated construction systems in industrial facilities. This approach enabled the generation of more aware assessments, as it became evident that both factors impact the industrial building stock under consideration. In addition, this ensures a more reliable generalization of the outputs of the research. Geometrical, architectural, and structural features of the buildings investigated were observed through digital (via Google StreetView, satellite images and areal views available on Regional cartographical datasets) and on field survey campaigns. The data collected were organised using Geographical Information Systems (GIS) tools to produce a geo-referenced database.

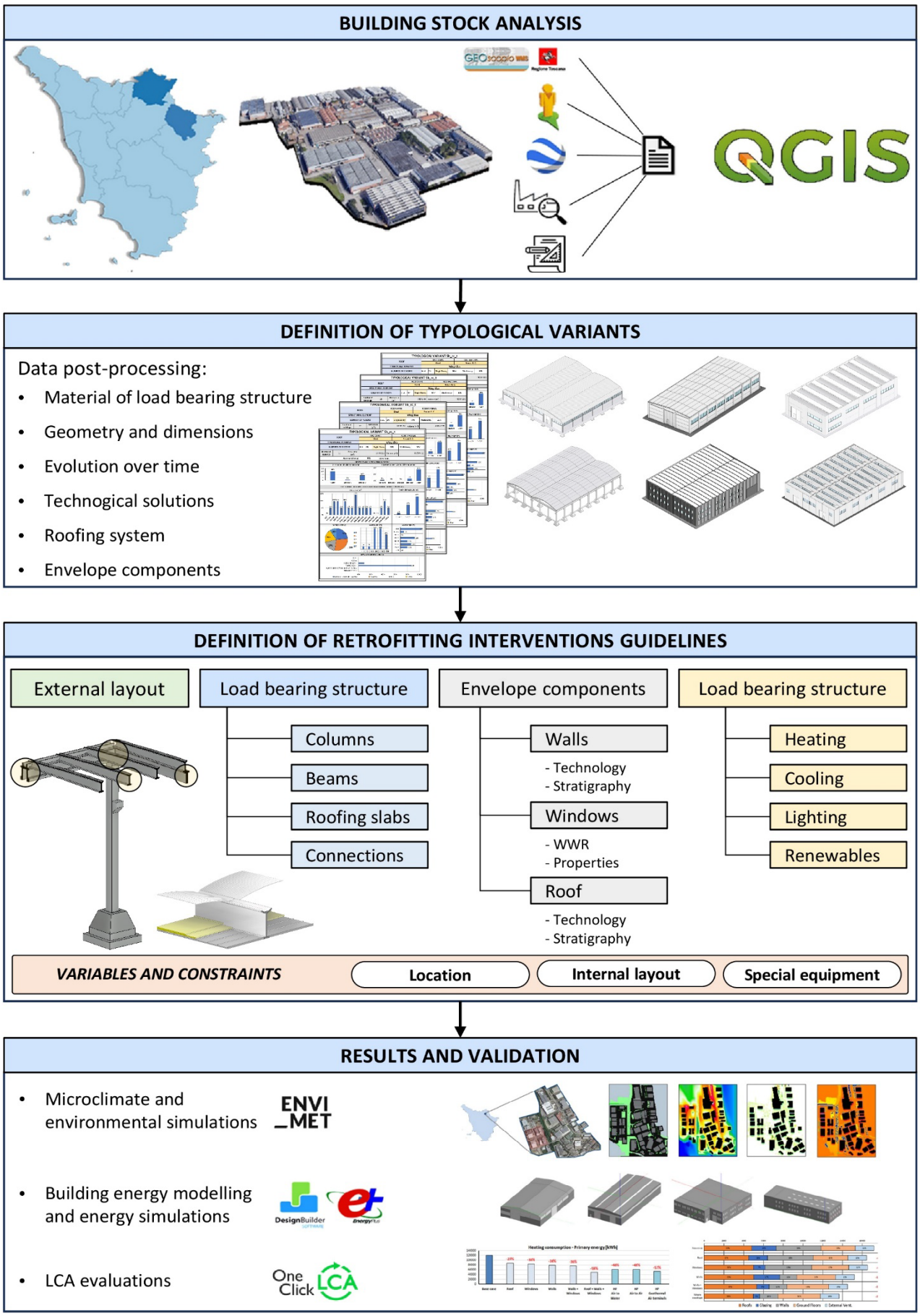

Figure 1.5 Detailed workflow of the research. *Source: elaboration of the author.*

Data were exported and post-processed using Excel spreadsheets, configured to conduct comprehensive statistical analyses. Important parameters such as construction periods and materials were identified, to trace the evolution and implementation of precast concrete construction systems over the years. Further analysis delved into the identification of distinctive and recurring features to identify the most widespread typological variants. Notably, the number of storeys, the configuration of roofing solutions, and the structural layout emerged as the most influential factors at this regard, as they have considerable implications for the architectural aspects and for the selection of construction components. The main typological variants were further analysed distinguishing various sub-categories based on structural connections or external infill solutions. This phase culminated in the development of comprehensive and descriptive datasheets, along with Building Information Modelling (BIM) models of hypothetical representative buildings and technical drawings illustrating the most characteristic details of the various variants and their respective subclasses.

This critical assessment allowed for the development of diverse hypotheses for integrated redevelopment, targeting deficiencies in building and system components to enhance overall facility performance. Redevelopment measures were proposed based on the characteristics of the typological variants assessed, aligning with the standards set by National regulations pertaining to both structural integrity and energy efficiency.

Regarding load-bearing elements, attention was devoted to the geometry, relative relationships, and connections of such components. Various alternative configurations were observed for external walls, encompassing positioning with respect to the load-bearing structure, types of components utilized, and their stratigraphy. Parameters such as window-to-wall ratio and the thermal and visual properties of glazed areas were also considered. Conversely, roofing solutions exhibited a narrower range of variability within the context of single typological variant. In this case the presence of special components, such as skylights, and the adopted stratigraphy served as reference points for formulating retrofitting proposals.

Furthermore, system and HVAC solutions were addressed to propose redevelopment or replacement, integrating on-site energy production using renewable sources, a feature currently absent in approximately 90% of the buildings surveyed. Dedicated building energy simulations were produced at this regard looking for the most effective heating solution coupling also multicriteria decision making tools. As for energy production, the implementation of storage solutions was also evaluated. However, when devising hypotheses for retrofitting interventions, additional parameters at the

building scale, warranted consideration. The geographical location of buildings dictated the requisite insulation levels for the respective climate zones, while the urban context significantly influenced the selection of intervention strategies. The internal layout, delineating zones designated for various purposes, necessitated careful consideration to ensure HVAC systems operated under optimal conditions, guaranteeing adequate comfort levels. Special equipment in working areas, such as cranes or machinery, constituted a critical variable to be addressed when implementing interventions to be foreseen in the indoor environment, such as the thermal insulation of the external walls from inside or false ceiling installation.

Moreover, intervention strategies were formulated also at the urban context level, suggesting cooling and greenery measures aimed at improving external microclimate conditions and enhancing the aesthetic appeal of industrial districts. These interventions were carefully evaluated in consideration of the most recurrent characteristics of existing urban layouts, factoring in mutual distances between facilities, the available space, and the characteristics of paved or built surfaces.

To validate the effectiveness of the measures delineated in the preceding phase, a selection of real case study buildings was made from the pool of investigated structures, trying to include each category. Following on-site surveys, interviews with companies, and data collection endeavours, energy models of the chosen facilities were developed, and dynamic energy simulations were conducted. Retrofit configurations of envelope components and enhanced systems were integrated into the models to evaluate their effectiveness and estimate their impact. Key parameters considered in this assessment encompassed energy consumption patterns, the thermal equilibrium of the buildings, internal environmental conditions, and the well-being of workers. In addition, results were enriched through sensitivity analysis and Life Cycle Cost (LCC) assessments to effectively compare the measures to be included in the final redevelopment guidelines. When formulating the intervention protocols, attention was paid to avoid significantly invasive measures, thus mitigating the risk of prolonged suspension of operational activities.

1.4 References

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2 BACKGROUND AND STATE OF THE ART

An extensive review of the current trends in the scientific literature addressing industrial buildings targeting the performances of these facilities was performed to provide a solid knowledge basis. This preliminary research was conducted to focus on the following key aspects:

- Exploration of contemporary scientific research trends and fields of interest concerning industrial buildings;

- Examination of the strategies and solutions utilized for redevelopment in industrial facilities;

- Collection of the reference reglementary body.

The chapter will be organized as it follows:

- 2.1 Scientific literature review
    - 2.1.1 Building performance
        - 2.1.1.1 Sustainability
        - 2.1.1.2 Retrofit solutions
        - 2.1.1.3 Indoor lighting
        - 2.1.1.4 HVAC and internal conditions
        - 2.1.1.5 BIM applications
    - 2.1.2 Energy
    - 2.1.3 Structural issues and seismic performance
    - 2.1.4 Main findings and conclusions
- 2.2 Regulatory framework
- 2.3 References

2.1 Scientific literature review

For ensuring a rigorous and comprehensive review process and robustness of the results, a rigorous methodology was implemented, as depicted in Figure 2.1. The results of this analysis were deepened in a dedicated scientific paper entitled "*Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions*", published in Journal of Building Engineering [1].

This framework consists of three essential stages:

- The searching phase, in which search boundaries and results filters were set;

- The analysis phase, when bibliometric tools were used and publications directly related to the key areas of study were reviewed;

- The discussion phase, that involved the collection of the main results of the research and their analysis.

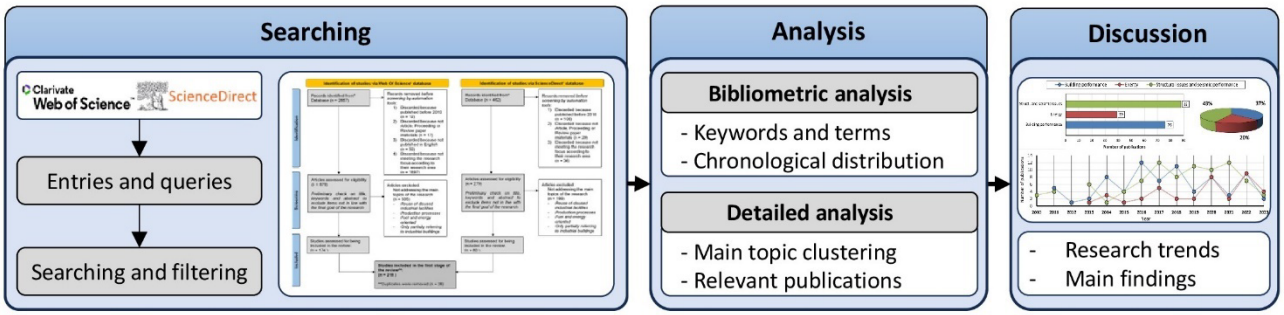

Figure 2.1 Literature review methodological steps. *Source: elaboration of the author.*

The Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method [2] was used to ensure the robustness of the review, performed considering Web of Science [3] and ScienceDirect [4] databases, to ensure comprehensive coverage of publications [5]. To navigate the expansive databases effectively, advanced research tools were employed, leveraging queries featuring Boolean operators to delineate inclusion and exclusion criteria. For addressing building typology, the terms Industr* *or* Manufactur* followed by Building* *or* Facilit* *or* Hall* were included in the searching query. The Boolean operator *and* was used to introduce the topics of the search and detail the analysis. Structur* *or* Architectur* *or* System* *or* Energ* *or* Environment*. For the structural aspects, the term Seismic is added introduced by *or*, while the System related topic is considered in detail by introducing the terms Heating, Cooling, HVAC, Lighting through the *or* operator.

Two primary types of keywords were utilized: one pertaining to the specific type of building under examination and the other encompassing various potential topics addressed by the publications. In the latter case, the research was deepened to include different types of building equipment or structural problems under investigation. Given the constraints of the ScienceDirect search tool, several queries were necessary to explore each topic thoroughly.

Further filtering criteria were set to restrict the review to scientific articles, proceedings, or review papers published after 2010 in English to focus on the most recent developments of the scientific

research at global level. Concurrently, studies not aligning with the designated research area, as per the classification provided by the interrogated online catalogues, were disregarded.

A two-stage verification process was then employed to assess the eligibility of the papers, initially targeting titles, keywords, and abstracts. Subsequently, a comprehensive examination of the content of each paper was conducted and studies only partially dealing with industrial facilities were eliminated. In particular, several publications dealing with production processes were retrieved, about manufacturing energy needs, and the reuse of old factory buildings.

Following the screening procedure, 142 studies were gathered from the Web of Science database, while 101 were retrieved from ScienceDirect: the two clusters were merged, duplicate entries were removed, resulting in a final selection of 203 studies selected. Figure 2.2 and Figure 2.3 illustrate the process adopted for the research and selection of the scientific contributions of interest according to the PRISMA procedure for both databases.

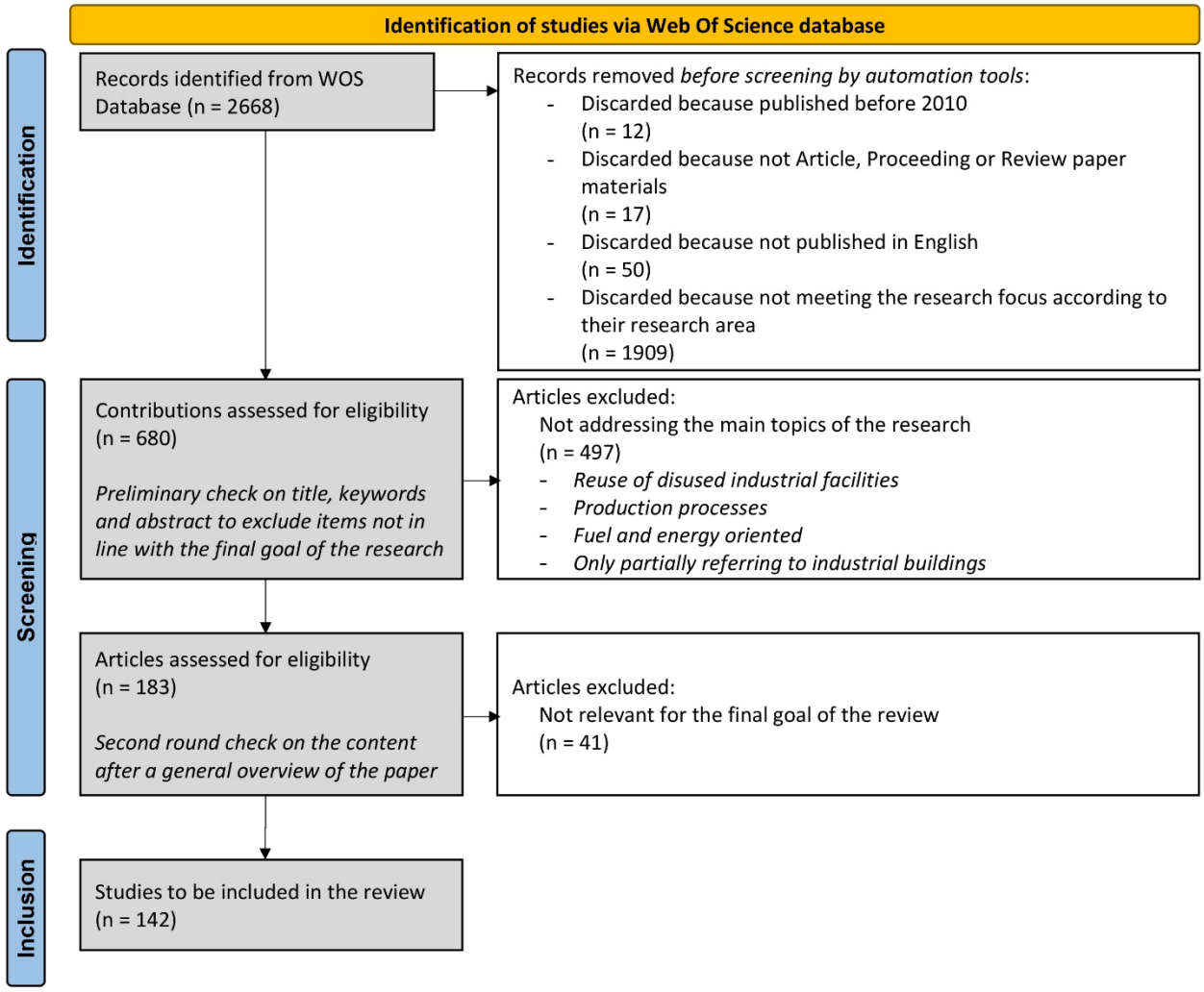

Figure 2.2 PRISMA 2020: publications from Web Of Science database. *Source: elaboration of the author.*

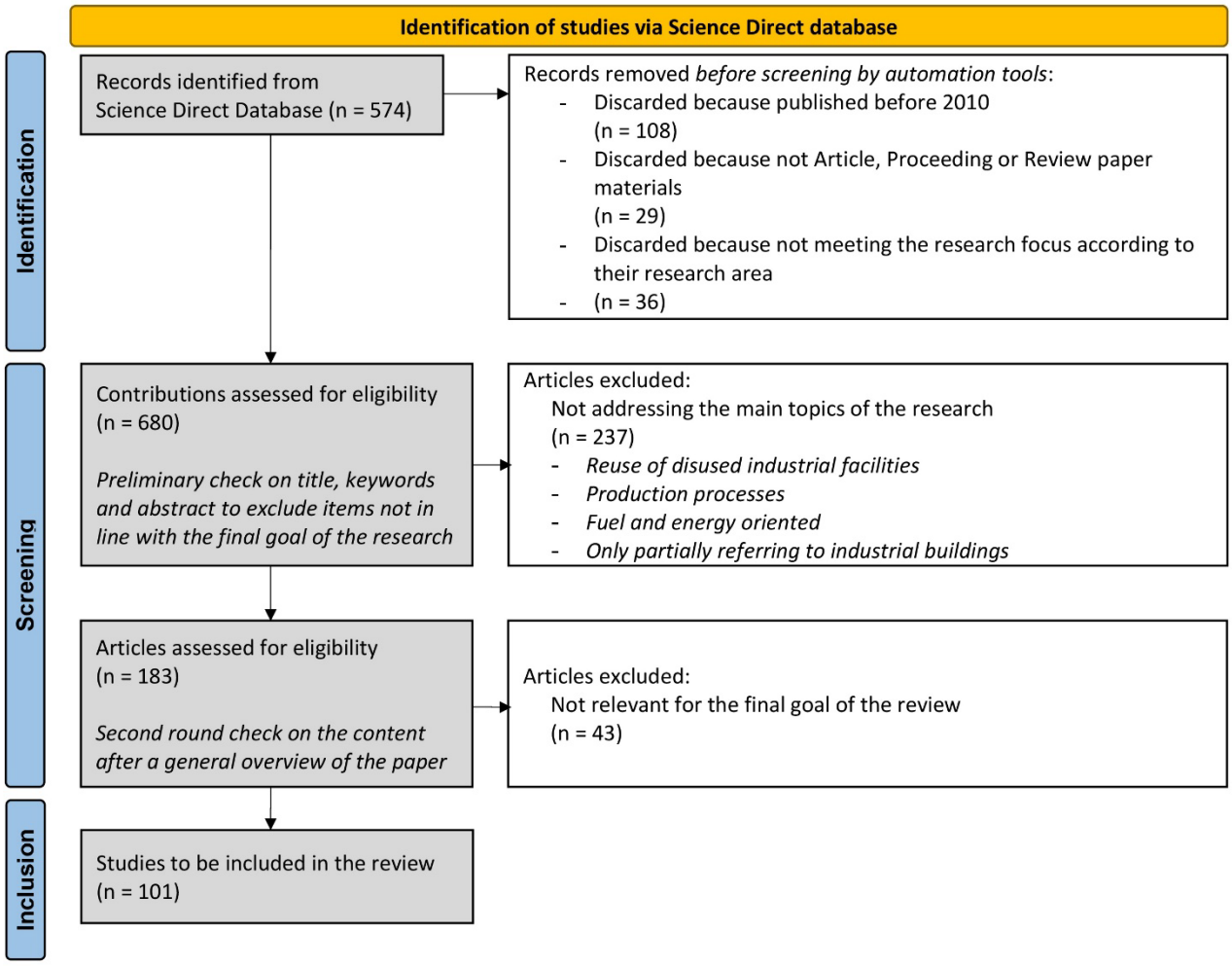

Figure 2.3 PRISMA 2020: publications from Science Direct database. *Source: elaboration of the author.*

Following the selection of the contributions, a bibliometric analysis was conducted with the VOSviewer software, an open-access computer-aided review tool freely available online. This software is recognized as one of the most effective one in science mapping application [6] [7], as demonstrated by its implementation in several studies [8]; in particular, it proved to be especially suitable for the analysis of emerging research fields [9]. In this research, VOSviewer was used for an initial overview of the publications, to analyse keywords' co-occurrence, and to produce graphical maps. Full counting analysis algorithms were addressed to ensure streamlined review procedures [10].

Initially, the distribution of studies over years was investigated. This analysis revealed a notable trend indicating a consistent rise in the interest toward the topic. The data showcased in Figure 2.4 providing compelling evidence of this consideration, with 26 and 25 publications released in 2020 and 2022 respectively.

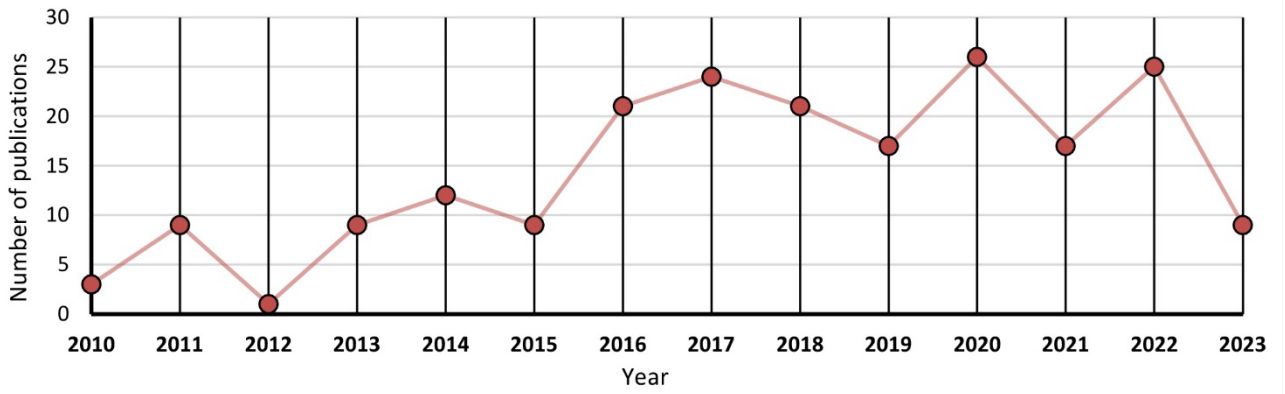

Figure 2.4 Chronological distribution of publications over the last decade. *Source: elaboration of the author.*

Subsequently, a keywords co-occurrence analysis was performed using VOSviewer, with particular attention given to keywords occurring at least three times. This analysis involved evaluating the frequency of keyword occurrences across publications to assess their interconnections and highlight the primary research domains. In Table 2.1 the main findings of this initial analysis are reported.

Table 2.1 Keywords clustering analysis produced by VOSviewer. *Source: Re-elaboration from Banti N (2024) Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions. Journal of Building Engineering 84:108615. https://doi.org/10.1016/j.jobe.2024.108615*

Cluster	**Number of terms**	**Terms**
1	6	Fragility curves Industrial buildings Precast industrial buildings Precast structure Seismic fragility
2	5	Buildings Dynamic simulation Energy efficiency Energy saving Sustainability
3	4	Building energy analysis Energy modelling HVAC Manufacturing energy analysis
4	4	Energy consumption Industrial facilities Model Optimization
5	3	Embodied energy Life cycle assessment Industrial building
6	1	Precast buildings

The six clusters identified focus on distinct themes: Cluster 1) structural and seismic issues, (Clusters 2, 3, and 4) building performance and energy, and (Cluster 5) environmental-related topics. Notably, Clusters 1 and 4 have no links with the others, outlining a gap in integrated studies about addressing structural issues, energy, and building performance. Group 6, formed by a single word, is an outlier due to its broader thematic scope. Using a similar approach, an analysis was conducted to generate a co-occurrence atlas of the most frequently used terms. 73 terms were pointed out and categorized into nine clusters by the software, as illustrated in Figure 2.5 and detailed in Table 2.2. The results of this mapping process overlap with the previous ones even if, by considering terms and not keywords, the analysis was able to delve deeper into specific topics of the previously assessed research areas. However, some clustering criteria appeared unclear, resulting in excessive subdivision of clusters or the inclusion of words that do not align well with others in the discipline as reported also by other authors in the literature that encourage using similar tools for initial screening purposes [26]. As such, a further evaluation of the clustering outcomes was necessary.

Figure 2.5 Visual map of the co-occurrence of terms produced by VOSviewer. *Source: elaboration of the author.*

Table 2.2 VOSviewer terms clustering. *Source: Re-elaboration from Banti N (2024) Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions. Journal of Building Engineering 84:108615. https://doi.org/10.1016/j.jobe.2024.108615*

Cluster	**Number of terms**	**Terms**	
1	14	Brace system Buckling Connections Cyclic testing Damage assessment Design Earthquake	Friction Nonlinear dynamic analysis Precast structures Seismic performance Seismic vulnerability Steel Structural design
2	11	Buildings Embodied energy Environmental impact Heat pump Life cycle assessment	Multi-objective optimization Parametric study Photovoltaic system Renewables Solar energy
3	11	Decision-making Demand-side management District heating Efficiency Energy storage	Generation Modelling and simulation Optimization Smart grid Storage-system Wind
4	9	Building energy performance Costs Economy Energy efficiency Energy saving	Green roofs Industrial districts Life cycle cost Sustainability
5	8	CFD simulation Daylighting Energy consumption Field measurement	Large space building Natural ventilation Skylights Thermal comfort
6	6	Building energy modelling Energy modelling Energy prediction	HVAC Neural networks Peak shifting
7	6	Air-tightness Dissipation Evaporative cooling	Fragility Industrial building Seismic retrofit
8	4	Analytic hierarchy process Carbon footprint	Energy management Heating
9	4	BIM Dynamic simulation	Overheating Thermal modelling

To avoid the fragmentation observed in the VOSviewer mappings, three general research topics were chosen to classify the 203 publications included in the review.

Considering the results of keywords analysis, studies in Cluster 1 primarily revolve around structural-related topics. Thus, the category "Structural issues and seismic performance" was retrieved, for a total of 88 publications, representing approximately 43%.

For the publications in Clusters 2, 3, and 4, a more accurate analysis was required due to their heterogeneous procedures and goals, even if they all discuss buildings performance at different extent. Publications focusing on energy features were distinguished by those focusing on building-scale analyses for envelope components and systems. The latter were joined with Cluster 5, which develops a LCA approach. Consequently, the categories "Energy" and "Building performance" were produced, accounting for 45 and 70 studies, respectively. The outcomes are depicted in Figure 2.6, alongside with the amount of publications for each theme and the share relative over the total number of studies.

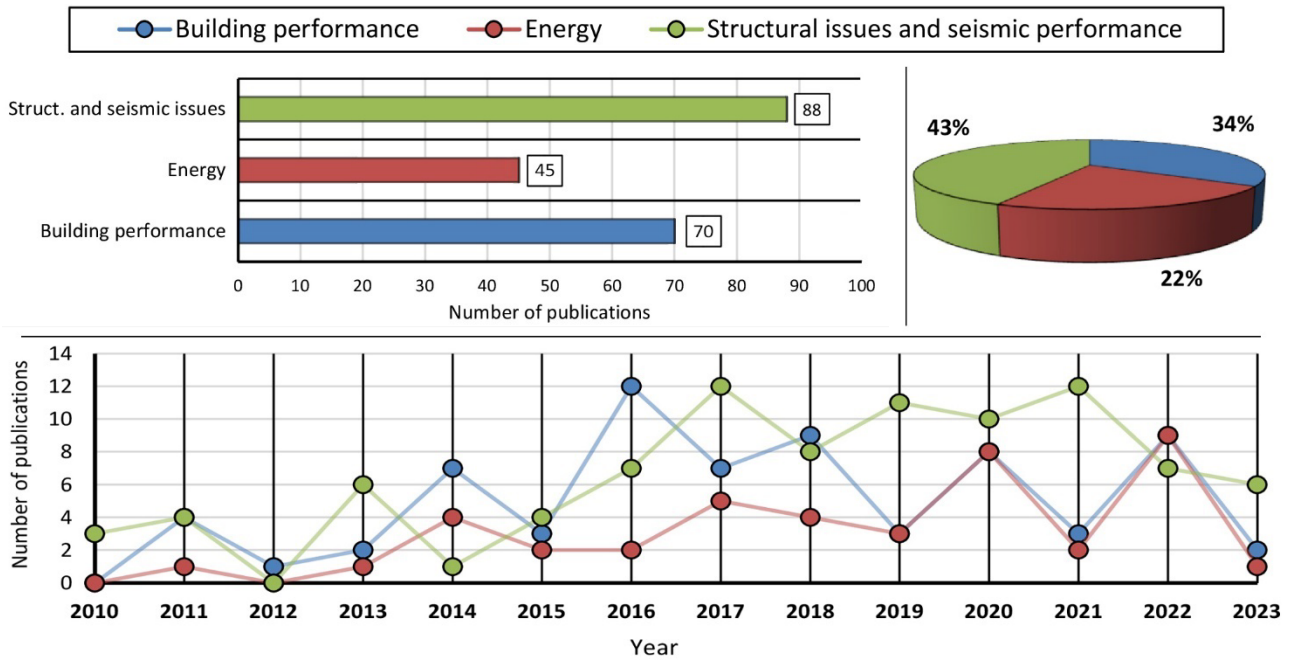

Figure 2.6 Thematic classification and research trends. *Source: Banti N (2024) Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions. Journal of Building Engineering 84:108615. https://doi.org/10.1016/j.jobe.2024.108615*

The structural and seismic behaviour of industrial facilities has increasingly become a focal point since 2014, driven by the incidence of seismic events in preceding years, which underscored the importance of this topic. In contrast, building energy performance of industrial facilities is an emerging field of research. While the former lacks extensive discussion, evidenced by the limited number of publications, a discernible upward trend is noticeable in recent years for the latter, that exhibits an inconsistent trend over recent years, punctuated by significant spikes in 2016 and 2022. Within each category, subclasses were indicated based on the specific themes addressed in each

publication. The relevance of each group was then analysed to gauge their significance in the scientific literature. To present the obtained results more effectively, each theme will be presented in detail.

2.1.1 Building Performance

Given their relevance in the context of this research, the contributions related to building performance have been extensively addressed to elucidate the primary research methodologies employed and key findings documented in the literature. Various subtopics were investigated to illustrate the different facets associated with the theme, as outlined in Table 2.3.

Table 2.3 Analysis of Building performance related studies. *Source: elaboration of the author.*

Topic	**Subtopic**	**Number of publications**
HVAC and indoor conditions	-	28
Retrofit	-	18
Sustainability	LCA – LCC	13
	Rating	
Indoor lighting	-	7
BIM applications	-	4

The bulk of available studies concentrates on HVAC systems and indoor conditions within industrial buildings. However, retrofit solutions for these types of buildings remain relatively underexplored, as does the topic of sustainability in relation to production facilities. Lighting conditions are studied in 7 publications. Additionally, BIM methodologies related publications were included given their application in studies about the evaluation of the performance levels in existing facilities.

2.1.1.1 Sustainability

13 publications dealing with sustainability issues, were split into 2 categories:

- rating systems and sustainability indexes for industrial facilities [11–14];
- life cycle analyses for aspects dealing with environment and economy.

The environmental impact is generally analysed on single facilities [15] and by referring to specific technologies [16, 17]. Life Cycle Assessment (LCA) was used also to rate different measures ensuring high sustainability standards for newly built facilities [18]. In addition, studies focusing on structural

frames [19], roofing panels [20] and facades [21] are retraceable. Moreover, the construction and operational costs are used to compare traditional and green building technologies to design industrial buildings [22]. By the way, a single study coupling LCC and LCA analyses at building scale was retrieved [23].

2.1.1.2 Retrofit solutions

Eighteen publications, which are summarized in Table 2.4, focus on retrofit interventions for existing industrial buildings, addressing both individual facilities and broader building stocks. Among these, three studies specifically investigate wider building stocks, with a focus on the scenarios of Ireland and Italy.

Horan et al. conducted a national-scale study to evaluate the potential for decarbonization through the installation of photovoltaic (PV) systems on the roofs and water harvesting technologies for commercial and industrial buildings in Ireland [24]. Their findings highlight the significant potential of utilizing the extensive roof surface of industrial facilities to enhance the effectiveness of such retrofit solutions. In Mediterranean regions, industrial districts often face challenges related to potential discomfort during summer heat waves. Guerri et al. examined this issue in the area of Florence, Italy, emphasizing the importance of urban layout and the balance between green and built areas in mitigating heat-related discomfort [25]. Their research suggests that strategic interventions in urban planning could potentially reduce Land Surface Temperature by up to 2°C, thereby improving thermal comfort. Similarly, Ciacci et al. proposed a similar approach, focusing on the adoption of green roofs in an industrial area in Tuscany [26]. Analysing the impact on environmental conditions and pollutant concentrations at a district scale, they demonstrated the potential benefits of green roofs in mitigating environmental impacts and improving air quality within industrial zones. Green roofing is also advocated by Berto et al. for an industrial facility in Northern Italy: while remarking the social benefits of green roofs installation, the authors highlight uncertainties regarding the economic sustainability of such interventions, underscoring the need for further research and incentives at this regard [27].

Most of the publications focus on retrofit measures at the building scale, implementing these interventions in real case studies. All of the buildings vary significantly in terms of their location, climate conditions, construction systems, industrial processes, and the redevelopment solutions proposed. Some publications concentrate solely on enhancing the performance of building envelope components.

Espino-Reyes et al. advocate for retrofit measures targeting roofing components, specifically recommending the installation of photovoltaic systems coupled with insulated or cool roofs in hot and temperate climate zones in Mexico [28]. Similarly, Mastrapostoli evaluates a cool roof fostering the application of a tetrafluoroethylene monomer fluorocarbon coating, resulting in a significant decrease in cooling energy demand in the summer period [29]. Moreover, the effectiveness of reflective coatings on roofs can be further enhanced when combined with an air cavity and ventilation[30].

Some studies focus exclusively on building systems, such as the work by Kim, that evaluates actions on air handling units, heating, cooling, and lighting systems with a life cycle cost approach [31]. Additionally, Katunsky et al. stress the effectiveness of automation and control systems in lighting, heat recovery systems, and the automated operation of doors and windows [32].

Retrofit-oriented studies typically assess multidisciplinary redevelopment strategies due to the generally low performances of existing industrial buildings in different fields [33]. These studies often take into account the needs of production processes and climate characteristics, as demonstrated in the research by Wang et al. [34]. For example, it's important to avoid excessive insulation levels in cases where there are high indoor heat generation processes [35]. Authors often consider economic aspects when rating redevelopment strategies. As stressed by Simson et al. [36], measures focusing solely on improving building envelope may not be advantageous in the mid to long term. Therefore, a combination of different interventions is often preferred, as evidenced by Dongellini et al. [37]. Similarly, Ascione et al. [38] highlight the economic profitability of addressing system and building installations rather than focusing solely on refurbishing envelope components. This study also assesses energy savings of up to 81%, particularly when including PV installation, which is identified as the most valuable intervention.

Some contributions in the literature focus exclusively on energy performance and internal comfort. For instance, Gourlis et al. conduct a detailed investigation of an existing industrial building located in Austria to mitigate overheating conditions. [39]. Their study suggests acting on the roof's albedo, walls insulation, and existing skylights to prevent overheating, coupled with rescheduled night natural ventilation. The same authors explore strategies to improve the energy performance, achieving heating energy savings of up to 52% and significantly reducing summer overheating, especially with the integral substitution of both roof and skylight components.[40]. A similar approach is undertaken

by Dervishi et al., although they obtain less appreciable energy savings and overheating prevention due to the different climate, the age of the building analysed and its construction technology [41].

In conclusion, several general observations can be drawn regarding the methodological approaches employed in the selected studies. To ensure the reliability of their findings, many contributions rely on on-site measurements and real-time monitoring of indoor conditions. Additionally, in terms of energy modelling and simulations, EnergyPlus emerges as the most utilized calculation engine, due to its interoperability with external software and its integration with Building Information Modelling (BIM) environments through dedicated plugins.

Table 2.4 Publications on retrofit strategies from the literature. Each entry provides a summary of the study, including the publication year, location and climate characteristics (Köppen classification when provided), the assessed measures, the primary focus of analysis, the software utilized, and key findings. *Source: Re-elaboration from Banti N (2024) Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions. Journal of Building Engineering 84:108615. https://doi.org/10.1016/j.jobe.2024.108615*

Ref.	**Year**	**Location**	**Energy saving measures**	**Focus of the analysis**	**Main results**
[32]	2013	Kosice (SK) Dfb	Automated integration in: Lighting; Heat recovery; Door operation.	Energy performance; Thermal comfort.	Energy saving potential of about 10-60%
[29]	2014	Oss (NL) Cfb	Tetrafluoroethylene monomer fluorocarbon coating	Energy performance; Surface temperature; Thermal comfort.	- Roof's albedo increased by 120% (from 0.3 to 0.67); - 73% decrease in cooling demand; - 5% increase in heating demand.
[35]	2014	Amsterdam (NL) Cfb	Building thermal insulation; Airtightness improvement; Skylights.	Energy performance;	- Lighting consumption prevails over heating and cooling demand; - The optimized solution is highly dependent on the internal thermal loads.
[37]	2014	Bologna (IT) Cfa	Building thermal insulation; Windows substitution; Gas-boilers substitution; Heat recovery; Variation of the heating set point.	Energy performance; Cost analysis.	- Combination of retrofit measures can produce: - 15% decrease in energy demand; - 100000 € economic saving; - Less than 6 years pay-back time.

[33]	2016	Beijing (CN)		Energy performance assessment	Assessment of poor performance factors: air leakages (3.1 ACH), condensation, poor insulation, low standard HVAC and air distribution.
[36]	2016	Helsinki (FI) Dfb	Walls insulation; Roof insulation; Windows substitution; Doors substitution; Ventilation system and heat recovery; LED lighting.	Energy performance; Cost analysis.	- Envelope retrofit may not beneficial within a payback period of 20 years; - Heat recovery adoption is the most cost effective solution; - LED lighting is highly beneficial; - A combination of the different measures is the most recommendable solution.
[42]	2016	Ulsan (KR) Cfa	PV installation; Roof insulation; Skylights installation, Lighting dimming control.	Energy performance; Cost analysis.	- Energy optimal solution results in LCC reduction equal to 11.5%: • PV panel ratio: 65%; • Skylight ratio: 17.8%; • Insulation thick: 0.26 m; - Cost optimal solution results in LCC reduction equal to 27.3%: • PV panel ratio: 1%; • Skylight ratio: 17.8%; • Insulation thick: 0.26 m.
[40]	2016	Berndorf (AT) Cfb	Scenario 1: Windows substitution; Roof insulation; Scenario 2: Windows substitution; Roof substitution; Skylights substitution.	Energy performance; Thermal comfort.	- Heating demand reduction up to 52% - Overheating reduction: • S1: Avg. T reduction: 0.2 °C Max. T reduction: 2.3 °C • S2: Avg. T reduction: 2.1 °C Max. T reduction: 6.3 °C
[39]	2017	Berndorf (AT) Cfb	Night natural ventilation; Cool roof elastomeric coating; External shading on south façade; Roof insulation; Skylights substitution; Windows substitution.	Energy performance; Thermal comfort	- Effective prevention of summer overheating; - Cool roof and solar shading give significant results in case of low internal loads.
[31]	2017	South California (USA)	AHUs; Chillers refrigerators; High efficiency fluorescent lamps.	Energy performance; Cost analysis.	The highest annual energy and cost savings is ensured by AHU, followed by lighting, and then the chillers

[30]	2018	Malaysia	Active and passive cool roof system with ventilation in air cavity and reflective coating	Energy performance; Surface temperature; Thermal comfort.	- Reflective coating reduce the metal roof surface temperature by 7 °C; - Integration of reflecting coating and air cavity ventilation reduce the attic temperature by about 13 °C.
[27]	2018	Trieste (IT) Cfa	Cool roof installation; Green roof installation	Energy performance; Cost analysis; Social impact.	- From the private investor's viewpoint cool roof is more advantageous; - Economic incentives are needed to promote the spread of green roofing; - Cost-benefit analysis favourable for the green roof because of its positive externalities and social impact.
[34]	2019	China	Passive energy savings measures; Efficient utilization of HVAC and lighting systems; Renewables and heat recovery.	Energy performance.	- Average reduction of about 16% in energy demand; - Heating and humidification systems show the greatest energy saving potentials; - Climate conditions influence the results.
[24]	2020	Ireland (IE)	PV installation; Water harvesting solutions.	Rooftop decarbonisation potential.	- Prioritising decarbonisation actions for the larger buildings; - PV installation results in up to 513 $ktCO_2$ savings; - PV installation results in GHG reduction equal to 4%; - Rainwater harvesting technologies result in 6 $ktCO_{2e}$ savings.
[38]	2020	Valenzano (IT) Csa	Combination of: Windows substitution; External automatic shading installation; Heat recovery; PV installation; Optimization of HVAC flow rates; Variation of heating set point.	Energy performance; Cost analysis.	- Energy savings up to 81%; - Economy savings up to 45%; - Prioritization of measures: - PV system; - Heat recovery; - HVAC schedule optimization.
[41]	2020	Durres (AL)	Scenario 1: Walls insulation; Roof insulation (S1/S2); Scenario 2:	Energy performance; Thermal comfort.	- 8% (S1) and 14% (S2) decrease in cooling energy demand; - 13% (S1) and 19% (S2) decrease in heating energy demand;

		Csa	S1; Skylights substitution; Increased summer ventilation.		- 1°C (S1) and 1,5°C (S2) decrease in internal temperature during summer.
[28]	2020	Mexico BSh, BSk, BWh, BWk, Cwa,Cwb	Cool roof; Roof insulation; Walls insulation; PV installation.	Energy performance; Cost analysis.	- Warm cities require the implementation of a cool roof on a non-insulated roof or its insulation; - Roof insulation is effective in temperate climates; - Walls insulation reduce the payback period in case of heating system installation;
[43]	2021	Liverpool (UK) Cfb	Walls insulation; Floor insulation; PV installation.	Energy performance; CO_2 emissions.	- Energy demand and CO_2 emissions reduction by 56% acting on building envelope; - CO_2 emissions reduction by 56% installing PV.
[25]	2022	Florence (IT) Cfa	Changes in: Building area; Surface albedo; Trees coverage percentage; Grassland area.	External temperature; Land surface temperature.	- 50% of industrial buildings located in hot-spot areas; - Increasing vegetated areas and reducing built one result in a 2 °C drop in LST.
[26]	2023	Barberino di M.llo Csa	Green roofs; Trees planting	Energy performance; Environmental parameters; Pollutant concentration.	- External air temperature reduced by 1.5 °C; - Outer surface temperature reduced by up to 15 °C; - Wind speed at roof level reduced by 50%; - Effective particulate absorption effects; - 15% energy savings for both cooling and heating demand.

2.1.1.3 Indoor lighting

Visual comfort and the energy consumptions related to the lighting system are highlighted as key topic in the literature. The main studies retrieved about this topic are reported in Table 2.5.

As assessed by Katunsky et al. for an existing manufacturing hall in Slovakia, natural lighting alone doesn't' ensure to meet the level required by the current standards [44] but the relevant contribution of skylights, guaranteeing about 30% of the daylight factor, is highlighted.

The effectiveness of roof-lighting, is recognised also by Dolnikova et al. in a comparison of different skylights shapes [45]. Saddle roof openings have to be preferred also according to Mavridou et al. that conducted a parametric optimization [46].

The implementation of combined roof skylights and lighting control systems is investigated in the literature with energy savings ranging from about 30% [47] up to 80% in case of a sensors network and optimized distribution of lighting devices [48].

Wang et al. evaluate the effect of lighting control and natural ventilation on overheating hours, decreased as well as the energy demand and related CO_2 emissions [49]. However, during winter, lowering the thermal loads induced by lighting devices, causes an increase of heating energy demand by about 7% - 9% [50].

Table 2.5 Publications on indoor lighting conditions. Each entry provides a summary of the study, including the publication year, location, the assessed measures, the primary focus of analysis, the software utilized, and the main findings. *Source: Re-elaboration from Banti N (2024) Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions. Journal of Building Engineering 84:108615. https://doi.org/10.1016/j.jobe.2024.108615*

Ref.	**Year**	**Location**	**Energy saving measures**	**Type of analysis**	**Main results**
[49]	2013	London (UK)	Optimized combination of: - On/off lighting control; - Natural ventilation.	Energy performance; Thermal comfort; Lighting conditions.	- 70% decrease in lighting energy demand; - Reduction of overheating hours thanks to lighting control and natural ventilation; - 45% decrease in CO_2 emissions.
[50]	2014	Tianjin (CN)	- Continuous/off lighting control; - On/off lighting control; - Vertical and horizontal skylights.	Energy performance; Lighting conditions.	- 36% and 42% decrease in lighting energy demand; - 7% and 9% increase in heating energy demand.
[48]	2015	Xi'an (CN)	- Skylights; - Optimized distribution of lighting devices; - Lighting control sensors network.	Energy performance; Lighting conditions.	Up to 80% decrease in lighting energy demand during cloudy days;
[51]	2017	Kosice (SK)		Lighting conditions	- Natural lighting alone is not sufficient;

					- Skylights ensure 30% of the observed daylight factor.
[47]	2019	Coimbatore (IN)	- Continuous/off lighting control; - On/off lighting control; - Skylights.	Energy performance; Lighting conditions.	25% and 31% decrease in lighting energy demand
[46]	2019	Athens (GR)	- Saddle roof openings; - Horizontal roof skylights; - Vertical roof openings.	Lighting conditions	Sawtooth configuration with an average distance of 10-13 m is the best performing one
[45]	2022	Kosice (SK)	- Saddle roof openings; - Horizontal roof skylight; - Vertical roof openings; - Lanterns skylights.	Lighting conditions	- Roof-lighting is more efficient - than side-walls windows for lighting purpose; - Saddle roof openings with diffuse glazing are the best performing one.

2.1.1.4 HVAC and internal conditions

Publications addressing industrial facilities performance predominantly focus on indoor environmental conditions and HVAC systems. However, the diverse nature of production processes and climate characteristics present significant uncertainties when attempting to formulate general considerations.

According to Diaz-Elsayed et al. [52], the location of a building can influence annual energy consumption, with reported ranges from -10% to +8%. Similar observations are echoed in other studies within the literature [53].

Despite these limitations, Labat et al. [54] assessed a similar impact of process activities, HVAC systems, and lighting demand on the final energy balance of various case study buildings in France. Additionally, different operational tasks result in distinct occupancy schedules, activity levels, and internal loads associated with required machinery. Performing a comprehensive review of data from multiple facilities in the USA, Bawaneh et al. [55] noted an average energy consumption of approximately 28 W/m^2 for heating, cooling, and lighting systems. This underscores the significance of considering various factors beyond just production processes when evaluating energy consumption in industrial settings.

Given the unique characteristics of industrial buildings and the significance of internal thermal loads, Mawson et al. [56] advocate for the adoption of proactive HVAC systems capable of interacting with process-related demand. Furthermore, depending on the nature of activities conducted within these buildings, the presence of contaminants and associated indoor air quality concerns should be carefully evaluated using dedicated evaluation indexes [57]. Additionally, a multicriteria approach should be employed when designing ventilation systems [58].

In terms of worker well-being, innovative techniques that integrate real-time indoor monitoring results with subjective surveys among employees have been proposed [59]. Another important aspect is the impact of external door opening operations on airflow patterns, indoor temperature, and external infiltration [60]. Brinks highlights the need for clear estimation methods for the contribution of external doors to the thermal and energy balance, which is often unclear and inaccurate when using conventional formulations from national regulations [61].

Minimizing air leakages is highly recommended for energy-saving purposes. Tanasic et al. emphasize the importance of minimizing air leakages, as energy simulations may yield misleading results compared to real data, particularly regarding internal air temperature [62]. Stratification phenomena due to the considerable internal height of industrial halls are also addressed, with Porras et al. reporting vertical temperature difference profiles of about 0.3 °C/m - 0.7 °C/m during warmer months [63].

The influence of outdoor temperature on indoor air stratification is significant, despite the mitigation offered by air conditioning systems, as in the study by Kurnitski et al. [64]. Ahmed et al. advocate for the use of ceiling-installed radiant panels over air heating units, particularly when air change rates are low [65]. Radiant floor heating is suggested as a profitable solution, with its thermal storage potential allowing that allows to run heat pumps during night hours with lower electricity price [66].

Building envelope integrated solar collectors have been proposed as a means to pre-heat external air [67] [68] [69] [70]. Internal air distribution methods have been discussed in the literature, encompassing natural [71], mechanical [72] and hybrid ventilation [73]. Critical operational conditions and energy usage patterns were identified. Significant cost and energy savings can be obtained by adjusting setpoint operating schedules [74] [75] and reducing external air supply [76].

Various cooling strategies have been investigated, with an emphasis on the potential exploitation of natural free cooling, as advocated by Nezamdoost et al., along with HVAC solutions [77]. De Angelis

et al. emphasize the impact internal heat gains on indoor conditions and stress the need for mechanical ventilation, underscoring the energy-saving ensured by indirect evaporative cooling when used in humid climates [78].

Guan et al. [79] evaluate the performance of a control air-conditioning system based on liquid desiccant, reporting approximately 23% energy savings with further improvement potential through airflow ratio optimization. Evaporative cooling solutions are also tested by Kowalski et al. in Poland regions, suggesting that indirect evaporative solutions using external air should be preferred over those using exhaust air recirculation [80].

Wang et al. assess variable speed-driven chilled and cooling water systems in an industrial building in Taiwan, reporting energy savings ranging from 5% to 30% [81]. When conducting an overall assessment of industrial building operating conditions, Zhou et al. stress the need for considering both energy demand and comfort, taking into account all influencing parameters [75].

Chinese et al. and Bac et al. have both undertaken a thorough and multidimensional approach to select heating-oriented HVAC solutions tailored specifically for medium-sized manufacturing facilities [82] [83]. Their methodologies involve the integration of various parameters and evaluation criteria, reflecting a holistic understanding of the complex requirements and challenges inherent in industrial heating systems including factors such as thermal performance, energy efficiency, operational costs, environmental impact, occupant comfort, and system reliability. By considering this wide array of parameters, the selection process is ensured adequate robustness focusing not only on the heating needs of medium-sized manufacturing facilities but also optimizing performance and sustainability.

2.1.1.5 BIM applications

The application of Building Information Modelling (BIM) methodologies to studies involving manufacturing facilities is a recent trend in the literature. Table 2.6 provides an overview of the key features observed in these studies. Garwood et al. demonstrate the application of BIM in generating reliable Building Energy Models by leveraging point cloud surveys [84]. Meanwhile, Gourlis et al. highlight the advantages of these approaches, which enable the simultaneous evaluation of systems, machines, and processes, ultimately leading to energy savings and anticipating future synergies and advancements towards fully harnessing the potential of BIM [85]. Building upon their previous work, these authors have recently expanded their research to validate a methodology for defining digital

twins in industrial facilities [86]. Furthermore, as-built BIM models serve as valuable repositories for integrating data on building performances, as for the assessment of water [87].

Table 2.6 Publications implementing BIM methodologies in analysing industrial buildings from the literature. Each entry provides a summary of the study, including the publication year, the location and peculiarity of the case study building, the software used and the main findings. *Source: Re-elaboration from Banti N (2024) Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions. Journal of Building Engineering 84:108615. https://doi.org/10.1016/j.jobe.2024.108615*

Ref.	Year	Location	Case study	Main results
[84]	2017	Sheffield (UK)	Factory 2050 building	• Conversion from Point Clouds to BIM and BEM models; • Accurate energy models can be produced.
[85]	2017	Berndorf (AT)	Historical metal-band cutting and forming factory; New construction bakery and meat factory.	• BIM to BEM approach in industrial construction is a completely novel aspect; • Cost-benefit balance is generally highly advantageous; • Coupled simulation including building, systems, machines and processes would consistent energy savings; • Further developments of open interfaces are necessary for the full exploitation of BIM potential.
[86]	2022	Austria	New construction bakery and meat factory	• Validation of a methodology for the definition of digital twins of manufacturing oriented facilities; • BEM application of BIM models.
[87]	2022	Kolin (CZ)	House of Culture building	• Roof leakages assessment; • Integration with BIM model.

2.1.2 Energy

In the realm of energy-related publications, the literature yields 39 research works addressing various aspects, encompassing both building-scale and regional-scale studies. A comprehensive overview of these topics is presented in Table 2.7, which delineates the different subtopics.

Table 2.7 Energy related publications: subtopics and number of studies. *Source: elaboration of the author.*

Topic	Subtopic	Number of publications
Generation and management	Renewables	10
	Storage	7
	Control and monitoring	4
	CHP	2
Modelling and forecasting	-	7
Economy	-	3

Microgrid	-	3
District heating	-	2

Energy generation and management play pivotal roles in ensuring the efficient operational phase of industrial and manufacturing facilities, a topic extensively discussed in the literature. In recent years, there has been a focus on analysing control and monitoring procedures for smart energy management. Validation of monitoring systems has been reported, along with evaluations of power metering and management information systems [104] [105]. Additionally, there is emerging experimentation with artificial intelligence technology in this field, yielding promising results [106]. Machine learning techniques applied to control strategies have demonstrated the potential for reducing peak energy demand by up to 15% through the decoupling of HVAC and production-related loads [107].

In the realm of generation systems, combined heating and power generation emerges as promising for industrial facilities, given their diverse energy needs. This approach demonstrates significant benefits for both economic and environmental perspectives. Machalek et al. evaluate reductions of approximately 10% and 23% in primary energy demand and CO2 emissions, and a payback period of 8 years [108]. Moreover, this payback period can be further reduced depending on the control strategy implemented, as proposed by Calise et al., who advocate for an innovative hybrid electric-thermal load tracking system [109].

The integration of renewable energy sources is also evaluated in the literature, driven by the need for a transition towards a carbon-free economy. Herrando et al. assess a cogenerated cooling, heating, and power system incorporating solar panels, thermal storage, and a heat pump as the optimal solution for an industrial building in Spain [88]. This integrated system outperforms standalone PV-based solutions, reducing environmental impact by more than 30%. Abuzaid et al. evaluate PV installation using a life cycle approach for an industrial facility in the UAE. Despite the considerable productivity of the plant relative to irradiation conditions, the payback period is short, although efforts to decarbonize the production phase of the panels are encouraged [89].

Economic considerations are particularly crucial when assessing renewable energy applications in developing countries or sparsely industrialized areas, such as South Russia [90], Philippines [91], Bangladesh [92], Pakistan [93] and Trinidad and Tobago [94]. In such cases, the necessity for government subsidies and financial incentives to make renewable energy projects economically viable is emphasized. To promote the exploitation of renewables, various solutions are available,

including ground-source heat pumps[95] and biomass fuelled systems, that allow reducing energy dependence on the grid and manging waste properly and effectively [96].

As renewable energy sources exhibit non-deterministic behaviour, energy production must contend with potential mismatches between power demand and supply. Consequently, there has been a notable increase in interest in energy storage solutions for industrial applications, evident in the literature. The adoption of energy storage technologies empowers industrial companies to implement effective energy management procedures [97] and capitalize on demand shifting to off-peak hours, resulting in cost reductions of approximately 12%[98, 99].

According to Elio et al., among various energy storage options, air compressed storage offers the highest return on investment [100]. However, mitigating the substantial initial investment costs necessitates the precise sizing of storage batteries, a task achievable through the application of decision theory [101]. Additionally, authors underscore the necessity for a comprehensive revision of electricity pricing rates and financial incentives to facilitate the deployment of industrial energy storage [102]. Camarero et al. highlight that, even with anticipated compensations for surplus energy, storage batteries may not be profitable unless there is a significant drop in their prices. Cost-effectiveness is attainable only when a self-consumption rate of 70% is achieved, particularly in PV systems integrated with energy storage [103]. The integration of energy storage solutions with renewable energy production enhances their economic viability, as demonstrated by Arteconi et al., who explore the coupling of thermal energy storage with heat pumps for cooling purposes [99]. Furthermore, multigeneration solutions incorporating photovoltaic panels, wind turbines, biomass, diesel burners [104] or tidal generation [105] to power industrial facilities are also investigated in the literature.

In recent years, the evaluation of energy generation from renewables has expanded to encompass its integration within microgrids and shared energy consumption models. Bartolucci et al. examine a mixed scenario involving industrial and residential facilities, determining that the load profile and PV plant are the most influential factors in reducing grid dependency and effectively managing storage batteries [106]. Additionally, research explores real existing industrial microgrids, with suggested improvements focusing on optimizing HVAC management and utilizing thermal storage [107]. Smart energy management at the district scale is also investigated, with considerations for district heating and waste heat recovery [108, 109]. Numerous studies delve into the impact of solar collectors and photovoltaic systems in emerging countries, particularly in light of recent energy price fluctuations

and advancements in technology, which have led to the emergence of new market mechanisms like peer-to-peer trading among prosumers [110–112]. Moreover, recent years have seen the application of new techniques to produce more reliable energy models, crucial for ensuring accurate evaluations of proposed energy efficiency measures [113]. While traditional techniques such as regression models [114, 115] and change-point process [116] have been prevalent, contemporary approaches leverage novel probabilistic models [117], deep machine learning [118, 119] and artificial neural networks [120]. These advanced methodologies promise enhanced accuracy and robustness in energy modelling and analysis.

2.1.3 Structural issues and seismic performance

The Emilia Romagna earthquake that struck Italy in 2012 catalysed a significant shift in focus towards understanding the structural behaviour of precast industrial facilities, igniting a burgeoning interest in this theme within the scientific community. Consequently, research examining the structural and seismic performance of industrial buildings began to proliferate in literature and continues to be prevalent today. This body of research encompasses a diverse array of subtopics, as delineated in Table 2.8. Most studies deal with vulnerability analyses and loss assessment topics, constituting 33% of the publications. The pertinent contributions are detailed in Table 2.9.

Table 2.8 Structural issues and seismic performance related publications: subtopics and number of studies. *Source: elaboration of the author.*

Topic	**Subtopic**	**Number of publications**
Vulnerability and loss assessment	-	29
Connections	Walls	19
	Column – foundation	
	Beam - Column	
	Roof – beam	
Earthquake related studies	-	15
Seismic retrofit	-	14
Façade panels	-	6
Design solutions	-	4
Typological characterization		1

Table 2.9 Publications focusing on vulnerability analysis and loss assessment. Each entry includes the publication year, the reference country, and the construction technology examined. Additionally, the approach adopted in the study is indicated, specifying whether it involves a classification of the existing industrial building stock, a case study facility, or an ideal hypothetical one. *Source: Re-elaboration from Banti N (2024) Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions. Journal of Building Engineering 84:108615. https://doi.org/10.1016/j.jobe.2024.108615*

Reference	Country	Building material	Building stock classification	Real case study building
[121]	Turkey	Steel		
[122]	Italy	Precast RC	X	
[123]	Portugal	Precast RC	X	
[124]	Italy	Precast RC	X	
[125]	n.a.	Steel		
[126]	Italy	Precast RC	X	X
[127]	Italy	Precast RC		X
[128]	Italy	Precast RC	X	
[129]	Italy	Precast RC	X	
[130]	Italy	Precast RC	X	
[131]	Turkey	Precast RC		X
[132]	Italy	Precast RC		X
[133]	Italy	Precast RC		X
[134]	Thailand	RC		X
[135]	Italy	Precast RC	X	
[136]	Turkey	Precast RC	X	
[137]	Turkey	Precast RC		
[138]	Turkey	Precast RC		
[139]	Ukraine	Steel	X	
[140]	Italy	Precast RC		X
[141]	Italy	RC		X
[142]	n.a.	Steel	X	
[143]	Italy	Precast RC	X	
[144]	Turkey	Precast RC	X	
[145]	Turkey	Precast RC	X	
[146]	Portugal	Precast RC	X	
[147]	Turkey	Precast RC	X	
[148]	Italy	Precast RC		X

Only a limited amount of studies deal with steel structure facilities [121, 125, 142] or cast-in-place reinforced concrete buildings [134, 141]. The majority of available research is centred on the Italian scenario [122, 124, 126–130, 132, 133, 135, 140, 141, 143, 148], followed by Turkey [121, 131, 136–138, 144, 145, 147] and Portugal[123, 146, 149]. To encompass a broad range of possible building configurations, several studies provide an initial overview of the national or regional building stocks considered, offering a typological classification [122, 123, 126, 128–130, 135, 136, 139, 143–147, 149, 150]. Additionally, many studies involve representative case studies to extract pertinent structural parameters and characteristics for use in numerical simulations or to validate their findings.

The literature extensively examines post-earthquake investigations of industrial buildings across various countries, including China [151, 152], Chile [153, 154] , and notably Italy, which constitutes the focal point of approximately two-thirds of the research. Del Gaudio et al. provide a comprehensive review of past significant seismic events and their associated damage scenarios[155]. Other studies concentrate on the repercussions of the Emilia Romagna earthquake in 2012, examining historical manufacturing buildings [156] and precast concrete structures [157–164]. Batalha et al. [165] in their review of the aforementioned research, underscore the vulnerability of precast reinforced concrete industrial buildings, citing prevalent issues such as short-column effects, connection failures, and detachment of external cladding panels.

Structural connections are a key focus of analysis, with thorough examinations of beam-to-column [166–175] roof-to-beam [176–178], column-to-foundation [179, 180], and walls-to-structure [181–184] connections. External wall assessments encompass steel [185] and precast structures, including in this case reinforced masonry infills [186, 187] or precast cladding panels installed both horizontally [188, 189] and vertically [190].

Despite existing deficiencies in industrial buildings, the literature suggests prioritizing structural retrofitting over demolition and reconstruction from a life cycle perspective, as advocated by Raposo et al. [191]. Seismic retrofitting options are extensively discussed, primarily targeting precast facilities, with only one paper addressing steel frame structures [192]. Common retrofit strategies include the installation of dissipative braces or beam-to-column friction connection devices [193–198]. Other studies explore shear walls [199], rigidity elements [200] or an external exoskeleton [201]. Authors also evaluate the reinforcement of existing columns with steel jacketing, comparing various retrofit alternatives, including interventions on connections and external cladding [202–204]. Additionally publications explore novel [205–207] or optimized design solutions [208] for newly built facilities.

2.1.4 Main findings and conclusions

In Figure 2.7, a comprehensive overview of the main findings obtained is provided. The most significative evidence collected following the review carried put can be synthesized as it follows:

- Despite being an overlooked area in the scientific landscape, industrial buildings have garnered increased attention in recent years, particularly in terms of building performance and energy-related aspects, marking an emerging field of research. Conversely, the structural integrity of concrete

precast industrial facilities has become a focal point in literature, spurred by seismic events that occurred in Italy in 2012.

- The energy demand for heating, cooling, and lighting operations often receive insufficient attention when exploring energy efficiency in industrial facilities. However, existing literature underscores that these demands can be compared with the ones for production activities, requiring a closer examination and consideration in energy management initiatives.

- The estimation of operational energy demand in industrial buildings is affected by numerous uncertainties. One major challenge lies in accurately quantifying external air infiltration, which is often considerable due to poor maintenance conditions, leading to compromised air-tightness within these facilities. Additionally, specifying internal heat gains becomes crucial for enhancing the quality and reliability of energy building simulation procedures, especially given the significant impact of machinery-related thermal loads on the overall non-process energy demand. Due to the substantial influence of local factors on the behaviour of existing industrial buildings, generalized conclusions are difficult to derive from individual publications. Therefore, a comprehensive review becomes imperative to offer a broader perspective on various topics, transcending the limitations of case-study-oriented studies.

- Redeveloping heating, cooling, and lighting solutions is often prioritized over interventions aimed at improving envelope performance due to its cost-effectiveness. Ensuring proper internal air temperature and distribution, along with meeting ventilation requirements, is crucial for maintaining indoor conditions and safeguarding worker well-being. Implementing heat recovery units, smart control and management solutions, as well as installing high-efficiency heating generators or heat pumps, are highlighted as highly beneficial measures. To prevent summer overheating, passive solutions such as enhanced natural ventilation and free cooling can be deployed. However, evaporative cooling systems are considered promising but may not be suitable for strictly controlled environments, as their operation is influenced by external conditions.

- The significant internal area of industrial buildings, combined with the typically limited number of openings in the external envelope, can lead to a considerable energy demand to maintain adequate lighting conditions in work areas, as highlighted in numerous studies. In response to this challenge, various approaches are explored, including modifications to skylights and windows, as well as the replacement of existing lighting fixtures with LED technology.

- Solar radiation emerges as the most promising avenue for promoting renewable energy into industrial buildings, owing to its feasibility for architectural integration. However, the widespread adoption of storage devices remains limited due to the associated high costs. Meanwhile, the exploration of shared energy consumption via microgrids or economic compensation models shows potential profitability for industrial settlements. Despite these promising avenues, further research is warranted in this direction, as the existing studies are insufficient to provide a comprehensive understanding of this topic.

- Retrofit solutions in industrial buildings are often analysed in terms of individual building components or addressing specific aspects such as structure, architecture, technology, or energy efficiency. Research on envelope refurbishment typically delves into strategies aimed at improving thermal insulation properties, replacing skylights and glazed areas, or implementing cool roof solutions. However, a holistic, multidisciplinary approach is frequently absent in these analyses, with only a limited number of studies adopting such an approach. At the same time, when deliberating on redevelopment strategies for industrial buildings, greater emphasis should be placed on qualitative variables such as flexibility and reliability, alongside initial financial investments, compared to other intended use buildings.

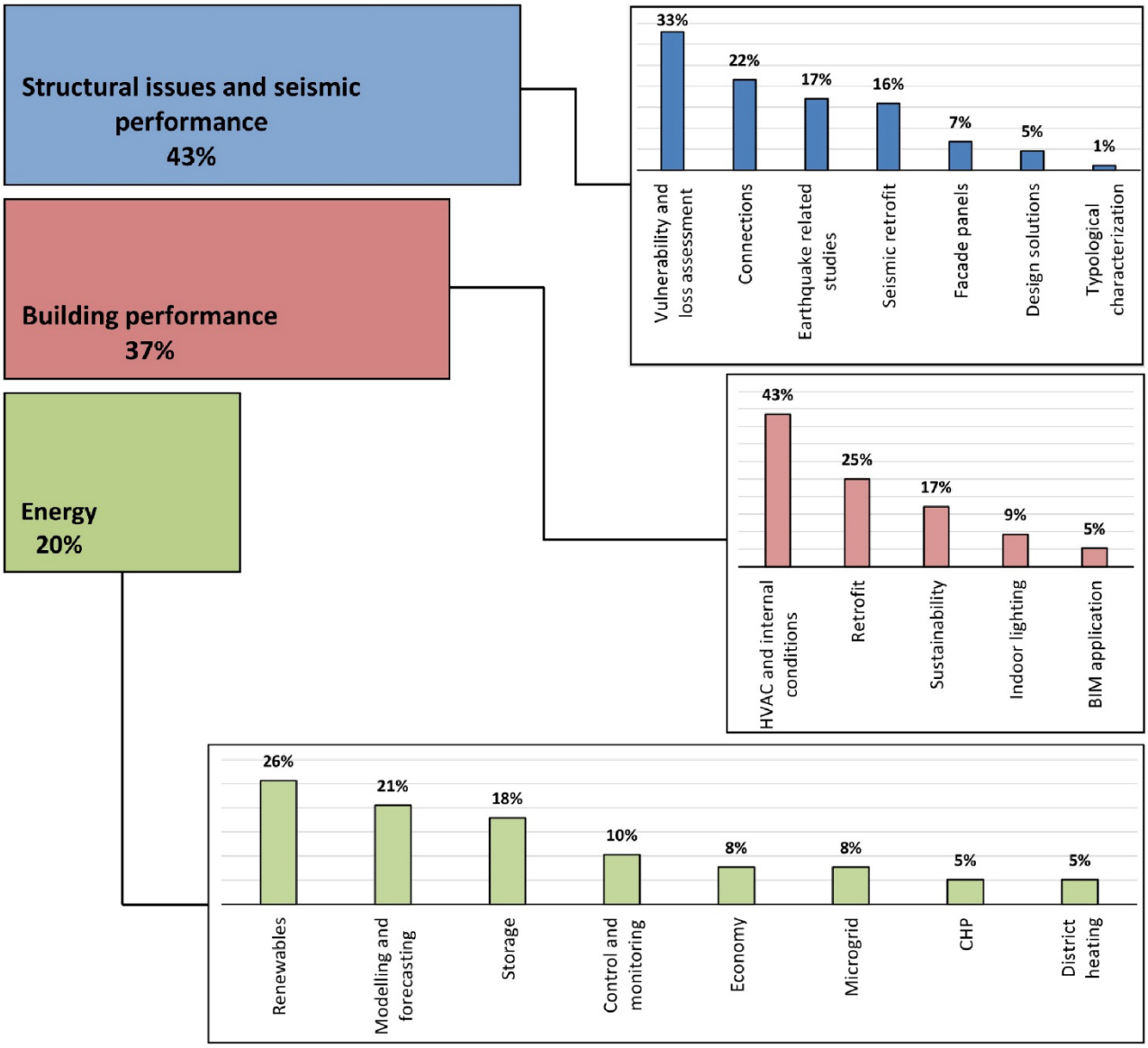

Figure 2.7 General overview of the findings. *Source: Source: Re-elaboration from Banti N (2024) Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions. Journal of Building Engineering 84:108615. https://doi.org/10.1016/j.jobe.2024.108615*

2.2 Regulatory framework

- **Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings** [209]

- **Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings** [210]

- **Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings** [211]

- **A Renovation Wave for Europe** - greening our buildings, creating jobs, improving lives, European Commission, 2020 [212]

- **European Climate Law**, 2021[213]

- **Legge 9 gennaio 1991, n.10** "Norme per l'attuazione del Piano energetico nazionale in materia di uso razionale dell'energia, di risparmio energetico e di sviluppo delle fonti rinnovabili di energia." [214]

- **Decreto del Presidente della Repubblica 26 agosto 1993, n. 412** "Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, comma 4, della legge 9 gennaio 1991, n. 10." [215]

- **Decreto Legislativo 19 agosto 2005, n.192** "Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia." [216]

- **Decreto del Presidente della Repubblica aprile 2009, n.59** "Regolamento di attuazione dell'articolo 4, comma 1, lettere a) e b), del decreto legislativo 19 agosto 2005, n. 192, concernente attuazione della direttiva 2002/91/CE sul rendimento energetico in edilizia." [217]

- **Decreto Ministeriale 26/6/2009 – Ministero dello Sviluppo Economico** "Linee guida nazionali per la certificazione energetica degli edifici." [218]

- **Decreto Legislativo 3 marzo 2011, n.28** "Attuazione della direttiva 2009/28/CE sulla promozione dell'uso dell'energia da fonti rinnovabili, recante modifica e successiva abrogazione delle direttive 2001/77/CE e 2003/30/CE." [219]

- **Legge 3 agosto 2013, n.90** "Conversione in legge, con modificazioni, del decreto-legge 4 giugno 2013, n. 63, recante disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazione energetica nell'edilizia per la definizione delle procedure d'infrazione avviate dalla Commissione europea, nonché altre disposizioni in materia di coesione sociale." [220]

- **Decreto interministeriale 26 giugno 2015** "Adeguamento linee guida nazionali per la certificazione energetica degli edifici." [221]

- **Decreto Interministeriale 26 giugno 2015** "Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici." [222]

- **Decreto legislativo 8 novembre 2021 , n. 199** "Attuazione della direttiva (UE) 2018/2001 del Parlamento europeo e del Consiglio, dell'11 dicembre 2018, sulla promozione dell'uso dell'energia da fonti rinnovabili." [223]

- **Decreto legislativo 9 aprile 2008, n. 81** TESTO UNICO SULLA SALUTE E SICUREZZA SUL LAVORO [224]

- **Ente Nazionale Italiano di Unificazione - UNI 10351:2021** "Materiali da costruzione - Proprietà termoigrometriche - Procedura per la scelta dei valori di progetto." [225]

- **Ente Nazionale Italiano di Unificazione - UNI EN ISO 10456:2008** "Materiali e prodotti per edilizia - Proprietà igrometriche - Valori tabulati di progetto e procedimenti per la determinazione dei valori termici dichiarati e di progetto."[226]

- **Ente Nazionale Italiano di Unificazione - UNI EN ISO 7730: 2006** "Ergonomia degli ambienti termici - Determinazione analitica e interpretazione del benessere termico mediante il calcolo degli indici PMV e PPD e dei criteri di benessere termico locale." [227]

- **Ente Nazionale Italiano di Unificazione - UNI/TS 11300-1** "Prestazioni energetiche degli edifici Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale" [228]

- **Ente Nazionale Italiano di Unificazione - UNI EN 16798-1:2019** "Prestazione energetica degli edifici - Ventilazione per gli edifici - Parte 1: Parametri di ingresso dell'ambiente interno per la progettazione e la valutazione della prestazione energetica degli edifici in relazione alla qualità dell'aria interna, all'ambiente termico, all'illuminazione e all'acustica."[229]

- **Ente Nazionale Italiano di Unificazione - UNI 10339** – "Impianti aeraulici a fini di benessere. Generalità, classificazione e requisiti. Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura." [230]

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3 TERRITORIAL BUILDING STOCK ANALYSIS

The research focused on the existing industrial building stock in Tuscany, with extensive surveys conducted across two different areas. The aim was to assess both the quantitative and qualitative aspects of the built heritage, leading to a detailed typological classification of the existing manufacturing facilities of the region. By highlighting common traits and unique characteristics of the different variants retrieved, this stage of the research was conceived as a preliminary analysis to identify critical issues affecting industrial facilities. The study encompassed eight municipalities in Mugello and twelve in Casentino, examining more than 1000 manufacturing or industrial facilities. Both the areas selected present homogeneous characteristics in terms of geo-morphological features and history. Even if characterized by the presence of forests and areas devoted to agricultural and farming activities, the main centres of both areas host a well rooted industrial and manufacturing tissue. The peculiarities of both the regions will be later briefly detailed.

Below, the scheme of the subsections included in the chapter is reported:

- 3.1 Background and previous studies
- 3.2 Methodology and analysis setup
- 3.3 Main results
    - 3.3.1 Casentino
        - 3.3.1.1 General overview of the building stock
        - 3.3.1.2 Identification of typological variants
    - 3.3.2 Mugello
        - 3.3.2.1 General overview of the building stock
        - 3.3.2.2 Identification of typological variants
    - 3.3.3 Description of the recurrent typological variants identified
        - 3.3.3.1 Variant V_m_ar
        - 3.3.3.2 Variant Sl_rc_slb
        - 3.3.3.3 Variant Sl_m_tr
        - 3.3.3.4 Variant P_rc_b
        - 3.3.3.5 Variant P_rc_t
        - 3.3.3.6 Variant Sh_rc_t
- 3.4 References
- ANNEX A
- ANNEX B

3.1 Background and previous studies

The definition of recurrent building typologies is addressed by several studies in the literature, considering a wide set of different intended uses. The classification criteria adopted are based on architectural or structural features.

This is particularly evident in the case of archaeological sites, where the understanding of the overall characteristics of ancient structures is crucial for their conservation and restoration [1]. Similar studies were conducted also with reference to existing historical residential constructions in Spain [2] [3] [4]. This research entailed identifying specific parameters relevant to the study's goals and the types of buildings being examined. Building height, total area, construction materials, and layout are some of the features typically considered in these studies as they offer valuable insights into the architectural and structural aspects of buildings, assisting in their classification and definition of their relation with the context. Similarly, specific areas in Southern Italy have been pointed out as case studies to assess the energy performance of traditional buildings in the Mediterranean region. [5]. Concentrating on a particular geographic cluster, researchers conducted a thorough investigation of the historical centres of several towns in Puglia. This involved analysing environmental, architectural, and technological aspects to identify the most common building types. A representative building from each category was chosen for detailed study, including energy audits to assess the potential impact of retrofitting proposals. Remarkably, the methodology used in the referenced study is similar to that of other research projects.

Classification and categorization studies were carried out also at larger scale, especially at European level thanks to several research projects promoted.

Between 2009 and 2012, 13 European nations collaborated on the Intelligent Energy Europe project "Typology Approach for Building Stock Energy Assessment" (TABULA) [6] [7] [8]. This initiative aimed to meet the requirements outlined in Delegated Regulation 244 issued by the European Union in 2012, which called for each member state to define reference buildings for various typological classes. Specifically, research groups studied the residential built heritage of each nation to identify recurring building variants based on location, construction period, size, shape, and other parameters related to energy performance. In the case of Italy, a classification based on six different time periods was proposed to track the evolution of building characteristics and the implementation of energy regulations [9]. The TABULA study was also used as information database to classify the existing

building stock from an energy performance point of view. Fon instance, the outputs of the study were used to estimate the energy saving potential of retrofitting interventions in the French context [10].

The need for integrated redevelopment of the built environment at European level, compelled researchers to define classification approaches applicable on different seismic and climatic zones across the continent [11]. In particular, structural and earthquake-related issues are particularly relevant in the scientific literature [12]. Studies about the definition of residential building structural typologies are currently retrievable in different geographical context such as Italy [13] or Serbia [14]. Moreover, in recent years, similar studies have been carried out also implementing automatized procedures based on machine learning techniques, even if the reliability of the outcomes in this case is still an open challenge [15].

In contrast to the extensive classification studies conducted for residential buildings, there are relatively few examples of extensive classification for industrial buildings found in the literature. One notable survey at the European scale can be inferred from the Precasteel report commissioned by the European Commission [16]. This report compiled comprehensive statistical data from various countries, focusing on the most common structural solutions, geometric dimensions, special equipment installed, and financial aspects. However, it is important to note that this research, affected by the partial availability of data for an only limited number of European nations, encompassed a broader range of building types, including commercial structures, and was primarily oriented towards structural analysis.

Most similar studies available, even at local scale extent, precisely focus on the structural and seismic performance. As previously introduced, these aspects have been addressed as crucial features for industrial facilities, especially in case of precast technologies solutions.

Following the earthquakes in Adana-Ceyhan (1998), Kocaeli, and Duzce (1999), inventories of industrial buildings were conducted in Turkey [17]. Subsequent investigations focused on collecting data from 65 projects of prefabricated reinforced concrete industrial buildings to analyse their geometric dimensions and the percentages of reinforcement used [18]. Similarly, studies in Portugal aimed to assess the seismic risk in this kind of buildings [19]. Through the analysis of 73 design documents of industrial buildings constructed over the last 50 years, researchers identified the four most common types prevalent in the Portuguese scenario.

In addition to extensive publications on the subject such as the one by Dassori [20], analyses have been conducted also in the Italian context to classify the industrial built heritage even if architecture and energy oriented investigations have been carried out only over limited portions of the Italian territory. In this regard, a survey of approximately 50 buildings in the industrial district of Maniago (Friuli Venezia Giulia) was conducted to recommend energy retrofitting solutions [21]. Based on the outputs of audits guided by the ITACA protocol for industrial buildings, the research outlined some measures targeting both envelope components and systems to improve energy efficiency.

Most of the studies focus on structural and seismic performance, mainly due to the tragic consequences of the earthquake in Emilia-Romagna in 2012 that prompted the publication of numerous scientific contributions on the subject [22].

A comprehensive study by Bellotti et al. provided a classification of prefabricated industrial buildings across significant portions of Italy. This classification was based on structural organization, number of floors, roofing elements, types of beams, and beam-column connections [23]. Data for this study were sourced from Confidustria of Piacenza in collaboration with the European Training and Research Centre in Seismic Engineering (Eucentre), the Tuscany Region, and the Network of University Laboratories of Seismic Engineering (ReLUIS). As a result, four types of recurrent buildings were identified at the national level.

A more detailed analysis was conducted by ReLUIS in collaboration with the Associazione Nazionale Industrie Manufatti Cementizi (Assobeton) to estimate the seismic resistance of precast manufacturing facilities. This involved collecting data from approximately 120 projects of industrial buildings constructed by ten major prefabricated manufacturing companies across different periods and regions in Italy [24]. Additionally, complementary documents were produced to classify the connection components [25] and provide project documentation [26].

Focusing on the Tuscany region, a comprehensive database was compiled through a survey campaign directly promoted by the regional seismic office to evaluate seismic risk in industrial areas [27]. This database contains information on over 2000 industrial buildings distributed across 29 municipalities. 31 alternative configurations were identified, focusing on structural material, frame direction, roof shape, and related structural solutions. Notably, prefabricated reinforced concrete structures, often featuring roofs constructed with prestressed Y-section beams, wing tiles, or double slope beams, assessed as the most prevalent solution. However, due to the expeditious approach adopted for the

survey, the study lacks sufficient information on various aspects, including structural connections and architectural features.

Other studies focusing on the Tuscan context include an analysis by Casotto et al. on the earthquake damage scenario for prefabricated structures in the southern part of the region [28]. This research, carried out with a similar methodology also at national scale [29] involved a preliminary classification of building typologies based on structure configuration: transverse portals and longitudinal frames with perpendicular roof beams emerged as a common solution. Additionally, a chronological classification was proposed relating the periods of construction with the evolution of structural performance regulations. As a result, only a small percentage of industrial buildings built in recent years have been assessed; consequently, the most of the existing built heritage is not complying with the prescriptions of the "Technical Standards for Constructions" released in 2008

Still considering Tuscany, a detailed classification was developed for prefabricated reinforced concrete industrial buildings in the province of Arezzo to assess potential economic damage from seismic events [30]. This study analysed 300 industrial buildings in terms of structure configuration(frames arranged transversely or longitudinally), construction period, and external cladding, identifying 7 recurrent typologies.

Coming to methodological aspects, in recent decades, innovative digital tools such as GIS and BIM have emerged. GIS enables comprehensive management of large datasets, serving as both operational tool and information repository by storing and processing georeferenced data. Its versatility makes it suitable for various uses, including assessing energy performance at a territorial scale [31] and, if combined with simulation software, GIS can aid in decision-making for retrofitting strategies and urban planning [32] [33]. Additionally, GIS systems are particularly effective in estimating solar potential on urban rooftops [34], with numerous studies conducted across different geographical contexts [35] [36] [37] [38] [39] [40]. The integration of information stored in GIS and BIM models is another promising resource [41], even if some authors have noted issues related to interoperability and communication between these different databases [42].

3.2 Methodology and analysis setup

For the territorial analysis carried out, in both Casentino and Mugello areas, the same methodological approach was applied. A general schematic overview of the procedure is reported in Figure 3.1.

The analysis was initially carried out targeting all the buildings with an independent load bearing structure characterized by a roofing span equal or greater than 8 m. However, smaller facilities sharing the same structural logic or realized recurring to similar construction systems and components were included in the recognition.

The key aspects of each step are described as follows:

- The GIS informative database available through the online dedicated portal of Tuscany Region was addressed as reference starting point for the analysis. It was possible to access and exploit the geometry layout of the assets of interest, along with other significative data associated with each of the geometry contained in the reference shapefile. A digital survey was conducted using tools for territorial recognition freely accessible online (Google Street View) [257] and the analysis of satellite images (Google Earth, Google Maps) [258] and aerial photographs (Geoscopio - Regione Toscana) [259]. Google Maps and Street View were used to assess the external envelope characteristics, while companies' websites provided additional information on interior spaces, systems, or special equipment. Following the digital survey, inspections were conducted at selected buildings to validate the data collected and verify the ones initially not reliable. In addition, information about structural components, envelope stratigraphy and other details were retrieved by original design documents.

- In QGIS each building was associated to the respective characteristics, therefore ensuring its georeferencing on the territory while creating an information database to be queried. Each building was analysed based on various alphanumeric attributes, including urban context, dimensional data, material of the load-bearing structure, configuration, and external envelope characteristics. Attention was focused on roofing components, external walls, and the presence of asbestos, skylights, and photovoltaic panels. External walls were characterized in terms of type (prefabricated panels or masonry infill), material, and the percentage of glass surfaces on the fronts. The entries to be complied were partially derived from the ones adopted during recognitions for expeditious seismic vulnerability assessments within the CARatterizzazione TIpologico- Strutturale dei comparti urbani (CARTIS) initiative and post-events AeDES forms [260][261][262], adequately integrated to include also architectural or energy and environmental related features.

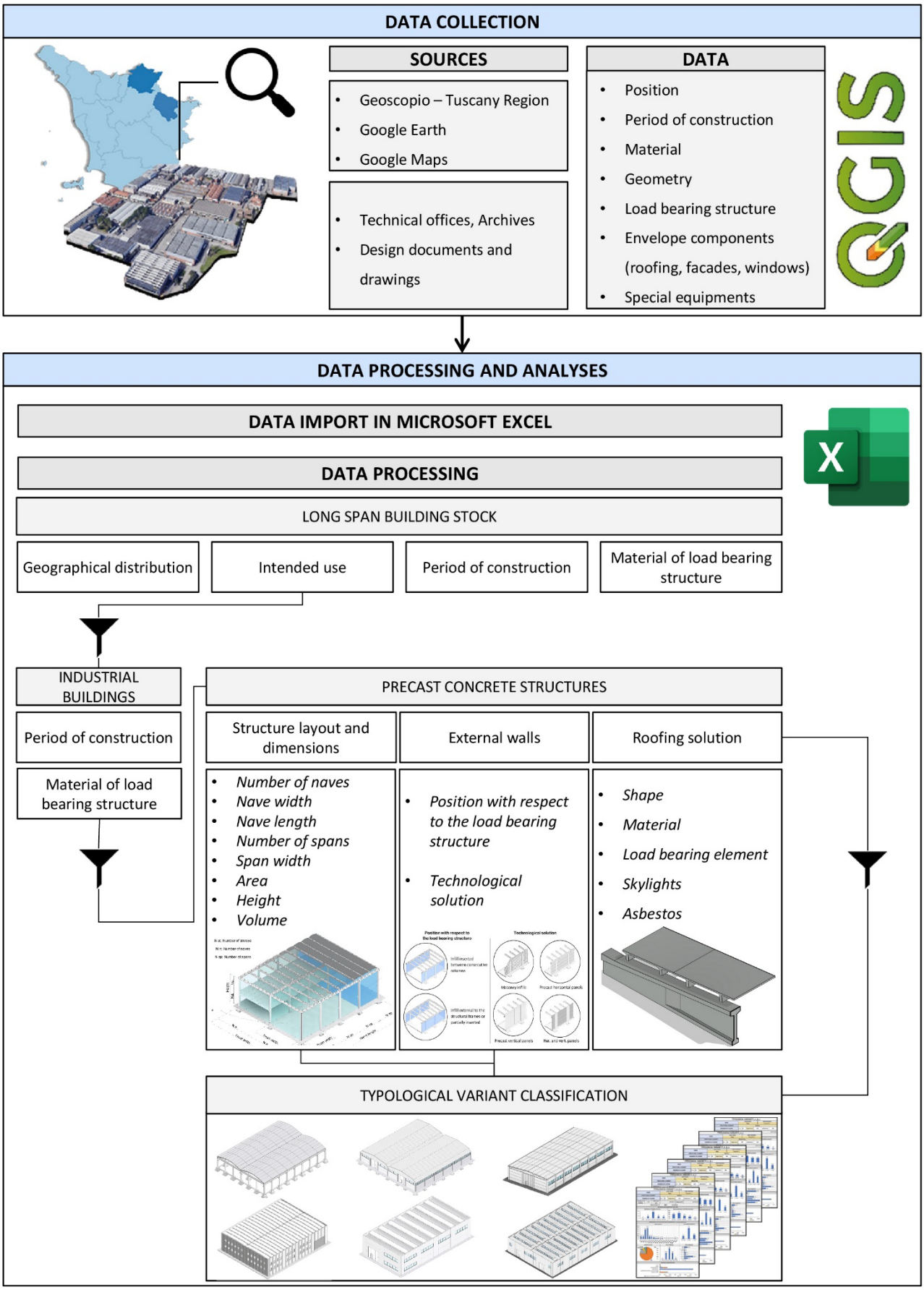


Figure 3.1 Research methodology applied for the territorial analysis of existing industrial buildings.

- Following the initial data collection in QGIS, subsequent investigations involved post-processing the data in Microsoft Excel. Buildings with incomplete or unreliable data from the survey campaign were excluded from the data processing stage. During this phase, schematic data sheets were developed to effectively manage the extensive information dataset and organize it properly. Analyses were carried out at different scale to properly outline both the general characteristics of the whole industrial building stock and the peculiarities of the various subset investigated. These aspects were analysed as it follows:

  - The initial phase of the analysis involved a general overview of the "long span" building heritage retraced. Data such as the number of buildings, their gross area, and built volume were reported both in absolute and relative terms, considering their geographical distribution, their age, the material used for load bearing components and the intended use of the facilities. In terms of construction periods, six time intervals were considered based on available aerial views, spanning from 1954 to 2007. Aerial views were accessible for the years 1954, 1978, 1988, and 1996. Although satellite technologies have increased data availability with more frequent flights in recent years, 2007 was chosen as the final reference year to maintain consistent intervals of approximately 10 years each. These values were further examined concerning the material of the load-bearing structures and the construction period. By analysing the intended use of the buildings, the significance of the industrial heritage was confirmed, laying the groundwork for deeper investigations in subsequent phases. To provide a comprehensive overview in this initial part of the study, the chronological distribution of buildings intended for production activities was compared with the technological and construction solutions employed.

  - Focusing on prefabricated reinforced concrete industrial buildings, their evolution over time was analysed including:

    i) average gross area;

    ii) average gross volume;

    iii) average height;

    iv) number of floors;

    v) width of the front;

    vi) width of the single nave;

vii) number of naves;

viii) total length of the nave;

ix) number of spans;

x) length of span.

The dimensional data cited above are referred to the scheme proposed in Figure 3.2.

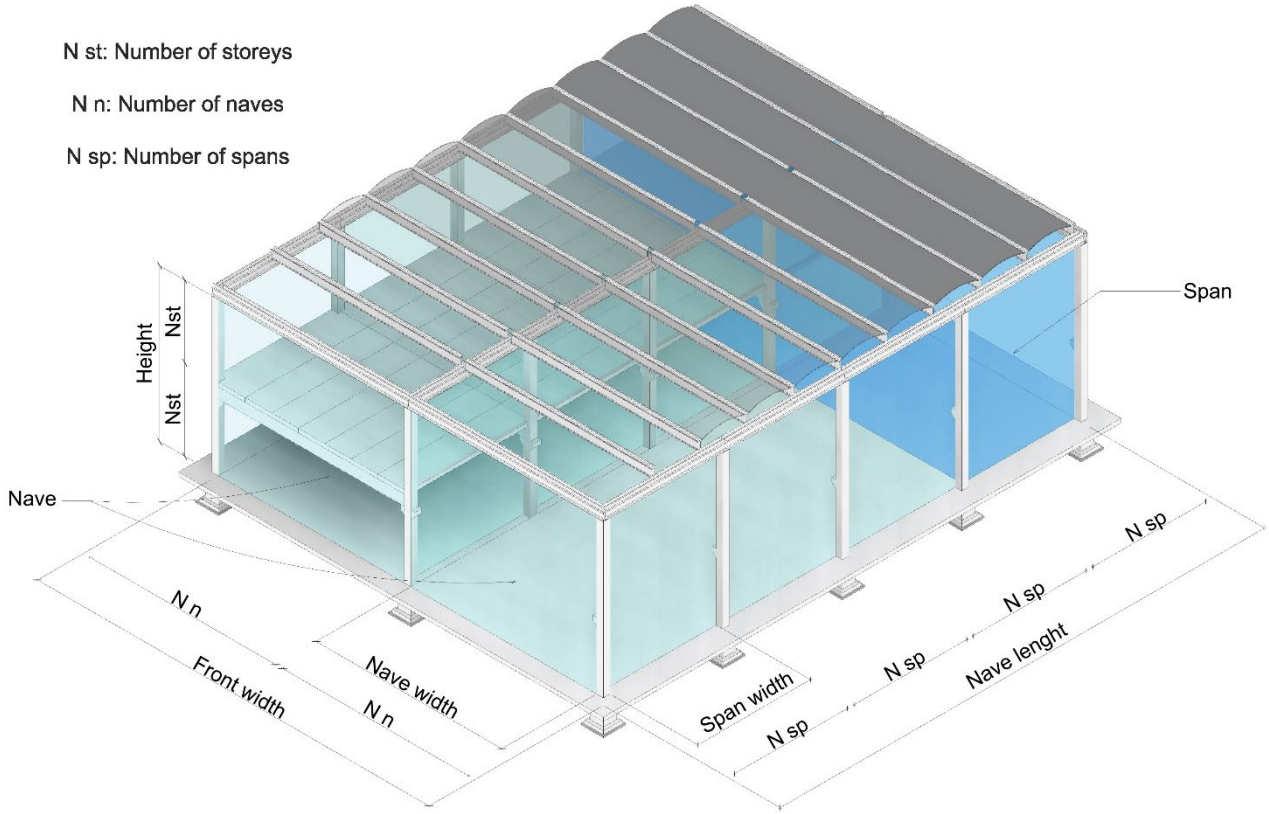


Figure 3.2 Dimensional data scheme adopted during the territorial analysis phase.

The analysis of building envelope characteristics was carried out distinguishing between roof and external wall components. For roofs, classification was mainly based on the shape of the roofing system and the material of the load-bearing elements. The parameters considered for the perimeter walls included the type of elements used (generally masonry infills, vertical or horizontal prefabricated panels) and their position with respect to the structural frame.

B1. This step was designed as a preliminary stage to identify the various typological variants of industrial building types. Additional statistics pertaining to internal distribution aspects and urban context were introduced. Specifically, data were gathered on building location (isolated or aggregated), number of floors, and presence of spaces designated for administrative or

management activities. Given the limited variability of configurations, this kind of buildings can be characterized by considering roofing solutions and external walls technologies. In particular, the roof configuration emerged as a crucial factor, significantly influencing both the structural and technological aspects of the entire building. For each period, statistical data were compiled as percentages based on the number of buildings and total gross area. Regarding external walls, their position relative to the vertical load-bearing structure was correlated with the technological elements utilized.

B2. Based on the outcomes of the preceding analysis, the predominant typological solutions for industrial buildings constructed with prefabricated reinforced concrete across various periods were determined. The roof shape, material, structural elements, and number of floors were selected as distinguishing features, while aspects related to external wall technology were considered secondary factors for detailed characterization of the identified variants. For each configuration, an illustrative sheet was compiled as reported in Figure 3.3. For brevity, we present a single case study, referenced throughout. The upper section of the initial part (a) collects key parameters like construction period, roof characteristics, and elevation organization. Subsequent pages offer a comprehensive overview of dimensional data, encompassing average plan surface, building height, and layout of aisles including their widths and lengths (b). The final segment presents information on external walls (c). The second section delves into a more detailed examination of the urban setting (d), provides insights into the structural arrangement (e), including beam and pillar sections (f). For each typological variant identified, a BIM model of a virtual building summarizing recurrent characteristics was developed using Autodesk Revit. From these models, summary drawings (Figure 3.4) were generated to visually represent the findings and offer precise illustrations of construction details.

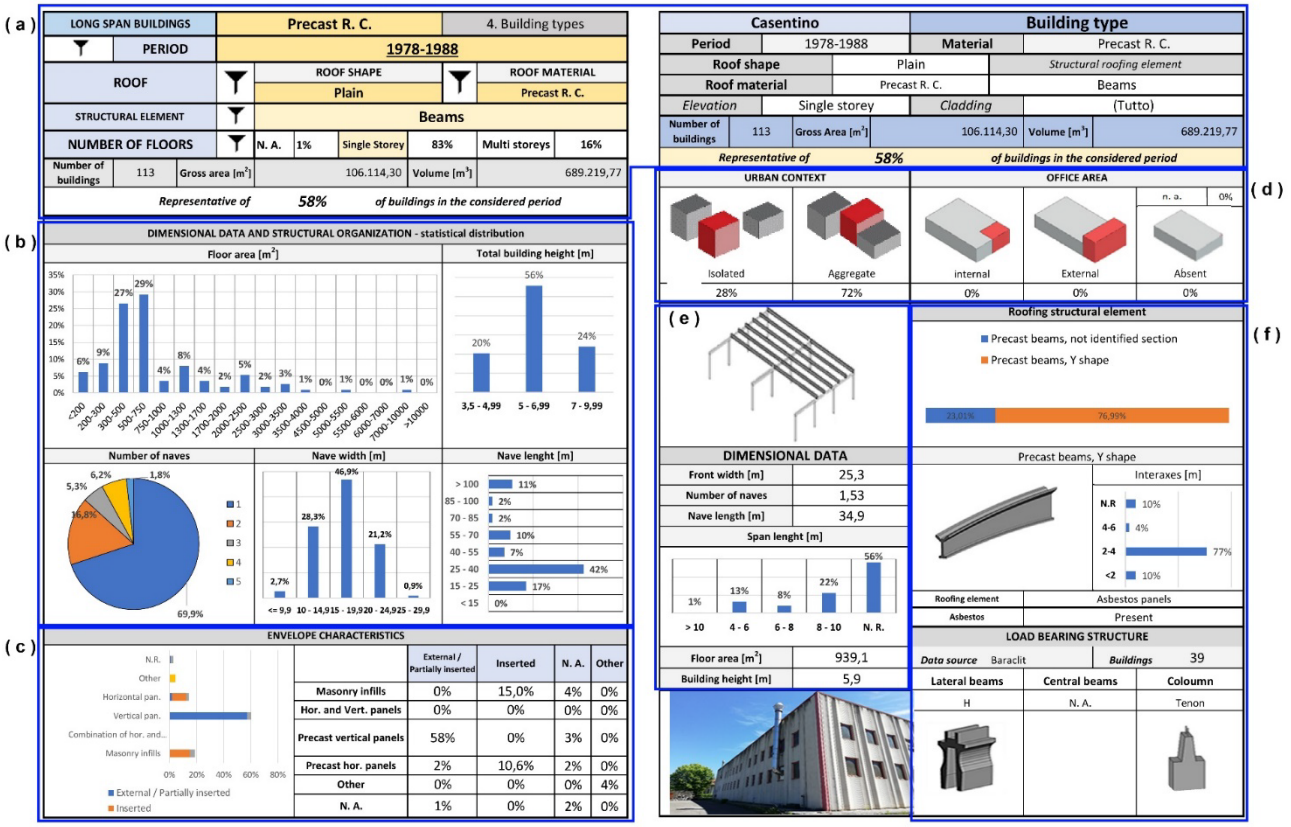


Figure 3.3 Descriptive data sheet of a typological variant: (a) identification parameters (i.e. period, roofing type, number of floors, etc.); (b) average dimensional data (i.e. surface, height, naves width and length); (c) external walls characteristics (type and position); (d) urban context and relation with administrative division (isolated or aggregated building); (e) structural layout (i.e. front width, number of naves, nave length, span length, floor area, column height); and (f) structural components (i.e. load bearing elements, sections, roofing beams inter- axes, etc.).

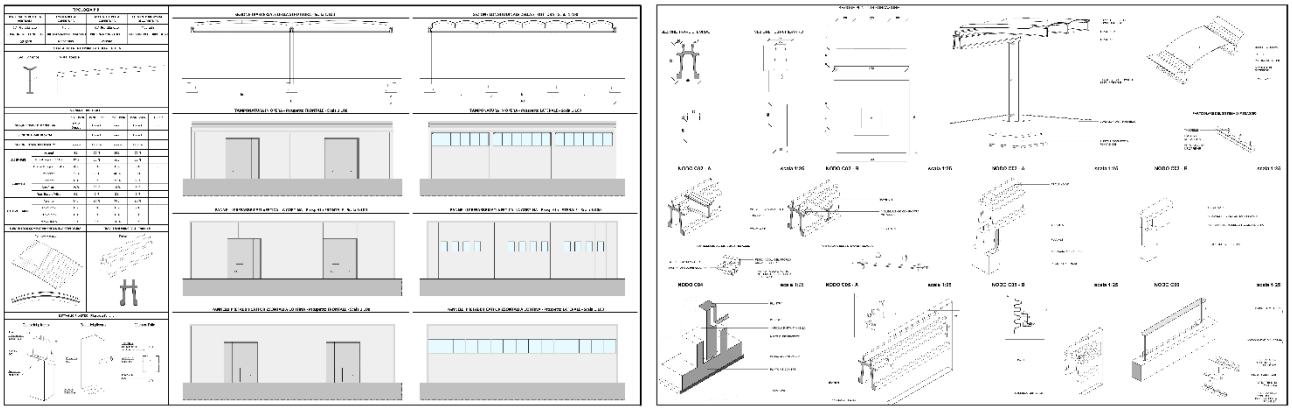
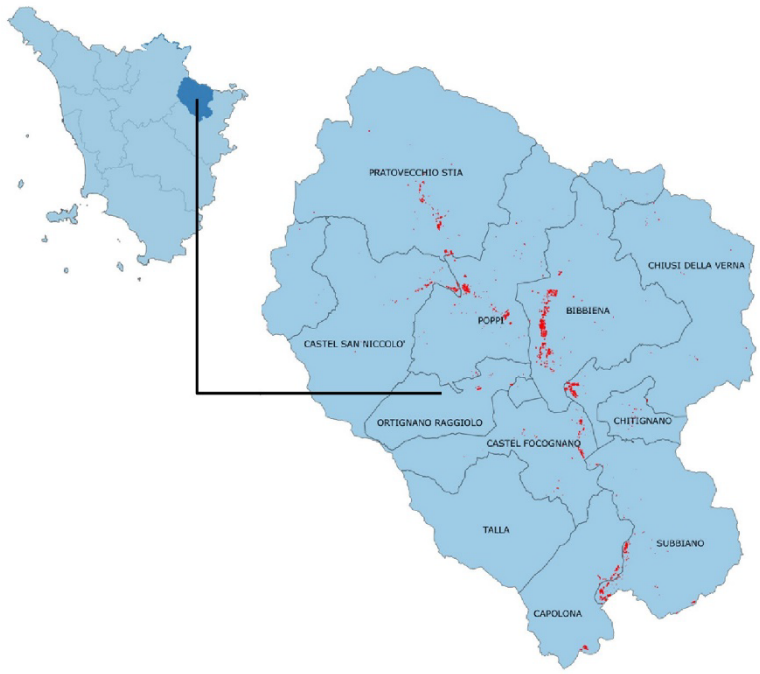


Figure 3.4 Details drawings and BIM models of a representative hypothetical facility derived on the average characteristics of the reference typological variant.

3.3 Main results

3.3.1 Casentino

Casentino was included in the research for its notable concentration of precast producers, leading to the extensive use of precast construction systems in industrial buildings. This region corresponds to the valley formed by the upper stretches of the Arno River and is entirely within the Province of Arezzo, spanning across the territories of 12 different municipalities. In Figure 3.5 the location within the regional territory is highlighted along with the identification of the municipalities included.



CASENTINO	
Municipality	**Area [km²]**
Poppi	138.23
Talla	102.36
Bibbiena	97.06
Montemignaio	86.45
Capolona	83.18
Chiusi della Verna	78.21
Pratovecchio - Stia	60.20
Ortignano - Raggiolo	56.65
Chitignano	47.37
Castel San Niccolò	36.47
Subbiano	26.07
Castel Focognano	14.72
	826.98

Figure 3.5 Details about the Casentino area: geographical location, municipalities and territorial extension.

3.3.1.1 General overview of the building stock

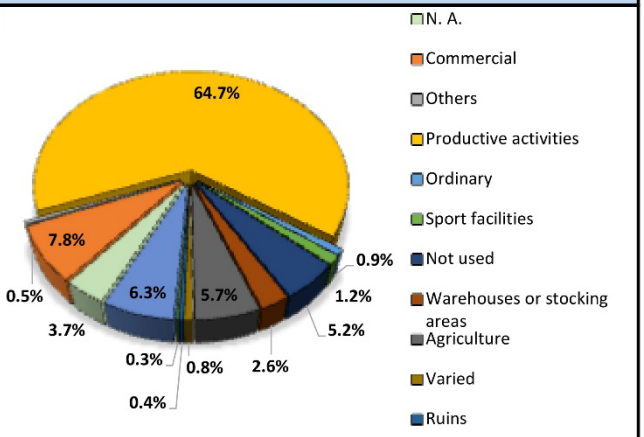
Globally, 1044 long span structures were identified across the Casentino area and in Figure 3.6, a general overview is provided.

LONG SPAN BUILDINGS STOCK - CASENTINO

GEOGRAPHICAL DISTRIBUTION

Municipality	Buldings	Gross area [m^2]	Volume [m^3]
Bibbiena	362	412'687	2'645'305
Capolona	63	53'925	378'833
Chiusi della verna	97	111'906	814'222
Subbiano	110	143'272	1'189'365
Chitignano	9	4'028	22'505
Montemignaio	1	171	436
Talla	5	2'341	10'127
Ortignano Raggiolo	24	20'410	122'458
Pratovecchio Stia	120	103'019	667'638
Poppi	130	109'422	710'617
Castel San Niccolo'	53	55'579	431'317
Castel Focognano	70	44'824	298'769
CASENTINO	*1044*	*1'061'584*	*7'291'591*

INTENDED USE



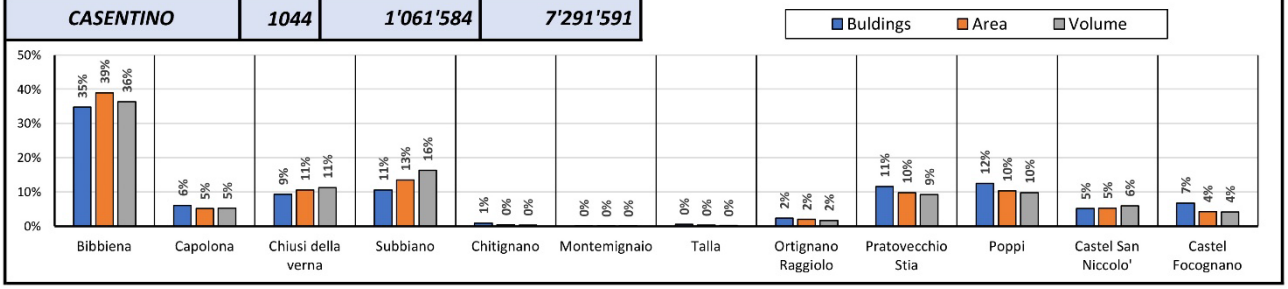


Figure 3.6 Long span buildings stock of Casentino. geographical distribution and intended use analysis.

Considering the intended use of these facilities, 65% of them are dedicated to industrial or manufacturing activities that hence represent the most common destinations for this kind of buildings. Commercial activities (supermarket, retails, malls, etc.) come second covering 8% of the buildings.

Focusing on the geographical distribution, it clearly emerges that the municipality of Bibbiena is hosting most of these buildings, covering about 35% of the total amount. All the other municipalities are by far less represented, as only Pratovecchio-Stia, Poppi, and Subbiano host about 10% each. The latter is characterized by a recent development as demonstrated by the higher concentration in terms of volume denoting the adoption of more advanced construction systems capable of covering wider spans and usually implementing multi-storeys solutions.

This trend can be retrieved also considering the graph reported in Figure 3.7, where starting from the 1996 the built surface and volume percentages are greater than the ones in terms of number of

buildings. Considering the periods of construction of long span facilities, the old ageing of the buildings was assessed: 61% of structures were built before 1988. Starting from the period 1988-1996 a progressive decline in the construction of this kind of facilities can be retraced, and only 7% of the buildings assessed on the territory dates after 2007.

Precast reinforced concrete emerged as the most frequently adopted construction technique (61.1% of buildings) followed by cast in place reinforced concrete (15.8%) and steel (8.4%). The predominance of prefabrication can be justified considering the high concentration of precast producers' companies in the Casentino area, some of them still active nowadays.

MATERIAL OF THE VERTICAL LOAD BEARING STRUCTURE				PERIOD OF CONSTRUCTION			
Material	Buildings	Gross area [m^2]	Volume [m^3]	Period	Buildings	Gross area [m^2]	Volume [m^3]
Masonry	68	27'214	158'064	< 1954	19	8'211	63'987
Steel	88	88'861	594'082	1954-1978	333	308'398	1'880'885
R. C.	165	107'406	633'557	1978-1988	279	247'330	1'611'479
Precast R. C.	638	776'921	5'570'901	1988-1996	162	124'903	871'998
Wood	2	802	4'813	1996-2007	176	209'294	1'576'803
Not Assessed	83	60'381	330'174	> 2007	75	163'448	1'286'439
TOTAL	1044	1'061'584	7'291'591				

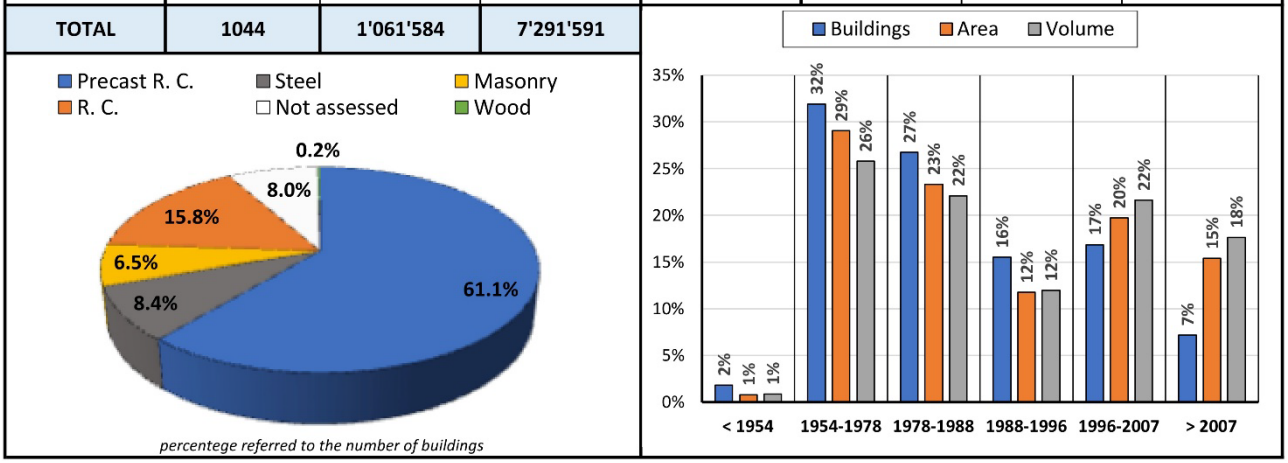
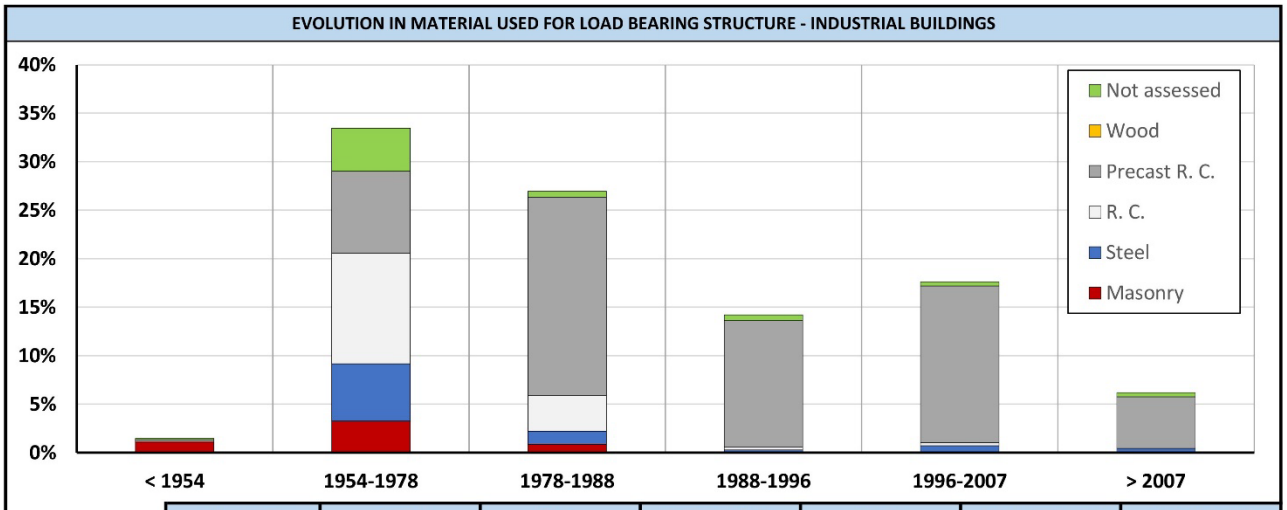


Figure 3.7 Material of the vertical load bearing structure and period of construction of long span buildings in the Casentino area.

These aspects were deepened specifically considering industrial intended buildings, focusing at the same time on both chronological and technological evolution over years. As emerging from the data reported in Figure 3.8, steel and cast in place reinforced concrete were diffused until 1978, covering 17.6% and 34% respectively in the 1954-1978 interval. The widespread adoption of precast solutions is clearly retraceable in the region: staring from a 25% percentage in the period 1954-1978, it reached 75.6% in the following decade (1978-1988) to become predominant nowadays. Globally, precast reinforced concrete technology has been adopted in 63.4% of industrial intended facilities, following the same trends previously assessed for the long span building stock. Also for the other materials, the

results can be substantially overlapping both qualitatively and quantitatively. These evidence are aligned with results of similar studies at both regional and national levels [23], that let to assess that only 6% of precast structures in Tuscany were built after 2003 and 55% of buildings before 1996 on a National scale.



	Masonry		Steel		R. C.		Precast R. C.		Wood		Not assessed		TOT. Period	
< 1954	*8*	**1.2%**	*0*	**0.0%**	*1*	**0.1%**	*0*	**0.0%**	*0*	**0.0%**	*1*	**0.1%**	*10*	**1.5%**
1954-1978	*22*	**3.3%**	*40*	**5.9%**	*77*	**11.4%**	*57*	**8.4%**	*0*	**0.0%**	*30*	**4.4%**	*226*	**33.5%**
1978-1988	*6*	**0.9%**	*9*	**1.3%**	*25*	**3.7%**	*138*	**20.4%**	*0*	**0.0%**	*4*	**0.6%**	*182*	**27.0%**
1988-1996	*0*	**0.0%**	*2*	**0.3%**	*2*	**0.3%**	*88*	**13.0%**	*0*	**0.0%**	*4*	**0.6%**	*96*	**14.2%**
1996-2007	*0*	**0.0%**	*5*	**0.7%**	*2*	**0.3%**	*109*	**16.1%**	*0*	**0.0%**	*3*	**0.4%**	*119*	**17.6%**
> 2007	*0*	**0.0%**	*3*	**0.4%**	*0*	**0.0%**	*36*	**5.3%**	*0*	**0.0%**	*3*	**0.4%**	*42*	**6.2%**
TOT. Material	36	**5.3%**	59	**8.7%**	107	**15.9%**	428	**63.4%**	0	**0.0%**	45	**6.7%**	675	

Figure 3.8 Evolution in material used for the load bearing components over time and relative distribution.

Notably, a clear evolution in building technology can be retraced also within the same precast concrete cluster starting from the analysis of geometrical and compositive aspects. Thanks to refinement in technical knowledge, expertise, and production processes the building structural components progressively developed over time to cover wider spans and greater lights. As reported in Table 3.1, both nave and span dimensions sensibly increased: considering the average values retrieved in the buildings on the territory, an increment equal to 24% and 61% can be assessed comparing the facilities built in the 1954-1978 period and the most recent ones. As it will be introduced later in the discussion of the results, the evolution in nave width is strictly connected with the technological progress over time of precast solutions that led to the adoption of different roofing components. Given the relevance of the theme, in Figure 3.9 a detailed analysis of nave width trend over time is presented. From the graph, the progressive diffusion of wider naves facilities clearly emerges. Considering the Casentino building stock, buildings tend to present naves with slightly higher width if compared to the regional values, usually between 14 and 16 m [23]. The increase in

the width of the spans and their number led to a progressive augment of total nave length over time. Notably, the average value of this dimension proved to be particularly high in older structures: this is influenced by the presence of large-scale industrial settlements belonging to precast producer companies, realized in the 1954-1978 period recurring to prefabricated components. Similarly, large facilities were built after 2007 with a considerable nave length. Therefore, also the average buildings area underwent a progressive increase over the decades. At the same time, the diffusion of multi-level facilities certified by the increase in buildings' height, led also to buildings with a larger volume.

Table 3.1 Evolution of dimensional data over time in industrial precast concrete buildings.

		Period of construction				
		1954-1978	**1978-1988**	**1988-1996**	**1996-2007**	**> 2007**
Average building dimensions	**Span width [m]**	6.09	7.69	8.41	9.20	9.83
	Nave width [m]	15.67	15.91	16.87	17.96	19.43
	Total nave length [m]	51.55	37.30	38.58	37.80	57.19
	Area [m²]	1465	1040	838	1251	2748
	Height [m]	5.69	6.02	6.38	7.26	7.42
	Volume [m³]	9176	6859	5688	9007	19527

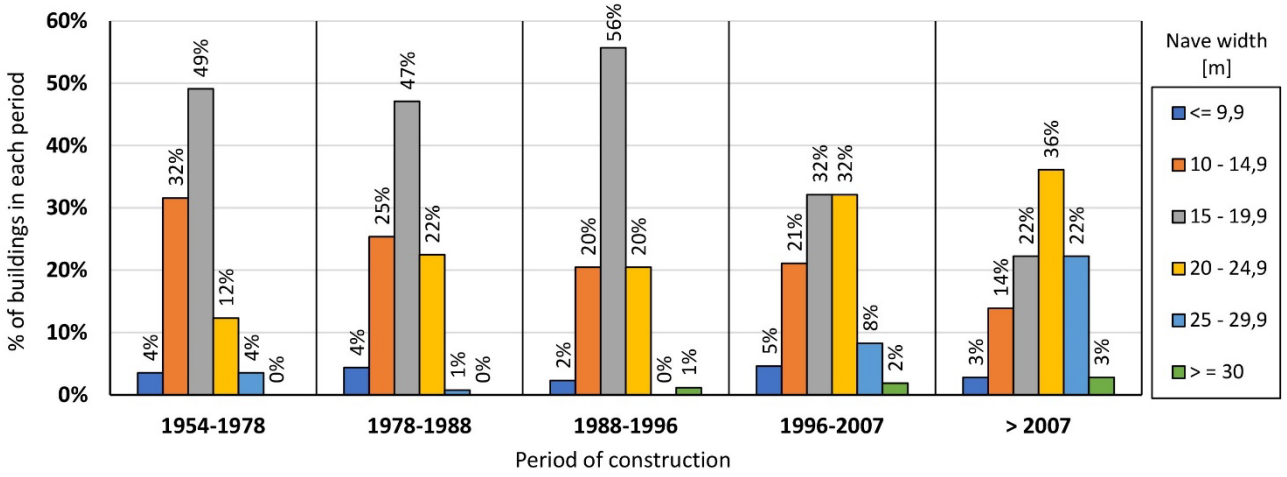
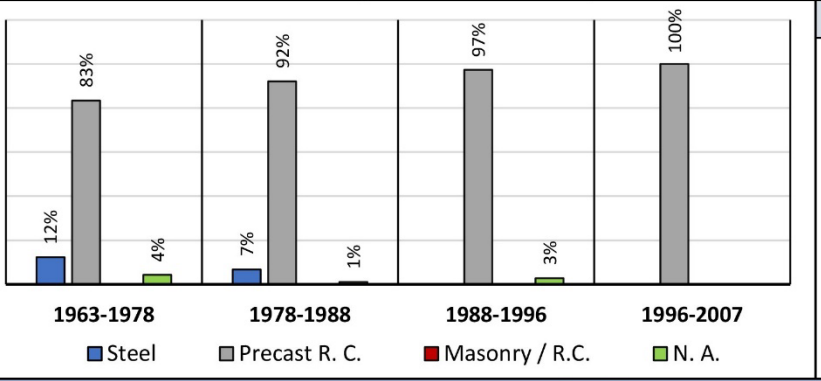


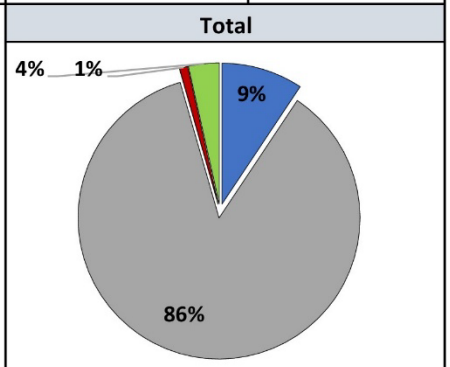
Figure 3.9 Evolution of nave width in the precast concrete industrial building stock in the Casentino area.

The technological roofing solution was adopted as a key parameter in defining the recurrent typological variants. The surveys conducted have indeed revealed a notable variety of forms and construction elements, highly influencing the overall structural, architectural and energy behaviour of the facilities. Specifically, the shape of the roof, the material of the load bearing elements and their typology were analysed In Figure 3.10 the main results of this assessment are presented, focusing

specifically on roofing material and shape. In a subsequent phase, the main load bearing structural components used in roofing systems were investigated and the findings obtained are reported in Table 3.2 and Figure 3.11.

Material of load bearing elements				
	Steel	Precast R. C.	Masonry / R.C.	N. A.
1954-1978	30%	54%	7%	9%
1978-1988	12%	83%	0%	4%
1988-1996	7%	92%	0%	1%
1996-2007	0%	97%	0%	3%
> 2007	0%	100%	0%	0%





Roof shape					
	Sloped roof	Vaulted	Plain	Shed	N. A.
1954-1978	19%	21%	51%	7%	2%
1978-1988	12%	4%	82%	1%	1%
1988-1996	9%	0%	90%	1%	0%
1996-2007	0%	1%	85%	13%	1%
> 2007	0%	0%	53%	47%	0%

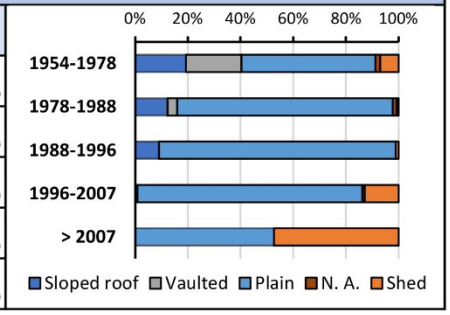


Figure 3.10 Analysis of roofing solutions for precast concrete industrial buildings in Casentino.

Table 3.2 Load bearing element, material and roof shape in precast industrial facilities of Casentino.

	Masonry / R.C.	**Precast R. C.**				**Steel**			**N. A.**	
	Arch beams	*Beams*	*Wing tiles*	*Slabs*	*N. A.*	*Arch beams*	*Trusses*	*N. A.*	-	***Total - shape***
N. A.	-	-	-	-	-	-	-	-	4	***4***
Plain	-	185	105	3	39	-	-	-	1	***333***
Shed	-	4	25	-	5	-	3	-	-	***37***
Sloped Roof	-	2	-	-	1	-	21	3	9	***36***

Vaulted	4	-	-	-	-	12	-	1	1	***18***
Total - element	***4***	***191***	***130***	***3***	***45***	***12***	***24***	***4***	***15***	***-***
Total - material	***4***	***369***				***40***			***15***	***428***

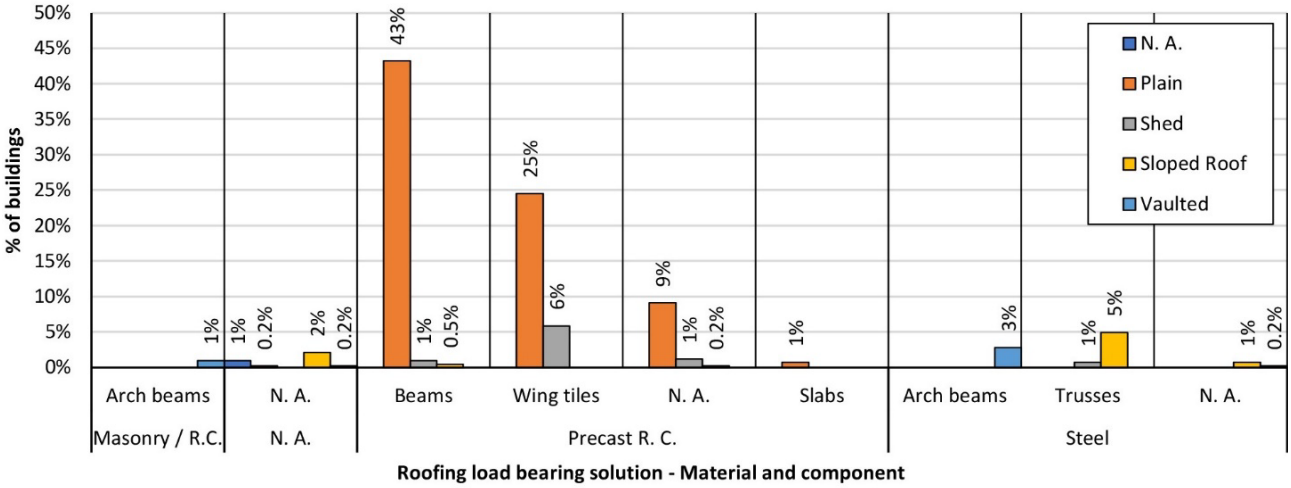


Figure 3.11 Load bearing element, material and roof shape in precast industrial facilities of Casentino: percentage distribution and graphical presentation of the results.

Notably, deepening the analysis, It is important to note, however, that there are structures for which the construction techniques could not be definitively identified due to objective challenges or difficulties encountered during the survey phase.

Precast roofing systems emerged as the main reference solution in precast industrial facilities. However, until the decade of 1978-1988, steel roofing systems were also adopted employing metal trusses or arched beams, giving the roofs a distinctive double-pitched or vaulted shape. Vaulted roofs could be obtained also adopting a partially prefabricated solution including prestressed precast arched beams to be completed with a latero-cement vault solution but only a few examples were retrieved in the region. Over time, however, roofs with prefabricated concrete elements have started to dominate the building landscape. This type of roofing systems relies on the use of elements arranged transversely on frames aligned with the longitudinal development of the building. Both beams and prestressed winged tiles were adopted. The latter, more recent and advanced from a technological point of view, has enabled the coverage of larger spans, sped up installation operations, and ensured better thermal insulation making the construction process more efficient and less time-consuming. Furthermore, the integration of dedicated skylight elements has led to the proliferation of roofs with a characteristic shed profile. In conclusion, the evolution of roofing systems reflects not only

technological advancements but also a growing attention on efficiency and sustainability in construction.

Within the perspective of roofing analysis, the presence and typology of skylights becomes a crucial aspect. The analysis, whose results are presented in Figure 3.12, was carried out considering the shape of skylights components and their relationship with the roof pitch plane formed by the completion elements deployed. Skylights were assessed in about one third of the precast industrial facilities on the territory. According to the results obtained, in 25% of the buildings skylights are adopted in inserted position with respect to the roofing plan extrados. In this case translucent components are installed between the opaque completion elements or, in case of precast wing tiles roofing elements, between consecutive load bearing elements. Skylight deployed according to a shed configuration have been adopted more frequently in recently built industrial facilities. This solution allows to achieve better natural lighting conditions, especially in large buildings where side windows may result inadequate to ensure proper visual comfort in the inner portions. This aspect was indirectly derived considering the average area of the buildings adopting skylights natural lighting: while buildings with a opaque roofing are characterized by an average area of about 1050 m^2, facilities with inserted or emergent skylights present wider plan dimensions covering 1520 m^2 and 3720 m^2 respectively. According to the results of the study, skylights started to be more frequently installed starting from the '90s, with the shed solution emerging with a higher share from the beginning of the 2000s.

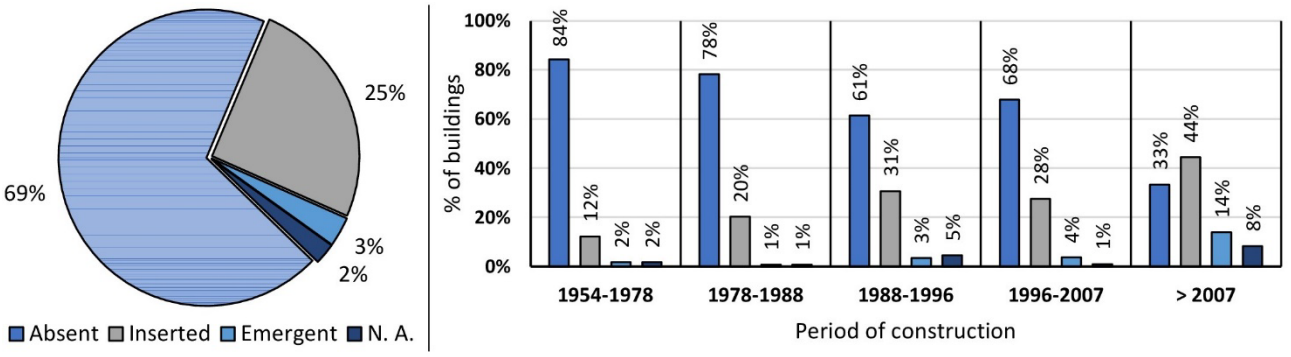


Figure 3.12 Characterization of skylights components in Casentino precast industrial buildings and evolution over time.

The roofing layer is furthermore extremely critical in industrial facilities due to the possible presence of asbestos-cement components, as retraced also during the recognition carried out in the research. This material was widely used in the past due to its numerous advantages under several points of view. Asbestos was used in fire cement components as it was economical, fire and chemically resistant, and it possessed excellent thermal and acoustic insulating properties. All these peculiarities

made it particularly suitable for being applied in the construction industry to produce several components, including roofing panels. However, the use of asbestos entails severe problems and health risks as the inhalation of asbestos fibres can cause extremely serious and potentially fatal lung diseases (i.e. asbestosis, mesothelioma, other forms of carcinoma). Due to these significant public health risks, Italy banned asbestos in 1992 by a specifically intended reglementary act (Legge 257 del 1992) that prohibited its production, use, and commercialization. Despite the ban, many industrial buildings constructed before this date still have asbestos-containing panels or cladding in their roofing. Therefore, targeted actions are crucial and prescribed in these existing buildings to ensure the safety of the environments and safeguard the health and well-being of workers. The necessary removal of these asbestos-containing components can at the same time represent an incentive to promote overall retrofitting initiatives: a regulatory obligation can be hence converted into an opportunity to enhance the energy efficiency and sustainability of industrial buildings, thus contributing to the creation of safer, healthier, and more sustainable environments. Given the relevance of the topic, specifically oriented statistics were produced.

The results of the analyses produced for the Casentino building stock are reported in Figure 3.13. Original, asbestos containing elements are still nowadays on place in the 30% of facilities, making removal and replacement interventions particularly needed in the area. Only 14% of the buildings have undergone roof remediation processes over the years, either through the complete replacement of roofing elements or interventions of fibres encapsulation. The latter was identifiable through the comparison of available aerial photographs and the typical reddish coloration of redeveloped roofings. The significant percentage of buildings for which it was not possible to accurately reconstruct the data is also related to the difficulty in precisely dating many of the buildings from the period between 1988 and 1996, thus straddling the enactment of the new regulations about asbestos. In the same figure, the results of the analysis aimed at determining correlations between the use of asbestos elements and specific structural roofing solutions are graphically presented. The findings revealed that roofs constructed using prefabricated concrete beams and metal trusses more frequently contain asbestos elements. Conversely, the introduction of prefabricated roofing panels, which occurred in more recent years, is associated with the spread of roofing completion elements made from alternative materials.

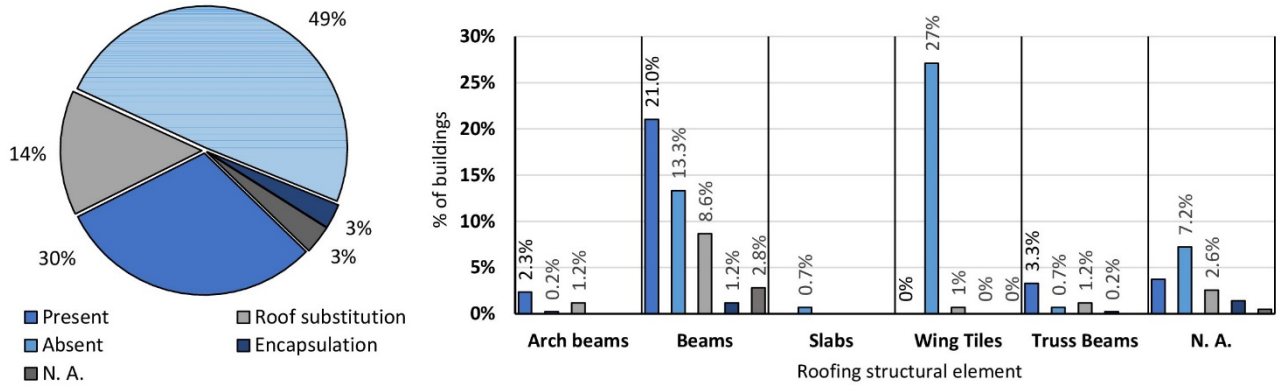


Figure 3.13 Analysis of the presence and distribution of roofing elements containing asbestos in precast industrial building stock of Casentino.

Keeping the focus on building envelope, the analysis was extended to encompass vertical perimeter wall solutions in industrial buildings is crucial for understanding and typologically classifying these structures. The study aimed at identifying possible correlations between building typologies and the construction elements employed, providing a foundation for the typological classification of industrial buildings. Vertical perimeter walls perform structural, aesthetic, and functional roles, influencing energy efficiency, acoustic insulation, and weather resistance. Examining the different solutions adopted over time in various industrial contexts allows for an understanding of the motivations behind design and construction choices, often balancing technical and economic needs, but disregarding the energy and environmental ones. This analysis is hence essential for the classification of constructed environments and for providing insights into the design and renovation of industrial buildings, promoting solutions that optimize overall building performance. The diverse types of vertical perimeter walls found in industrial buildings, were detailed according to specific criteria: the position with respect to the load bearing structure, material and elements used were considered as key parameters. As for the former, external infills were assessed to be located inserted between consecutive columns or placed totally or partially externally with respect to the structural elements. As for the technological solution, both on-site masonry infills and precast concrete panels were retrieved, arranged both in vertical and horizontal direction and even combined in more recent facilities. In Figure 3.14 graphical evidence of the possible combination is provided while in Figure 3.15 the distribution of the different external walls' configuration is presented.

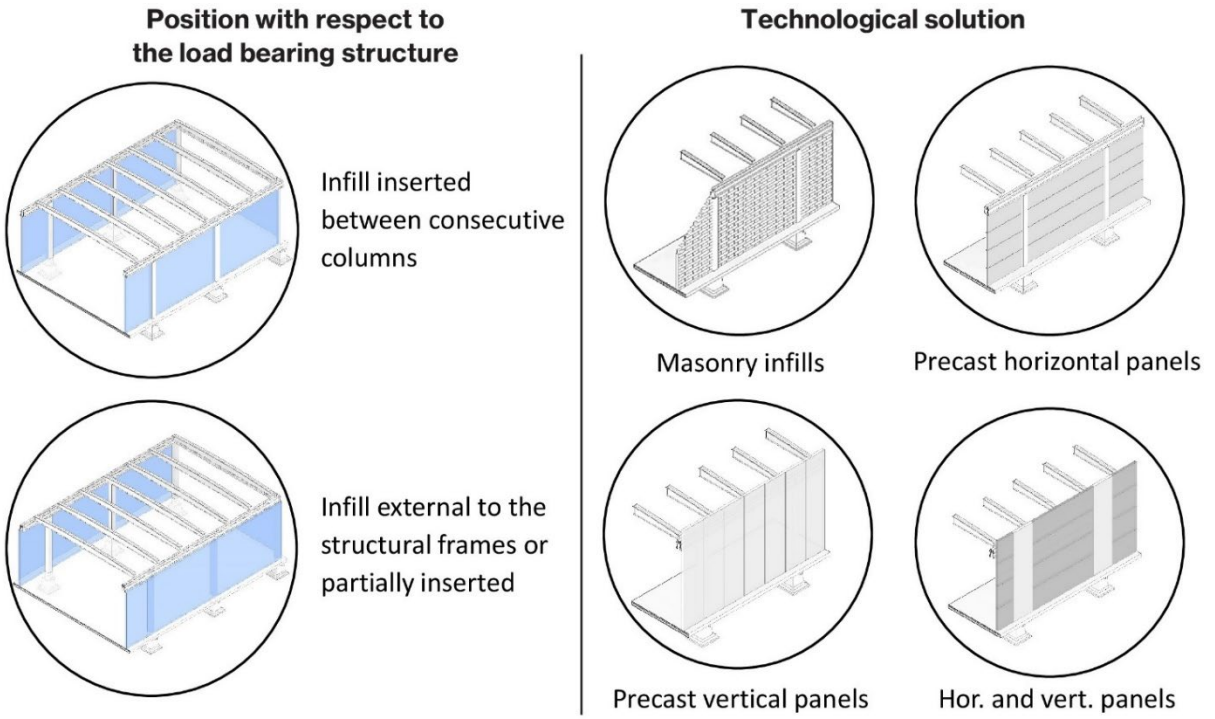


Figure 3.14 Characterization of external walls: alternatives assessed for infills position and technology.

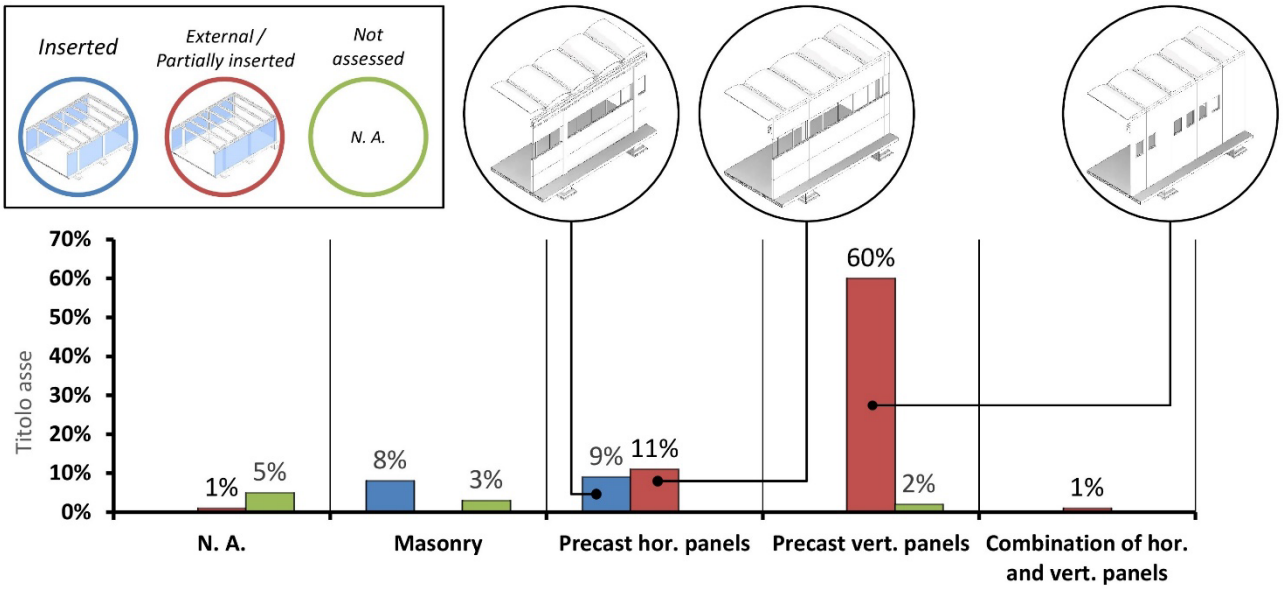


Figure 3.15 Analysis of the solutions adopted for external walls in terms of both position and technology in industrial precast buildings in Casentino.

In Casentino, precast vertical panels are clearly the most widespread technological solution for external cladding. These results are perfectly aligned with the findings of other authors that investigated the precast building stock of the province of Arezzo [30]. According to the cited study, horizontal precast panels are even less relevant when considering the whole province territory, proving the widespread adoption of precast solutions in Casentino valley. Notably this kind of elements are installed externally to the load bearing structure and are usually connected to the beams

of the structural frames by using metal joints and connection elements. In addition, different geometry are possible showing different profiles of the external surface and thickness of the internal lightening and insulating core as highlighted in Figure 3.16. The horizontal sections proposed were derived from original design drawings and are hence highly representative of the actual stratigraphy of precast cladding panels. These solutions were widely adopted up to the end of the 80s.

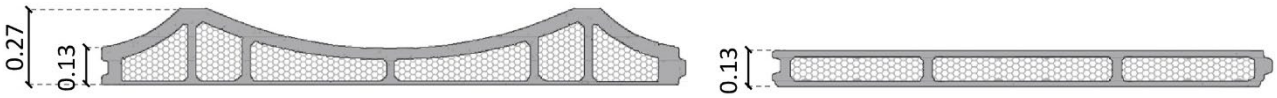


Figure 3.16 Horizontal sections of different cladding precast vertical panels.

Horizontal panels are also diffuse even if at a lesser extent, being retraceable in 20% of the facilities investigated. In this case both inserted and external positions are possible. Masonry infills are retrievable only in older buildings, as highlighted by the chronological analysis carried out and whose results are reported in Figure 3.17. While vertical panels were largely adopted all over the different periods considered in the analysis, horizontal panels experienced a slight increase in their diffusion in the last decades along with the increased number of multi-storey structures where they allow for larger windowed sections. Along with the enhancement of the prefabrication techniques and energy requirements, also the external envelope components experienced a clear evolution over time. Older prefabricated industrial buildings are characterized by on-site masonry infills or thin, lightly reinforced concrete panels (10-15 cm thick). These panels, lightened by incorporating EPS portions, were placed either vertically in external position or inserted into grooves specifically designed in the prefabricated columns. Technological advancements have led to the production of façade panels with increasingly more consistent insulating layers leading to thicker panels no more compatible with the previous installation solution. Consequently, starting from the 1988-1996 period, most of them was found to be placed externally to the columns, at which they are connected with specifically designed metal joints.

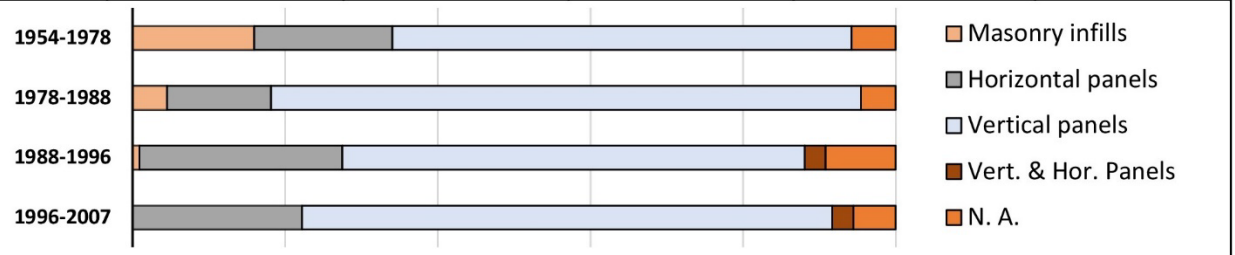
The construction solution for external walls directly affects the position of windows: vertical panels may include windows during the precast phase, while ribbon windows are used with masonry infills and horizontal panels.

Despite the variability of the technological solutions retrieved, it must be remarked that no correlation between the typology of infills and the roofing system and load bearing structure organization was

assessed, and all the variants found can be associated indistinctly with each of the structural typologies retrieved.

Technology

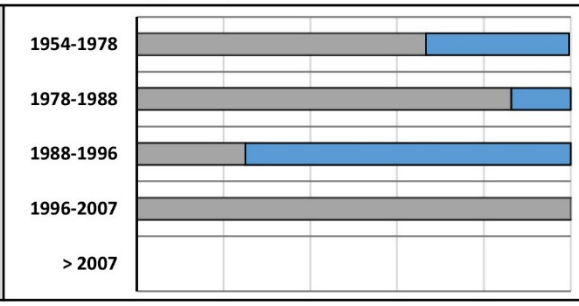
	Masonry infills	Horizontal panels	Vertical panels	Vert. & Hor. Panels	N. A.
1954-1978	32%	21%	39%	0%	9%
1978-1988	16%	18%	60%	0%	6%
1988-1996	5%	14%	77%	0%	5%
1996-2007	1%	27%	61%	3%	9%
> 2007	0%	22%	69%	3%	6%



Position

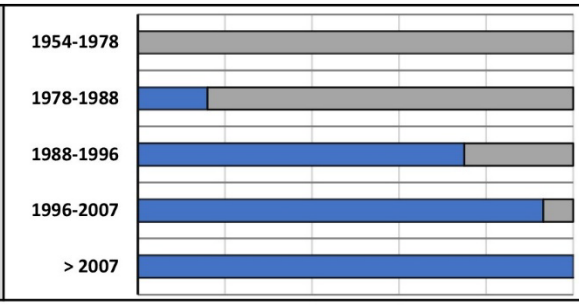
	External / partially inserted	Inserted	N. A.
1954-1978	0%	67%	33%
1978-1988	0%	86%	14%
1988-1996	0%	25%	75%
1996-2007	0%	100%	0%
> 2007	0%	0%	0%

Masonry infills



	External / partially inserted	Inserted	N. A.
1954-1978	0%	100%	0%
1978-1988	16%	84%	0%
1988-1996	75%	25%	0%
1996-2007	93%	7%	0%
> 2007	100%	0%	0%

Precast horizontal panels



	External / partially inserted	Inserted	N. A.
1954-1978	100%	0%	0%
1978-1988	96%	0%	4%
1988-1996	97%	0%	3%
1996-2007	100%	0%	0%
> 2007	96%	0%	4%

Precast vertical panels

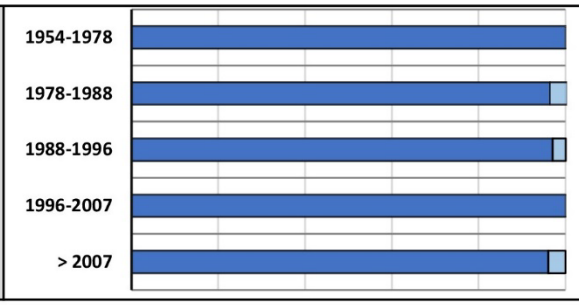


Figure 3.17 Chronological evolution of external walls solutions in Casentino.

3.3.1.2 Identification of typological variants

Despite the fragmented nature of the productive environment in Casentino, characterized by variations in company size, organization, business policies, and production processes, the building solutions employed exhibit common features. Notably, similarities have been identified in the construction site characteristics, which often feature regular geometries within specific urban settlement areas and their utilization for building purposes. Industrial buildings in this region display simple planimetric configurations, with a predominant longitudinal development that aligns with their structural layout, induced by the peculiarities connected to production related needs. Within this general uniformity of building typology, distinct variations emerge based on different structural organizations and roofing solutions that have evolved over time, as discussed in the previous section. The research has identified various solutions for prefabricated reinforced concrete industrial buildings, categorizing them into typological variations observed throughout different periods. As stated before, infills solutions proved to be somehow invariant with respect to the different structural layout alternatives retrieved and the typological variant classification was hence based on the roofing solutions in terms of material, shape, components and the type of structural element adopted for its realization. Globally, 5 typological variants were assessed, illustrating the evolution and adaptation of industrial building designs in Casentino and reflecting advancements in construction techniques and materials over time. A code is used to classify the identified typological variants, indicating:

- roof shape (P=Plain, Sl=Sloped, Sh=Shed, V=Vaulted);
- material (m=metal, rc=reinforced concrete);
- structural element (ar=arched beams or trusses, tr=trusses, slb= sloped beams, b=beams, t=tiles).

The various alternatives identified are simply listed below while a comprehensive description will be provided in the following of this discussion to include also the evidence obtained following the analysis of Mugello region. The typological variants assessed in the Casentino area can be synthesized as it follows:

- **Variant V_m_ar**: Buildings with vaulted roofs constructed from steel arched beams;
- **Variant Sl_m_tr**: Buildings with sloped roofs made from metal trusses;
- **Variant P_rc_b**: Buildings with flat roofs made from prefabricated beams in prestressed reinforced concrete;

- **Sub-Variant P_rc_b_s**: Single storey buildings with flat roofs made from prefabricated beams in prestressed reinforced concrete;
- **Sub-Variant P_rc_b_m**: Multistorey buildings with flat roofs made from prefabricated beams in prestressed reinforced concrete;

- **Variant P_rc_t**: Buildings with flat roofs constructed from prefabricated wing tiles in prestressed reinforced concrete;
- **Variant Sh_rc_t**: Buildings with shed roofs made from prefabricated wing tiles in prestressed reinforced concrete.

The relevance of each variant over time was assessed to express and retrace the evolution of precast concrete solutions, as reported in the graph of Figure 3.18. At this regard, P_rc_b variant was retraced with a quiet homogeneous distribution over the years, while other solutions are peculiar of specific periods such as V_m_ar and Sl_m_tr clearly referrable to older structures. The introduction of precast roofing wing tiles led to a progressive affirmation on the market of P_rc_t and Sh_rc_t typological variants, with the latter particularly widespread in the most recent years. In each period, a certain percentage of buildings impossible to be classified was retrieved, especially in case of older facilities.

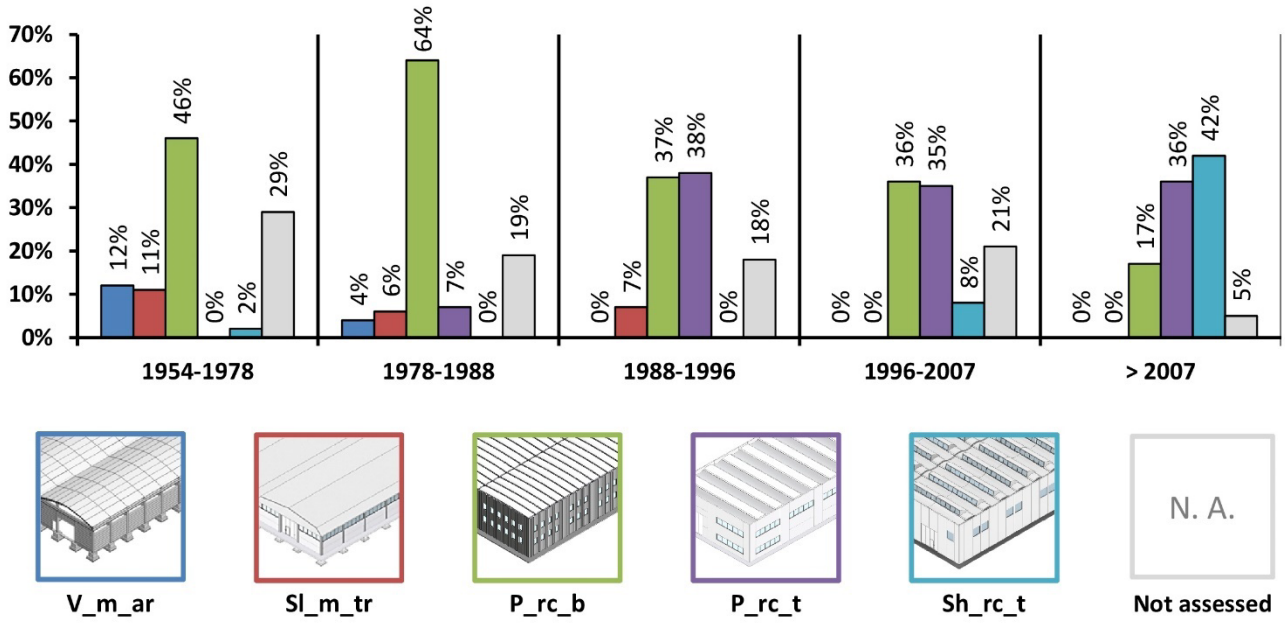
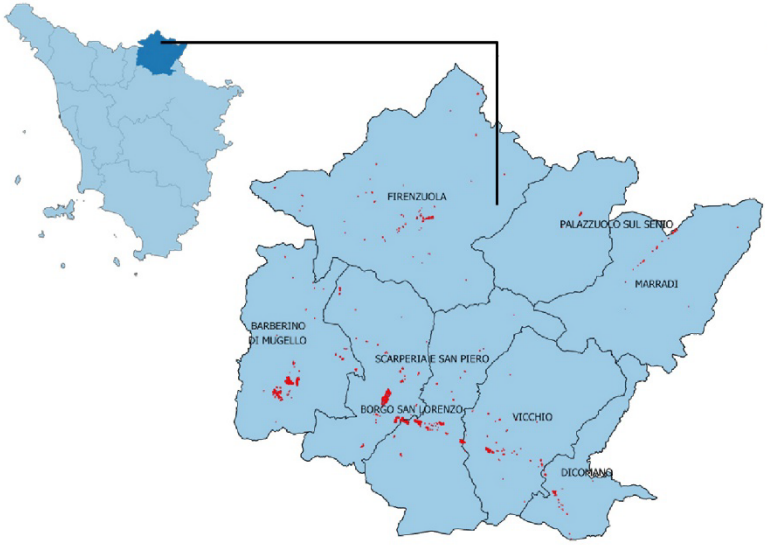


Figure 3.18 Diffusion of the typological variants identified in Casentino in each of the different periods considered in the analysis.

Synthesis statistical data are collected in the data sheets produced for each variant introduced collected in the section Annex 3.A.

3.3.2 Mugello

Mugello is located in the Northern part of the Province of Florence, and it includes 8 different municipalities. This area was included in the study to assess the possible influence of construction technologies and precast systems generally adopted in Emilia Romagna and Northern Italy, given the proximity to the regional borders. The geographical location is highlighted in Figure 3.19.



MUGELLO	
Municipality	**Area [km²]**
Firenzuola	272.12
Marradi	154.10
Borgo San Lorenzo	146.17
Vicchio	138.90
Barberino di Mugello	133.24
Scarperia - San Piero	116.02
Palazzuolo sul Senio	108.93
Dicomano	61.75
	1131.23

Figure 3.19 Details about the Mugello area: geographical location, municipalities and territorial extension.

3.3.2.1 General overview of the building stock

Globally, 1146 long span buildings were retraced in the Mugello area. In Figure 3.20 statistics relatives to the geographical distribution of the facilities and their intended use are collected. Long span buildings are mainly located within the perimeters of the municipalities of Barberino di Mugello, Borgo San Lorenzo, and Scarperia e San Piero. As for the intended use of these facilities, production activities cover about 61% of the entire building stock but also commercial and agriculture sectors are considerable, accounting for 10% and 11% respectively of the total amount of buildings.

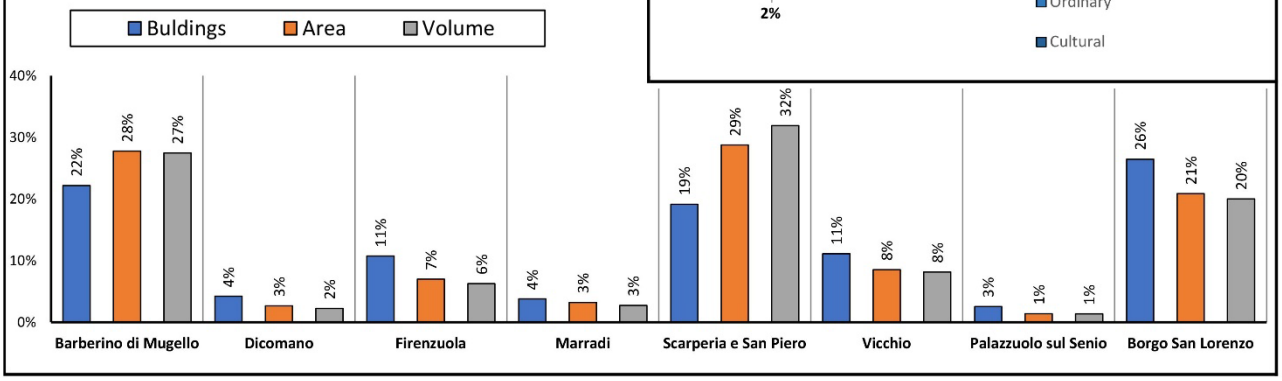
In figure 3.21, data about long span buildings dating and construction technologies are reported. Contrarily to the Casentino area, the prevalence of precast concrete technology is still dominant, but it is less pronounced (39%) as cast in place reinforced concrete was used in 33% of the facilities considered. This evidence is useful to remark the direct involvement of local precast companies in Casentino, where the share of cast in place structure was substantially halved. Focusing on the periods of construction, the trend of Mugello is overlapping with the one of Casentino. In this case too in fact

about 60% of long span facilities were built before 1988 and the percentages relative to more recent periods are comparable (16% in 1988-1996, 19% in 1996-2007, 8% after 2007).

LONG SPAN BUILDINGS STOCK - MUGELLO

GEOGRAPHICAL DISTRIBUTION

Municipality	Buldings	Gross area [m²]	Volume [m³]
Barberino di mugello	254	295'732	2'080'229
Palazzuolo sul senio	29	14'402	99'993
Dicomano	48	28'048	167'131
Vicchio	127	90'420	616'826
Scarperia e San Piero	219	306'330	2'418'550
Firenzuola	123	74'212	473'803
Marradi	43	34'029	205'394
Borgo San Lorenzo	303	222'399	1'516'238
MUGELLO	*1146*	*1'065'572*	*7'578'164*



INTENDED USE

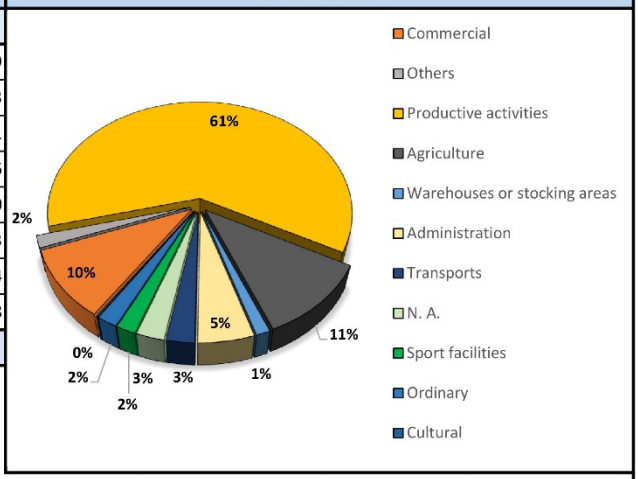
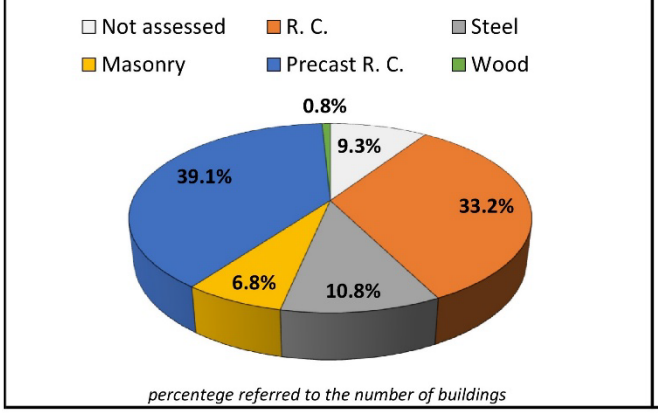


Figure 3.20 Long span buildings stock of Mugello. geographical distribution and intended use analysis.

MATERIAL OF THE VERTICAL LOAD BEARING STRUCTURE

Material	Buildings	Gross area [m²]	Volume [m³]
Masonry	78	36'572	212'268
Steel	124	116'861	759'435
R. C.	380	261'525	1'711'041
Precast R. C.	448	550'503	4'244'223
Wood	9	11'681	79'331
Not Assessed	107	88'430	571'867
TOTAL	1146	1'065'572	7'578'164



percentege referred to the number of buildings

PERIOD OF CONSTRUCTION

Period	Buildings	Gross area [m²]	Volume [m³]
< 1954	40	21'630	166'922
1954-1978	415	352'348	2'263'597
1978-1988	217	194'904	1'324'303
1988-1996	169	169'476	1'224'418
1996-2007	217	237'351	1'885'867
> 2007	88	89'864	713'058

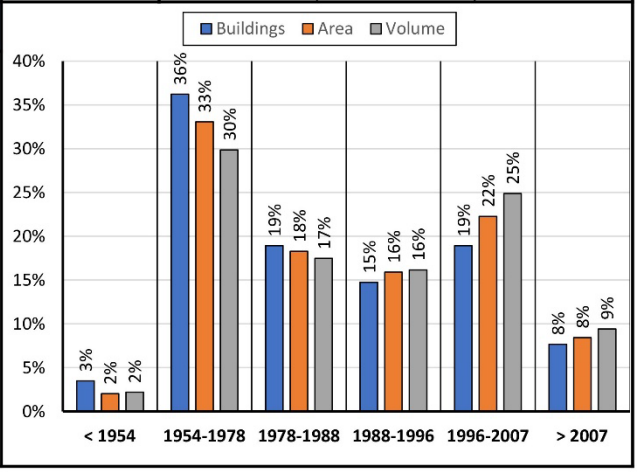
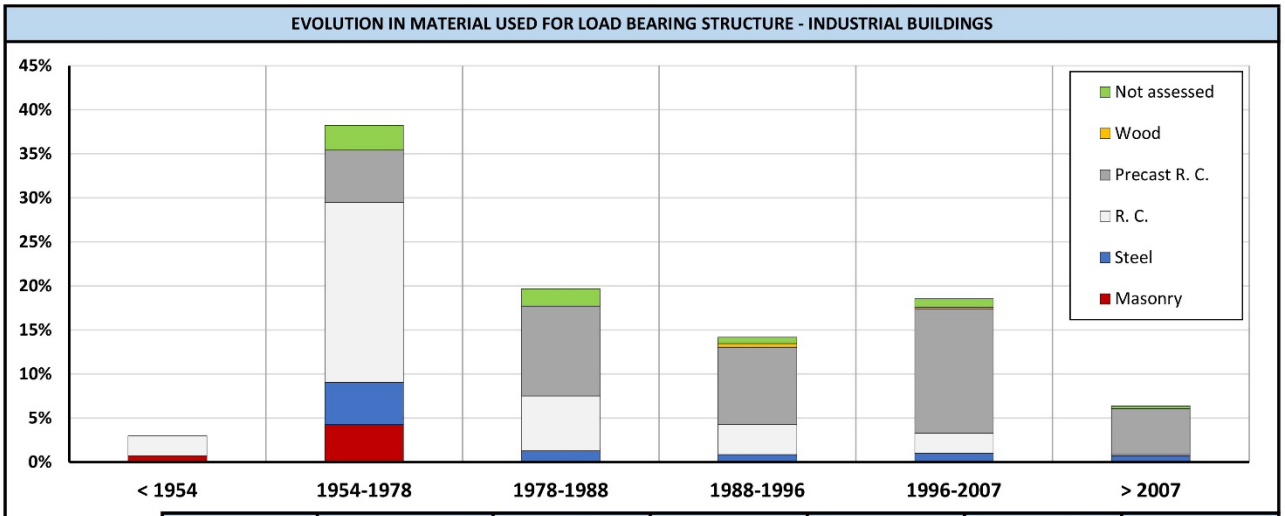


Figure 3.21 Material of the vertical load bearing structure and period of construction of long span buildings in the Mugello area.

Focusing on the 706 industrial facilities in the Mugello area, the evolution of construction solutions was traced according to data synthesized in Figure 3.22. Reinforced concrete buildings were by far dominant in first decades of the industrialization of the territory, accounting for 53% of buildings built between 1954 and 1978, when the prefabrication technique was still marginal (16%). Notably, starting from the subsequent period (1978-1988) precast concrete solutions, adopted in 52% of structures, rapidly established as the reference technology. However, a marginal percentage of cast in place buildings can be retraced until 2007. Masonry, appreciable only before 1978, and steel structures are by far less significant also in this case.



	Masonry		Steel		R. C.		Precast R. C.		Wood		Not assessed		TOT. Period	
< 1954	*5*	**0.7%**	*0*	**0.0%**	*16*	**2.3%**	*0*	**0.0%**	*0*	**0.0%**	*0*	**0.0%**	*21*	**3.0%**
1954-1978	*30*	**4.2%**	*34*	**4.8%**	*144*	**20.4%**	*42*	**5.9%**	*0*	**0.0%**	*20*	**2.8%**	*270*	**38.2%**
1978-1988	*0*	**0.0%**	*9*	**1.3%**	*44*	**6.2%**	*72*	**10.2%**	*0*	**0.0%**	*14*	**2.0%**	*139*	**19.7%**
1988-1996	*0*	**0.0%**	*6*	**0.8%**	*24*	**3.4%**	*62*	**8.8%**	*3*	**0.4%**	*5*	**0.7%**	*100*	**14.2%**
1996-2007	*0*	**0.0%**	*7*	**1.0%**	*16*	**2.3%**	*100*	**14.2%**	*1*	**0.1%**	*7*	**1.0%**	*131*	**18.6%**
> 2007	*0*	**0.0%**	*5*	**0.7%**	*1*	**0.1%**	*37*	**5.2%**	*0*	**0.0%**	*2*	**0.3%**	*45*	**6.4%**
TOT. Material	35	**5.0%**	61	**8.6%**	245	**34.7%**	313	**44.3%**	4	**0.6%**	48	**6.8%**	706	

Figure 3.22 Evolution in material used for the load bearing components over time and relative distribution.

Following the approach already adopted for the Casentino building stock, in Table 3.3 the evolution of main structural elements' size for precast buildings is highlighted. Considering the Mugello area, buildings gross area remained constant over time, since also recently built industrial districts are characterized by medium-sized facilities. Notably, nave width and length underwent limited fluctuations over time in their average dimensions and are comparable with the regional average (14 m -16 m) [23]. This result is clearly retraceable also in Figure 3.23 where the evolution of nave width

over time is reported considering different width intervals. On the other hand, a clear increase in the span width was assessed, suggesting the adoption of longer longitudinal beams for load bearing frames over time.

Table 3.3 Evolution of dimensional data over time in industrial precast concrete buildings in Mugello

		Period of construction				
		1954-1978	**1978-1988**	**1988-1996**	**1996-2007**	**> 2007**
Average building dimensions	**Span width [m]**	5.64	6.42	7.83	8.74	10.20
	Nave width [m]	15.62	16.74	16.73	17.85	15.86
	Total nave length [m]	45.33	40.46	36.84	37.96	40.95
	Area [m²]	1472	1335	1181	1292	1496
	Height [m]	6.52	6.61	7.63	9.45	7.66
	Volume [m³]	10760	9298	8758	11040	12957

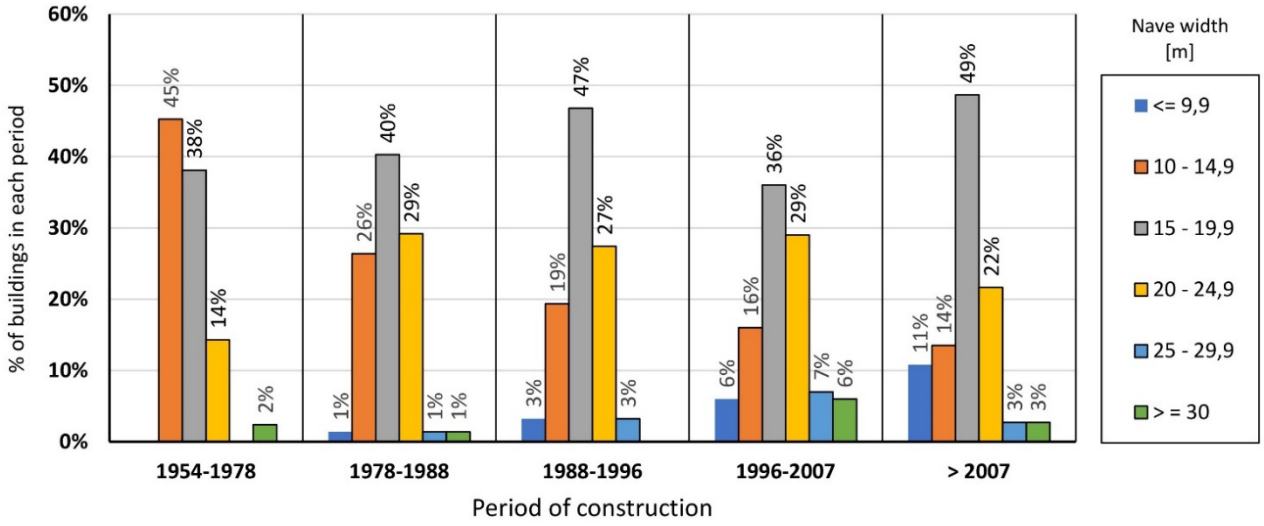
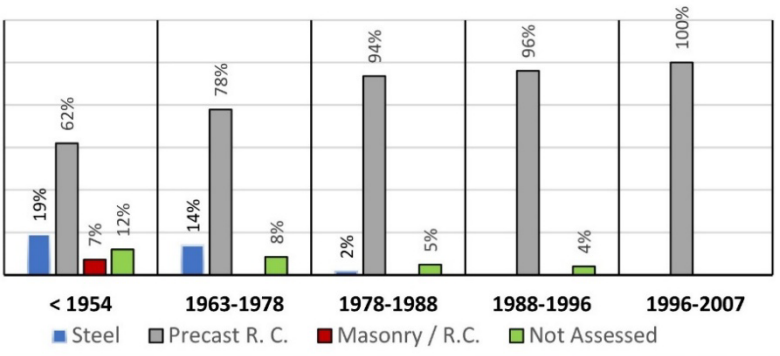
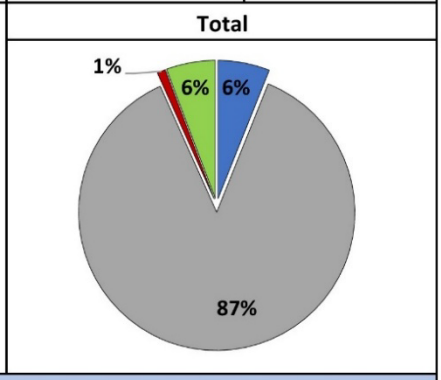


Figure 3.23 Evolution of nave width in the precast concrete industrial building stock in the Mugello area.

Following the procedural steps introduced for the analysis relative to the Casentino building stock, the roofing solutions for precast industrial facilities were characterized. The results, illustrated in Figure 3.24 and Table 3.4 let to assess similarities and discrepancies between the two building stocks considered. The shares of the different roofing solutions are overlapping in terms of the material of the load bearing elements, with precast concrete emerging as prevalent also in this case being adopted in about 87% of the facilities. However, differences were retrieved considering the main structural component used. In the Mugello area, precast prestressed concrete double sloped beams, not assessed in Casentino, were retrieved. The presence of this solution is symptomatic of the possible involvement of precast companies usually active in different areas. In Emilia Romagna for instance, this peculiar solution is generally predominant, being adopted in about 65% of precast structures, while in Tuscany it only accounts for 14% [23].

Material of load bearing elements				
	Steel	Precast R. C.	Masonry / R.C.	Not Assessed
1954-1978	19%	62%	7%	12%
1978-1988	14%	78%	0%	8%
1988-1996	2%	94%	0%	5%
1996-2007	0%	96%	0%	4%
> 2007	0%	100%	0%	0%





Roof shape					
	Sloped roof	Vaulted	Plain	Shed	N. A.
1954-1978	50%	14%	26%	10%	0%
1978-1988	46%	0%	51%	3%	0%
1988-1996	18%	0%	81%	2%	0%
1996-2007	9%	0%	87%	4%	0%
> 2007	5%	0%	68%	27%	0%

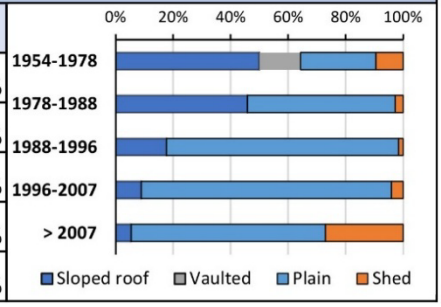


Figure 3.24 Analysis of roofing solutions for precast concrete industrial buildings in Mugello.

Table 3.4 Load bearing element, material and roof shape in precast industrial facilities of Mugello.

	Masonry/R.C.	Precast R. C.					Steel			N. A.	
	Arch beams	*Beams*	*Wing tiles*	*Sloped beams*	*Truss beams*	*N. A.*	*Arch beams*	*Trusses*	*N. A.*	-	***Total - shape***
N. A.	-	-	-	-		-	-	-	-	-	**-**
Plain	-	143	51	-		9	-	-	-	7	***210***
Shed	-	-	20	-		-	-	-	-	1	***21***
Sloped Roof	-	-	-	47	1	2	-	16	1	9	***76***
Vaulted	3	-	-	-		-	2	-	-	1	***6***
Total - element	***3***	***143***	***71***	***47***	***1***	***11***	***2***	***16***	***1***	***18***	**-**
Total - material	***3***	***273***					***19***			***18***	***313***

As for the analysis targeting skylights, the results obtained (Figure 3.25) are comparable with the ones retrieved over Casentino. Notably in this case a clear prevalence of emergent skylights was retraced in more recent facilities, where the shed configuration stands as the reference solution being adopted in 38% of the facilities built after 2007.

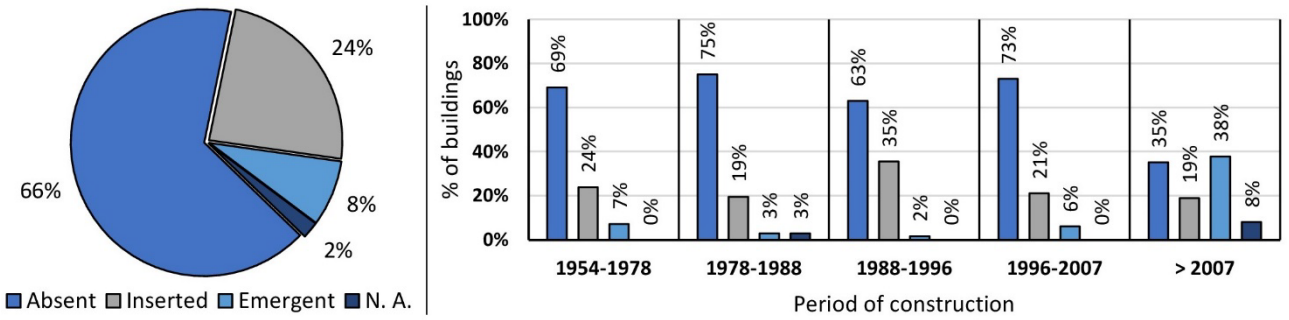


Figure 3.25 Presence and evolution of skylights in the precast building stock of Mugello.

The analysis carried out to assess the presence of asbestos containing components led to the results presented in Figure 3.26. The share of buildings affected by the presence of asbestos based components is in this case lower but still relevant as it covers 22% of the total amount of the facilities encompassed in the study. This reduced incidence can be easily referred to the construction period: most precast concrete buildings in Mugello were built after 1996, hence adopting adequate materials for roofing finishing and completion. For this reason, asbestos was assessed to have a lower incidence also in those roofing solutions usually implementing fibre cement components such as the precast beam-based ones.

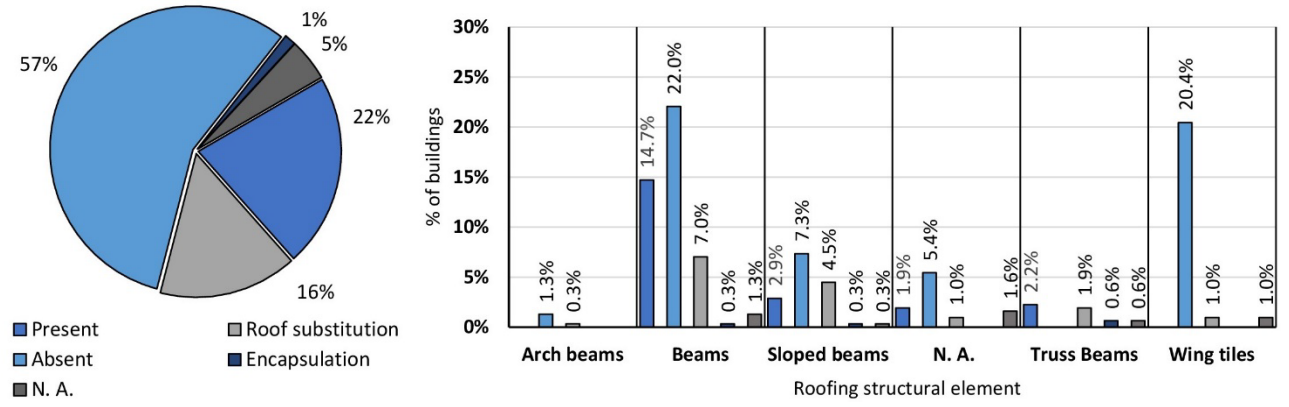


Figure 3.26 Presence and distribution of roofing elements containing asbestos in precast industrial buildings in Mugello.

Notably, given the consistent number of industrial buildings realized recurring to traditional cast in place concrete technologies, the roofing solution was detailed also in for this kind of buildings. The evidence of this further assessment, presented in Table 3.5, revealed that the technological

alternatives adopted are coincident with the ones implemented in precast buildings. This implies that many buildings constructed with traditional techniques for vertical load-bearing elements will also be affected by the same critical issues already raised in the case of prefabricated constructions, such as the presence of asbestos in the roofing. In about the half of the facilities examined, precast reinforced concrete beams were in fact installed as roofing structural elements also on cast in place frames. Similarly, metal trusses were adopted. Both these solutions will be later detailed. Latero-cement vaults with precast concrete arched beams, retraced in 21% of the structures was on the other hand the reference solution for older buildings, being characteristic of the earlier manufacturing buildings from the 1960s and 70s. This partially prefabricated solution features a vault, either more or less lowered, constructed from two segments of prefabricated reinforced concrete curved beams. These beams were positioned to create a three-hinged arch scheme, with lateral forces absorbed by metal chains. Thin hollow core slabs were placed between successive arches, and the structure was completed with an extrados slab. The protective and surface finish layer could be made with either traditional roof tiles (62% of the buildings analysed) or fibre-cement panels (30%). The presence of thermal insulation or waterproofing layers could not be determined with certainty in these cases.

Table 3.5 Characterization of roofing solutions in cast in place concrete buildings in Mugello.

	Masonry/R.C.	**Precast R. C.**		**Steel**	**Not Assessed**
	Arch beams	*Beams*	*Wing tiles*	*Trusses*	-
N. A.	-	-	-	-	19%
Plain	-	48%	3%	-	
Sloped Roof	-	-	-	9%	
Vaulted	21%	-	-	-	

As for the characterization of external walls solutions encountered in case of precast industrial buildings, the same technological solutions already introduced in case of Casentino were registered also in the Mugello area: masonry infills and precast panels can be hence considered as reference solution in this part of the region too. Anyhow, a different incidence of the alternative solutions mentioned above was assessed, as shown in Figure 3.27.

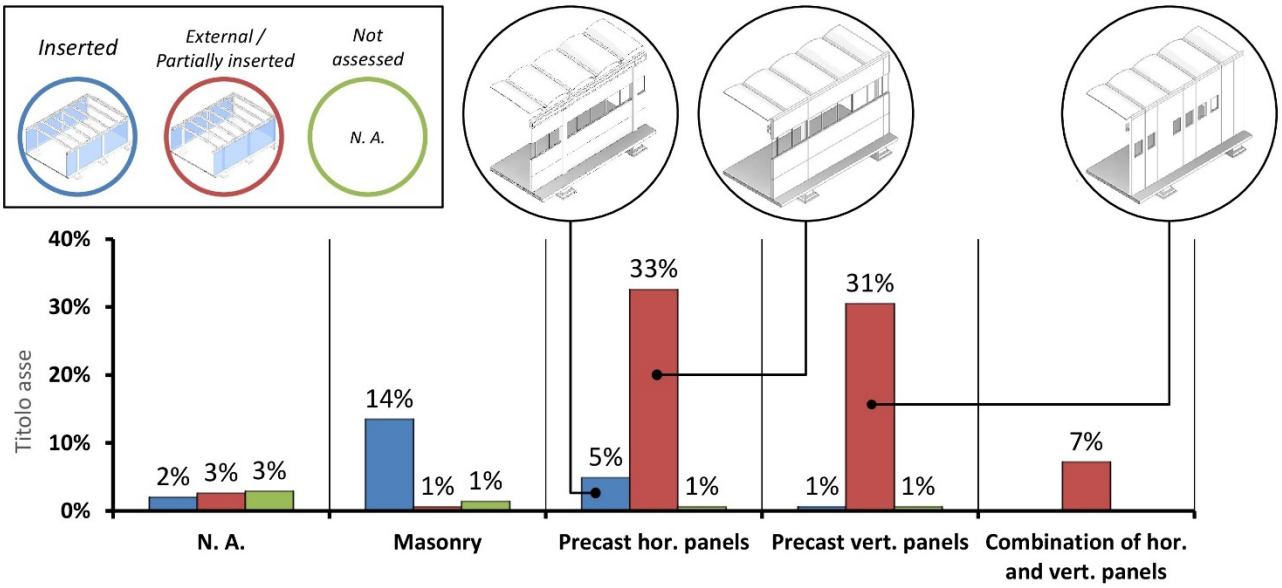
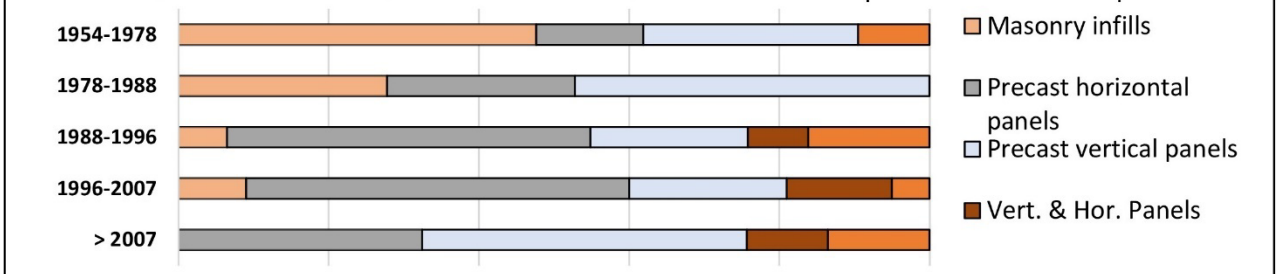


Figure 3.27 Analysis of the solutions adopted for external walls in terms of both position and technology in industrial precast buildings in Mugello.

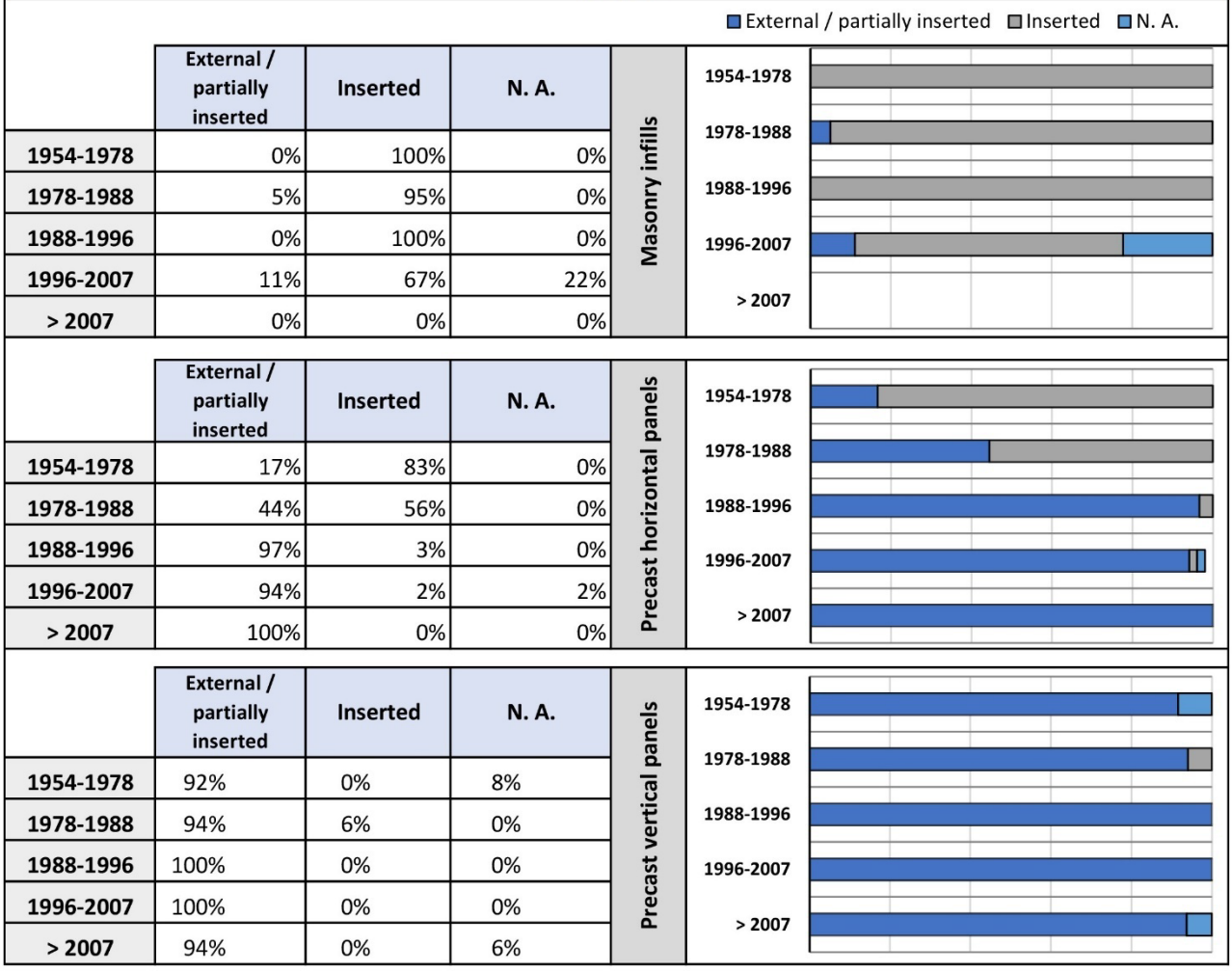
Remarkably, precast panels arranged horizontally and outside the structural elements are in this prevalent being registered in one third of the buildings. Vertical prefabricated panels, which in Casentino and Arezzo province reach a diffusion percentage of 60%, are here limited to only 30%. This share is certainly consistent but significantly lower, demonstrating the different solutions proposed by construction and prefabrication companies in geographically distinct areas. At the same time, there is also a greater concentration of buildings with perimeter walls made of masonry (14% in Mugello, 8% in Casentino). This data is once again symptomatic of a slower establishment on the market of entirely prefabricated construction systems in this part of the region. In more recent years, however, there has been a more frequent use of external walls created using a combination of horizontal and vertical prefabricated panels. Generally, the latter are placed in correspondence with the pillars while the horizontal ones are arranged in the mirrors between successive pillars guaranteeing greater compositional freedom in the creation of windowed portions, an aspect which is particularly relevant in multi-storey buildings. This evolutionary trend was retraced by postprocessing data according to the time intervals identified; the results of the analysis are reported in Figure 3.28: In older facilities, masonry infills were largely prevalent followed by precast vertical panels whose adoption over time followed an irregular trend with a maximum share of 47% and progressive decay until the inversion registered after 2007. Conversely, horizontal panels progressively gained importance in the market reaching the maximum diffusion between 1978 and 1996. Notably, as already mentioned for Casentino, also in this case they were initially placed inserted between columns through the preset grooves intended to host them according to a system retraced in this case until 1988.

Technology

	Masonry infills	Precast horizontal panels	Precast vertical panels	Vert. & Hor. Panels	N. A.
1954-1978	48%	14%	29%	0%	10%
1978-1988	28%	25%	47%	0%	0%
1988-1996	6%	48%	21%	8%	16%
1996-2007	9%	51%	21%	14%	5%
> 2007	0%	32%	43%	11%	14%



Position



	External / partially inserted	Inserted	N. A.
1954-1978	0%	100%	0%
1978-1988	5%	95%	0%
1988-1996	0%	100%	0%
1996-2007	11%	67%	22%
> 2007	0%	0%	0%

Masonry infills

	External / partially inserted	Inserted	N. A.
1954-1978	17%	83%	0%
1978-1988	44%	56%	0%
1988-1996	97%	3%	0%
1996-2007	94%	2%	2%
> 2007	100%	0%	0%

Precast horizontal panels

	External / partially inserted	Inserted	N. A.
1954-1978	92%	0%	8%
1978-1988	94%	6%	0%
1988-1996	100%	0%	0%
1996-2007	100%	0%	0%
> 2007	94%	0%	6%

Precast vertical panels

Figure 3.28 Chronological evolution of external walls solutions in Mugello.

In Figure 3.29 photographical evidence of the different cladding solutions acquired during on-site surveys in different Mugello industrial districts are collected.

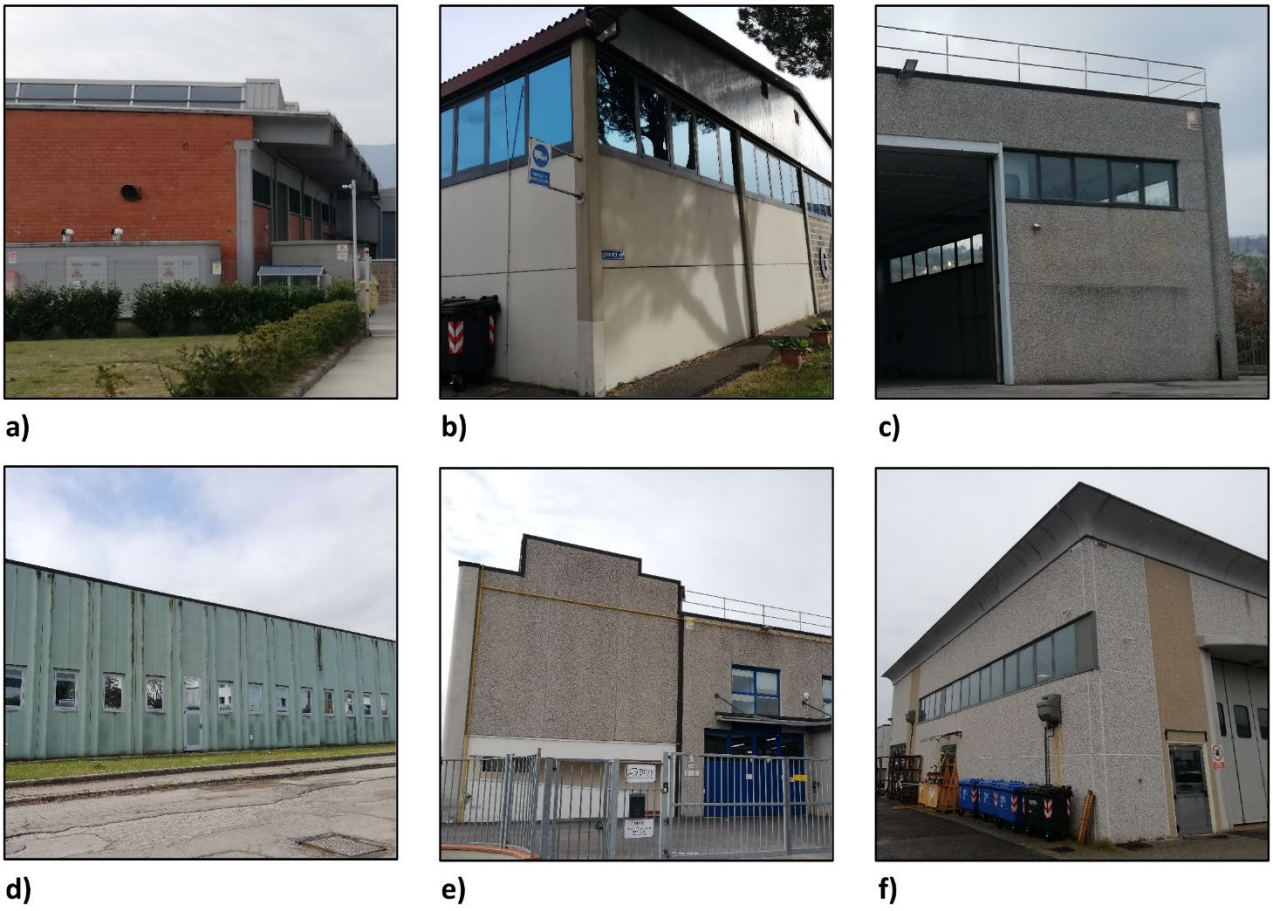


Figure 3.29 Technological alternatives for external walls in precast industrial buildings in Mugello. a) inserted masonry infills; b) inserted horizontal precast panels; c) external horizontal precast panels; d) external vertical precast panels, ribbed profile; e) external vertical precast panels, smooth surface profile; f) combination of external vertical and horizontal precast panels.

3.3.2.2 Identification of typological variants

Contrarily to Casentino, Mugello is characterized by the extensive recurs to cast-in-place solutions for industrial buildings even if the precast industrial building stock is still consistent. The classification of facilities into different typological variants was obtained also in this case following the same criteria previously introduced, addressing roofing configuration. Here also, 5 typological variants were identified, but some differences with the Casentino building stock emerged.

The typological variants alternatives assessed in the Mugello area are listed below:

- **Variant Sl_m_tr**: Buildings with sloped roofs made from metal trusses.
- **Variant Sl_rc_slb**: Buildings with sloped roofs made from metal truss precast concrete sloped beams;
- **Variant P_rc_b**: Buildings with flat roofs made from prefabricated beams in prestressed reinforced concrete;
    - **Sub-Variant P_rc_b_s**: Single storey buildings with flat roofs made from prefabricated beams in prestressed reinforced concrete;
    - **Sub-Variant P_rc_b_m**: Multistorey buildings with flat roofs made from prefabricated beams in prestressed reinforced concrete;
- **Variant P_rc_t**: Buildings with flat roofs constructed from prefabricated wing tiles in prestressed reinforced concrete;
- **Variant Sh_rc_t**: Buildings with shed roofs made from prefabricated wing tiles in prestressed reinforced concrete.

With respect to the typological alternatives introduced for Casentino, vaulted steel roofs are irrelevant in Mugello and this variant was consequently discarded. On the other hand, sloped precast beams forming portal frames emerged as particularly significant while they are not retraceable in Casentino. The other configurations assessed are overlapping in both technological features and diffusion over time, as from the evidence reported in Figure 3.30.

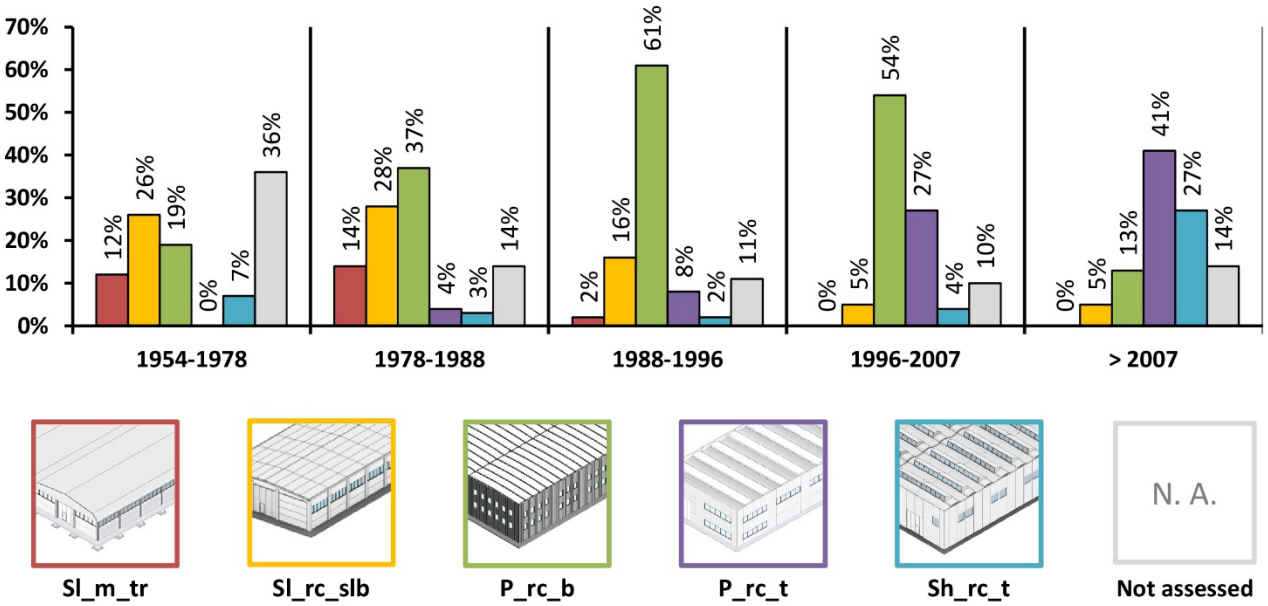


Figure 3.30 Diffusion of the typological variants identified in Casentino in each of the different periods considered in the analysis.

Synthesis statistical data are collected in the data sheets produced for each variant introduced collected in the section Annex 3.B.

3.3.3 Description of the recurrent typological variants identified

The detailed description of the different typological variants for industrial facilities, identified through the comprehensive territorial scale study, follows. The statistical data sheets supporting the discussion here presented are collected in The Annexes 3.A and 3.B, respectively referring to the Casentino and Mugello analysis. These typological alternatives, briefly listed in the previous paragraph, reflect the diverse construction periods, materials, structural elements, and roofing solutions employed across various industrial districts. By examining these typological variations, we can better understand the architectural and structural evolution of industrial buildings in the region. Referring specifically to structures built using prefabricated concrete systems, the various configurations of structural elements, connections between components, and external cladding solutions necessitate a detailed typological characterization. This is crucial as these factors significantly influence the overall seismic response of the entire structure. The awareness of the peculiarities of each category is pivotal for designing retrofit interventions that are not only effective but also replicable and scalable, ensuring that improvements can be systematically applied across similar structures to enhance energy efficiency, resilience, and overall functionality.

Recalling the evidence obtained through the studies carried out on Casentino and Mugello, the following typological variants will be presented:

- **Variant V_m_ar**: Buildings with vaulted roofs constructed from steel arched beams;
- **Variant Sl_m_tr**: Buildings with sloped roofs made from metal trusses;
- **Variant Sl_rc_slb**: Buildings with sloped roofs made from precast concrete sloped beams;
- **Variant P_rc_b**: Buildings with flat roofs made from prefabricated beams in prestressed reinforced concrete;
- **Variant P_rc_t**: Buildings with flat roofs constructed from prefabricated wing tiles in prestressed reinforced concrete;
- **Variant Sh_rc_t**: Buildings with shed roofs made from prefabricated wing tiles in prestressed reinforced concrete.

3.3.3.1 Variant V_m_ar

Variant V_m_ar is distinguished by the primary roofing elements made of arched steel trusses, with their use exclusively observed between 1954 and 1978 and only limited to the Casentino area. Despite their marginal representativeness over the whole building stock, this variant was included in the analysis due to its diffusion in the first decades of the industrialization of the territory and the considerable size of the buildings referrable to this typology.

This typological variant was used in Casentino for large industrial complexes, highly affecting the average dimensions assessed. Buildings classified under this category are notable for their extensive ground footprint, meaning they occupy a large horizontal area. This layout is organized to include multiple naves, each distinguished by significant length. The width of each aisle is determined by the maximum dimensions attainable by the covering elements used in construction, typically remaining below 20 meters due to the construction method limitations. Furthermore, owing to the specific configuration of the roof structure, these buildings are designed to be exclusively single-story, meaning they are developed on a single level without any superimposed floors.

Arched trusses are typically connected to prefabricated reinforced concrete beams with an Ω-shaped cross-section, aligned according to the longitudinal development of the facility and mounted on pillars featuring a tenon head. Alternatively, they can be installed directly onto the upper parts of columns using metal joints forming single transversal portals or on side beams. As for the external walls, both vertical and horizontal prefabricated panels were employed. The latter, appearing as predominant solution, are placed between the columns of the load-bearing structure.

Photos taken during on-site recognitions are collected in Figure 3.31 while the key elements of the typological variant described so far are illustrated in Figure 3.32.

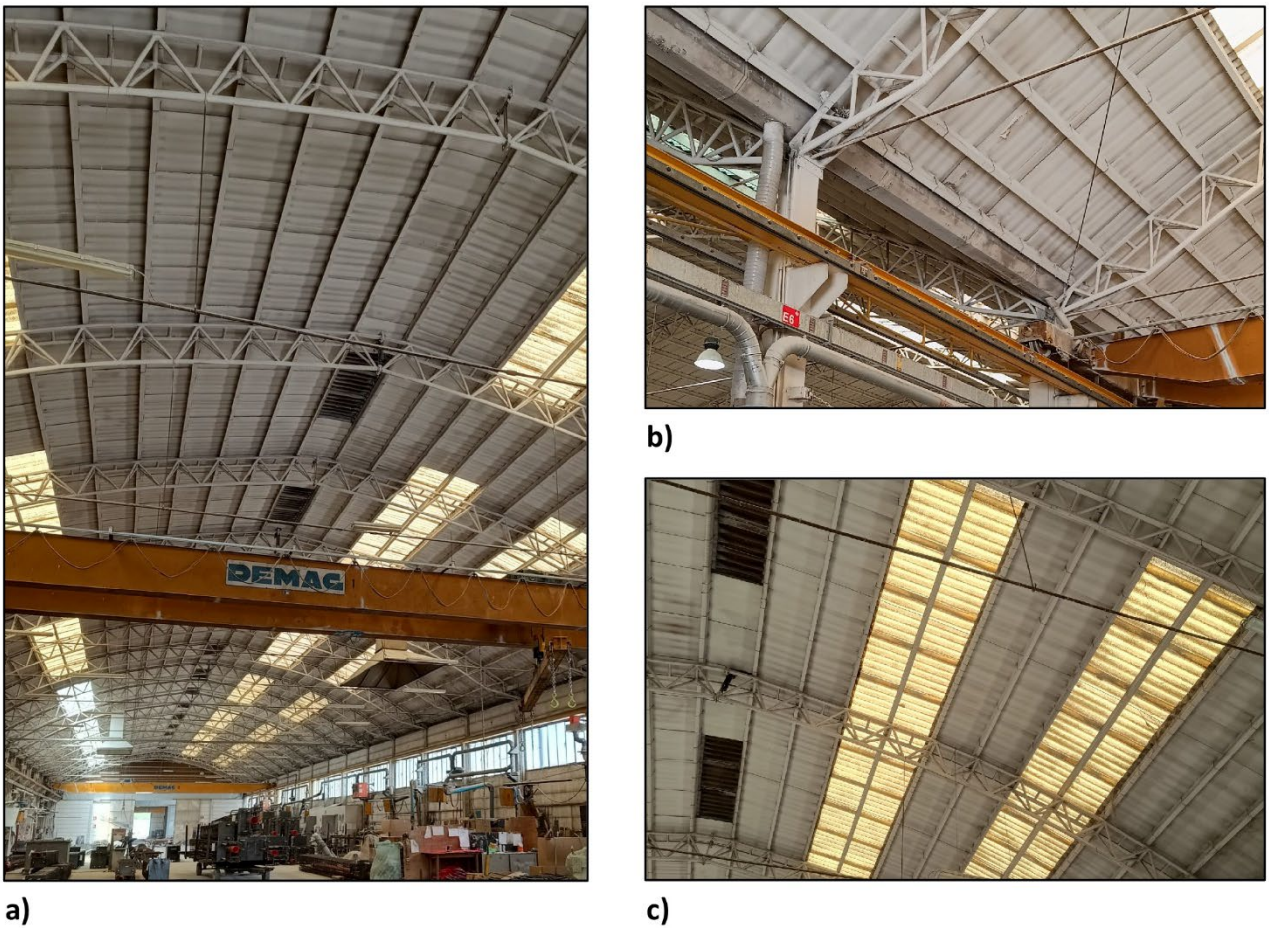
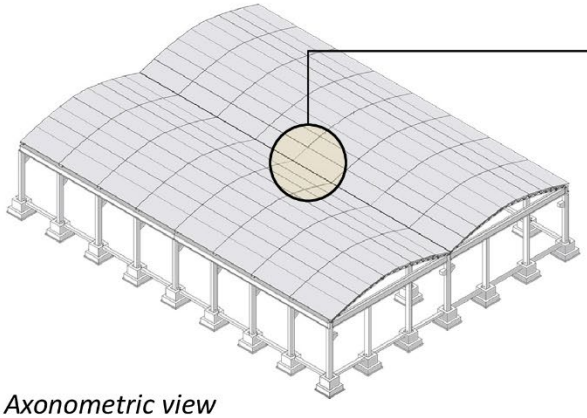
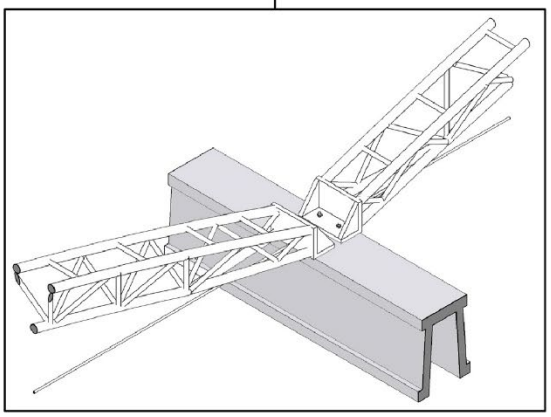


Figure 3.31 Photographical evidence of real existing buildings of the V_m_a variant: internal view (a) and details of arched trusses (b) and roofing completion with inserted skylights (c).t

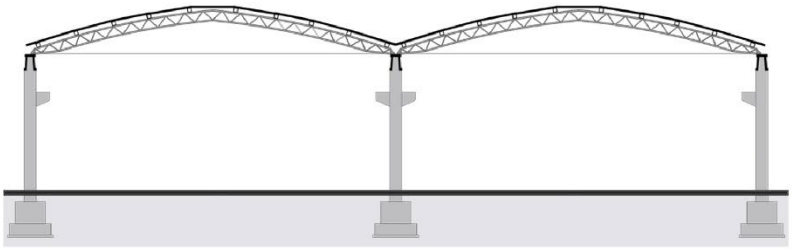
Load bearing structure



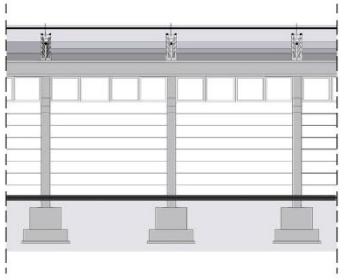
Axonometric view



Arch- trusses and beam connection



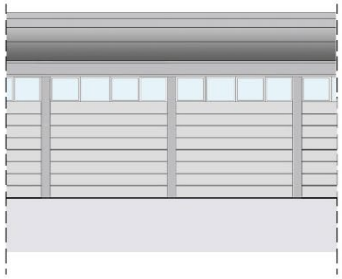
Transversal section



Longitudinal section

Elevations

Front elevation



Side elevation

Figure 3.32 Variant V_m_ar: graphical representations of the main distinguishing aspects.

3.3.3.2 Variant Sl_rc_slb

This typological variant represents the first historical solution of an entirely prefabricated construction system in Mugello, accounting for 15% of the precast industrial buildings analysed, mostly built between 1954 and 1978. Notably, this typology is widely prevalent in northern Italy and retrieved only in the Mugello area during the research carried out. Most of the buildings (about 70%) have a floor area between 500 m² and 1300 m², largely depending on the number of naves. Single naves are common in many facilities (about 80%), with widths ranging between 10 m and 15 m and average lengths between 40 m and 55 m. This variant almost exclusively includes single-story buildings, with 80% not exceeding a height of 8 m.

The portal frames, aligned transversely to the building's longitudinal development, consist of prefabricated columns and double-sloped beams. Regarding structural elements, different configurations for column-heads were assessed, including fork-shaped, L-shaped, or plain. The plain type is associated with dapped-end beams resting on the column head, possibly with metal pins. Full-end beams are used with L-shaped or fork-shaped columns, connected by simple resting on neoprene plates or metal pins. In case of fork-shaped head, metal bars or pins can be used and solidarized trough in-place place concrete casting, according to the most widespread configuration.

The most common roofing solution involves the use of precast concrete slabs of low height (20-30 cm) with a π section placed over the double-slope beams forming the load-bearing portal frames. In many buildings, skylights are inserted between consecutive slabs or emergent from the roof plane using self-standing metal frames. An alternative roofing system, found in a small percentage of buildings, uses precast concrete T-shaped purlins laid among consecutive gable beams, with the upper side shaped to host them. As for the finishing layer, both fibre-cement corrugated panels or waterproofing membranes were retrieved. Due to the difficulties in inspecting and the lack of comprehensive design documentation, the presence of thermal insulation and waterproofing layers on the roof could not be confirmed.

For external walls, the position relative to the load-bearing structure is a key distinguishing element in this case as a significant variability of solutions was retrieved. In case of cladding elements placed externally to the columns, precast concrete panels are used in both vertical and horizontal configurations. Walls inserted between structural columns are realized in this case with masonry infills built in place or precast panels, arranged horizontally and inserted in grooves of the lateral sides of the columns.

Photos taken during on-site recognitions are collected in Figure 3.33 while details of the structural elements and the different alternatives assessed are shown in Figure 3.34.

Figure 3.33 Photographical evidence of existing buildings of the Sl_rc_slb variant. External views of facilities with different external walls solutions: a) masonry infills, b) precast vertical panels, c) Horizontal precast panels); internal views and details of structures featuring alternative roofing solutions with purlins (d, e, f) and π slabs (g, h, i).

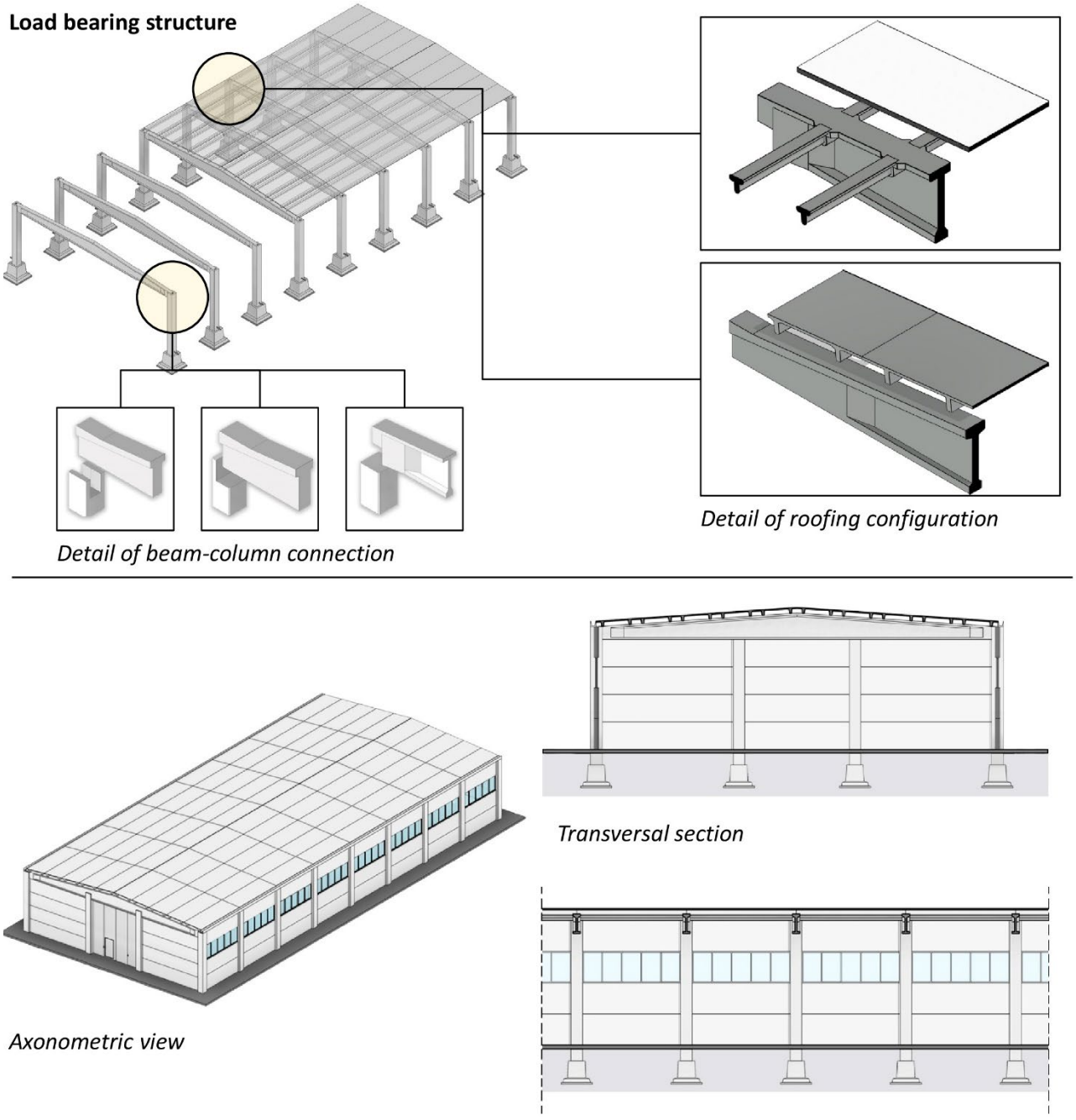


Figure 3.34 Variant Sl_m_tr: graphical representations of the main distinguishing aspects.

3.3.3.3 Variant Sl_m_tr

In the same years and with a similar structural logic, facilities featuring transverse frames with precast concrete pillars and metal trusses were also constructed. Despite their limited presence within the overall building stock, this variant was deepened due to its prevalence among older structures. In both Mugello and Casentino it covers only 5% of the facilities investigated but, especially in the former it is particularly appreciable among the oldest ones. These kinds of structures present an almost comparable distribution over the 1954-1978, 1978-1988, and 1988-1996 periods even if their share on each time interval changes.

The facilities retrieved are exclusively single-story ones and generally present a limited floor area (comprised between 300 and 500 m2), a single nave configuration and a total height lower than 7 m. In Mugello, bigger complexes are present being organized in multi-naves configurations with wider internal width.

In the buildings assessed on the territory, the metal trusses, double-pitched, are made with angular metal profiles and welded or bolted to metal junction elements placed on the head of the precast columns forming the vertical load bearing structure. For these buildings, simple corrugated asbestos-fibre cement slabs were used as finishing elements on the roof extrados. In some case a double layer of panels was retrieved, with the internal one forming a kind of counter-ceiling solution. The presence of thermal insulation, suggested by the permanent loads considered in the original design calculation documents consulted, could not be assessed with certainty.

As for the external walls, both masonry and precast solutions are adopted. In case of horizontal panels, only the inserted configuration was retrieved, aligning with the dated aging of these typological variant. This solution is particularly relevant in the Mugello building stock, where it is adopted in 50% of the buildings.

In Figure 3.35 photographical evidence of real case study building are reported and in Figure 3.36 a graphical representation of the main distinguishing characteristics of the variant is provided.

Figure 3.35 Photographical evidence of existing buildings of the Sl_m_tr variant. External views of the facility (a, b, c); internal views (d, e) and details of roofing structures and the related completion elements (f, g, h).

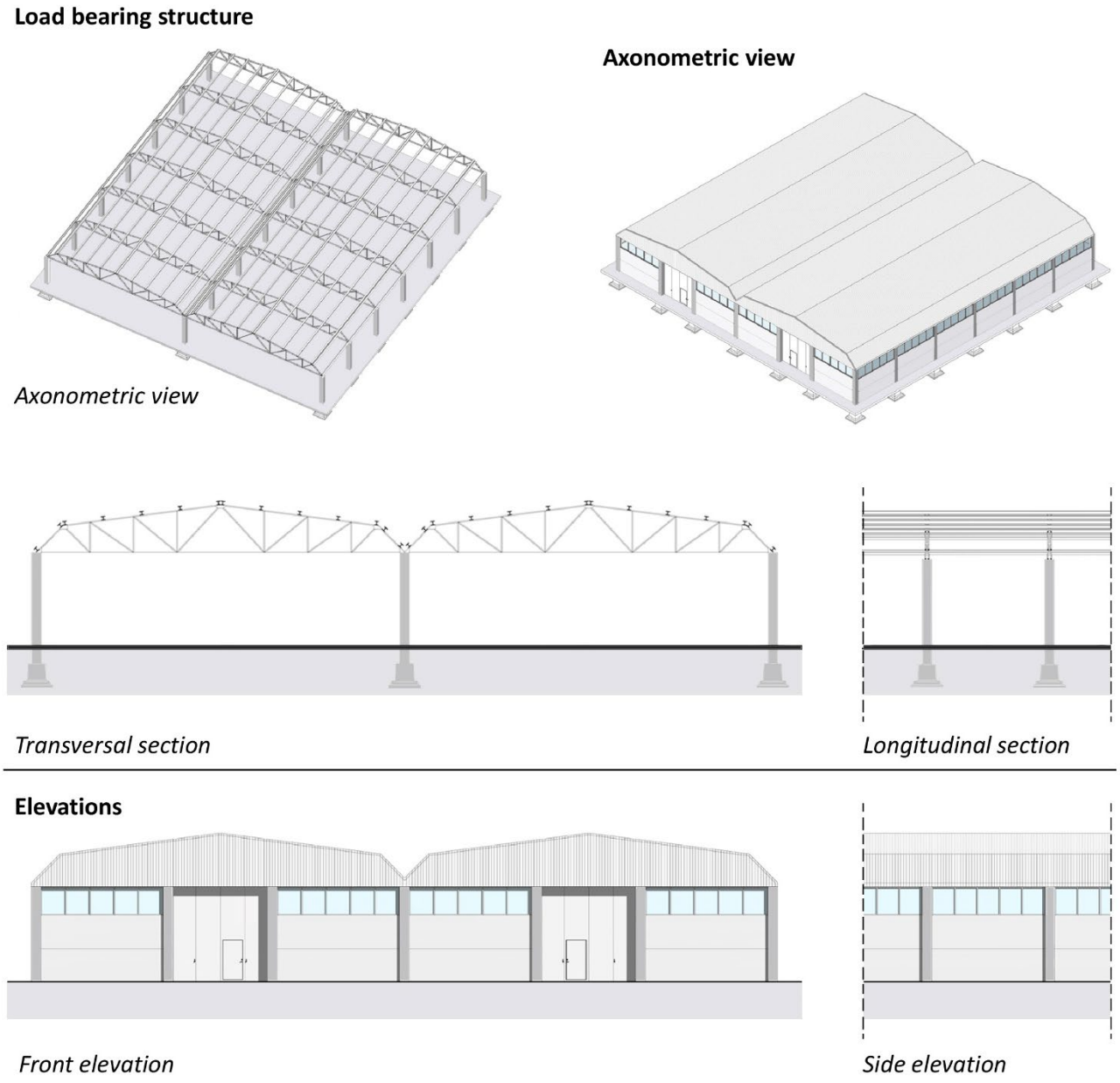


Figure 3.36 Variant Sl_m_tr: graphical representations of the main distinguishing aspects.

3.3.3.4 Variant P_rc_b

The typological variant featuring precast, prestressed roofing beam elements as structural components is the most representative one, covering about 45% of the total amount of buildings analysed. This trend can be retraced at regional level, where it covers 55% of precast structures according to the available studies [23]. In the Mugello region this variant experienced a slower diffusion over time while it started dominating the Casentino market already at the end of the 70s. In this case both single storey facilities (about 70%) and multi levels ones (roughly 30%) were identified. Anyhow, both the configurations share the same main distinguishing features. Generally, gross area ranges between 300 and 1000 m^2 and a clear prevalence of single nave facilities have been assessed, even if in Mugello an appreciable share of multi-naves buildings were retrieved.

The key aspects of the typological variant under consideration are illustrated in Figure 3.37.

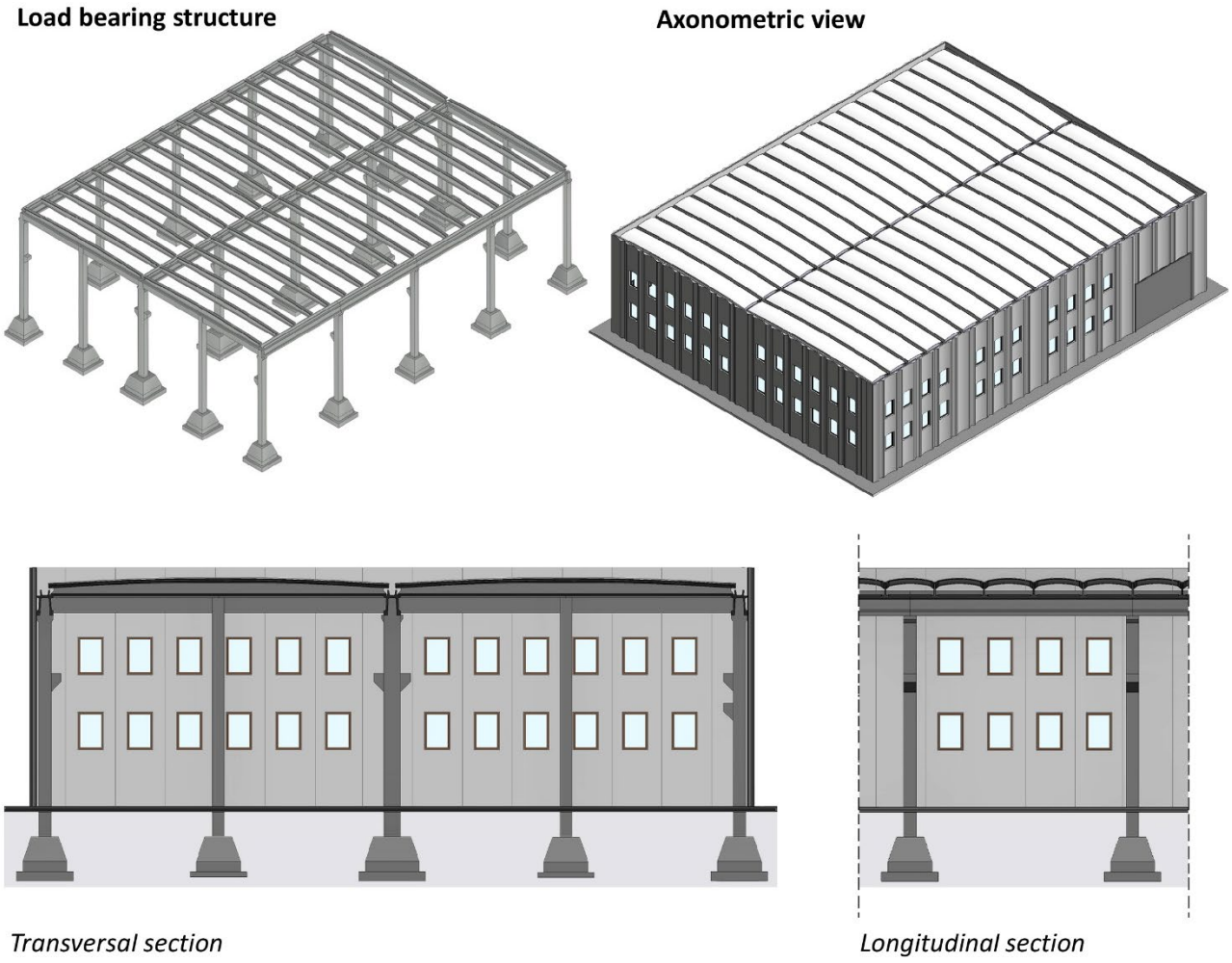


Figure 3.37 Variant P_rc_b: graphical representations of the main distinguishing features.

Roofing beams, generally characterized by a Y-shaped section and spanning approximately 20 m, are spaced with an interaxis comprised between 1.2 to 1.8 meters. In the oldest structures, the roofing beams usually presented a hybrid steel-reinforced concrete solution: the core is constituted by a metal truss, while both extrados plane and intrados base plate are made out by reinforced concrete elements. The technological evolution led to entirely precast beams, with different sections height and general design considering also the various span to be covered. The edges of the upper surface element sometimes have shaped profiles to accommodate the finishing elements to be placed between successive beams. Roofing beams are connected recurring to metal joints or cast in place solutions to the longitudinal frames. These typically features beams with Ω- or H-shaped sections, connected to tenon-headed columns with metal and a cast in place concrete pouring. Ω-section beams are common in older buildings and are suitable for smaller spans while the H-section beams represent an evolutionary advancement, capable of spanning greater distances due to its increased height. In the transverse direction, T-shaped beams supported by fork pillars often provide bracing against lateral forces. Columns located at the corners, present a specifically designed head, featuring both tenon and fork configuration in the two directions. The details of the structural elements and the different alternatives assessed are shown in Figure 3.38.

In Figure 3.39, the solution adopted for the roofing stratigraphy is presented. Roofing completion elements are collocated among successive beams both externally and internally. The external elements are typically curved fibrocement cupels, with occasional components of the same geometry made from polycarbonate or fiberglass to create skylights integrated into the roof plane. Internally, flat fibrocement panels are arranged on the wings of the beams, forming a continuous and thermally insulating ceiling solution at the underside. Original design documents revealed the presence of an insulating layer, typically rock wool or glass fibre, with a variable thickness of approximately 6 cm, laid above these panels.

Rainwater management is directly ensured by roofing beams, thanks to their slightly double sloped profile at the extrados, collect water from the vaulted cupels and channel it towards the beams of the frames arranged transversely. From there, it is directed to the downpipes. Depending on the configuration of the edge beam, different solutions have been observed. In case of Ω-section beams, rainwater collection is usually managed by metal gutters installed on site while the extrados of the upper recess of H-beams functions as a side gutter, discharging through connections to downpipes integrated into the vertical pillars. Alternatively, especially in older facilities, external downpipes have been observed.

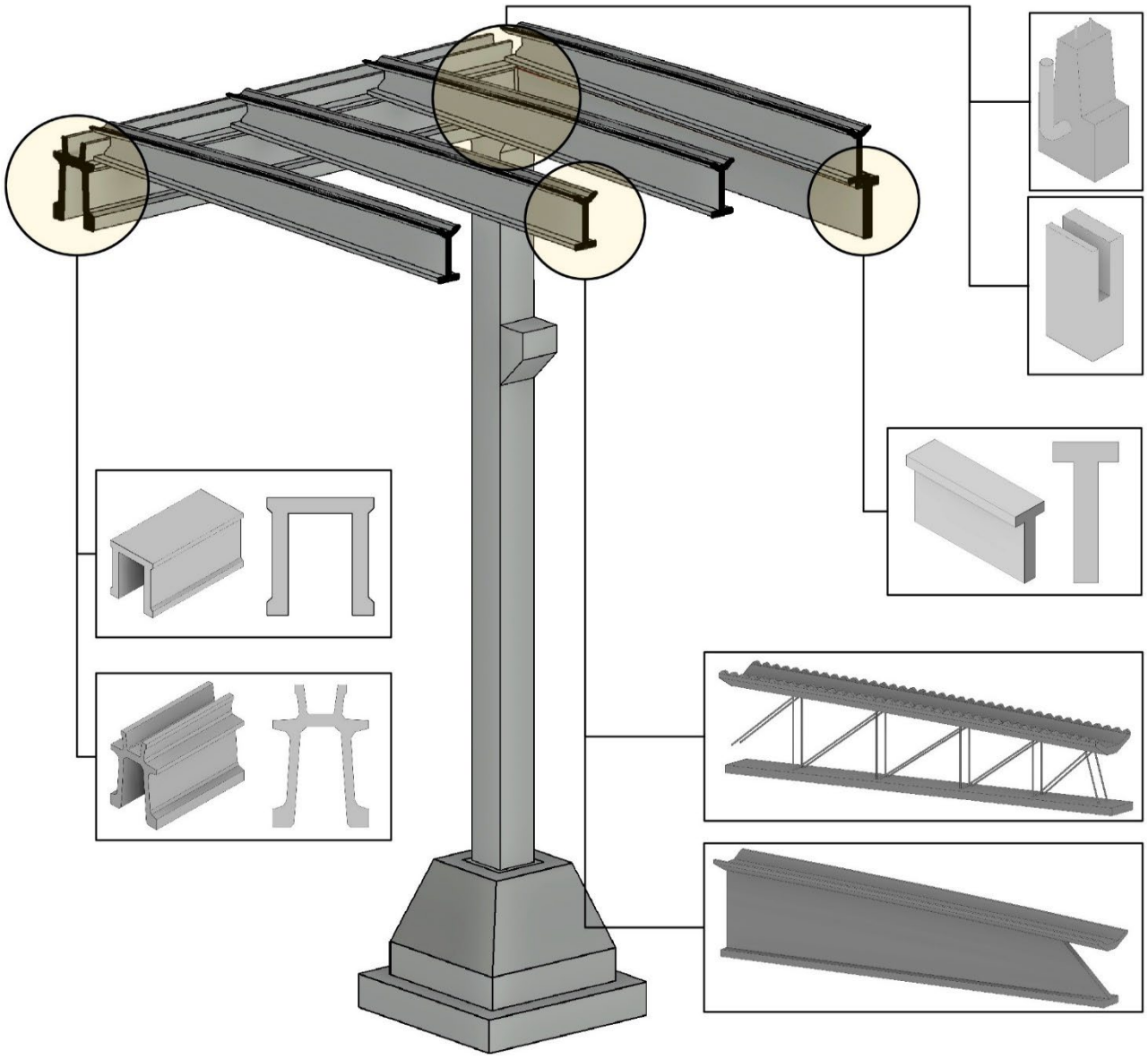


Figure 3.38 Details of the load bearing structure in P_rc_b variant buildings: alternatives assessed for side beams sections, columns head shape, roofing beam types and details of the T-section head bracing beam.

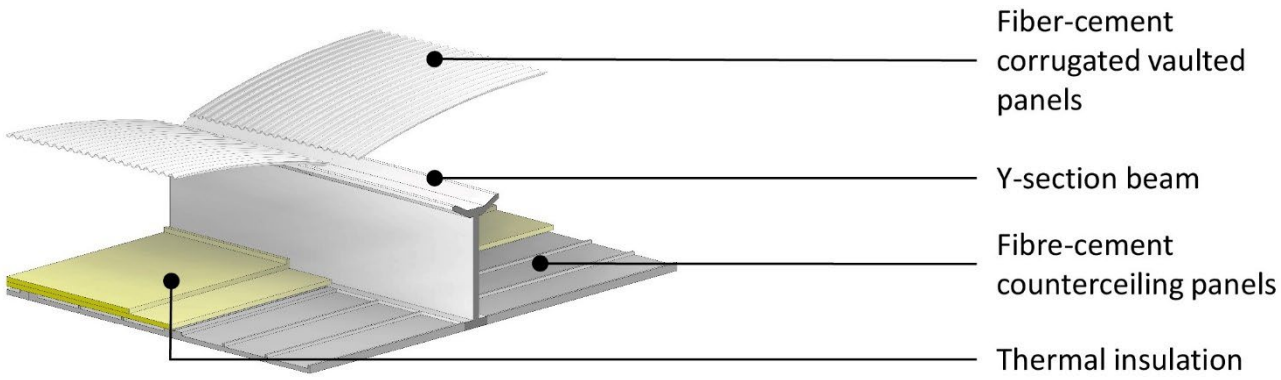


Figure 3.39 Details of the roofing stratigraphy in P_rc_b variant buildings.

Externally, walls have primarily been constructed using prefabricated vertical panels, while horizontal panels have been less commonly used, in recent decades for multistorey buildings and in external position. Remarkably, horizontal external panels are the most common solution for precast industrial buildings in Mugello. Older buildings sometimes feature masonry infills and horizontally inserted panels.

Figure 3.40 collect images of existing buildings referring to the typological variant described.

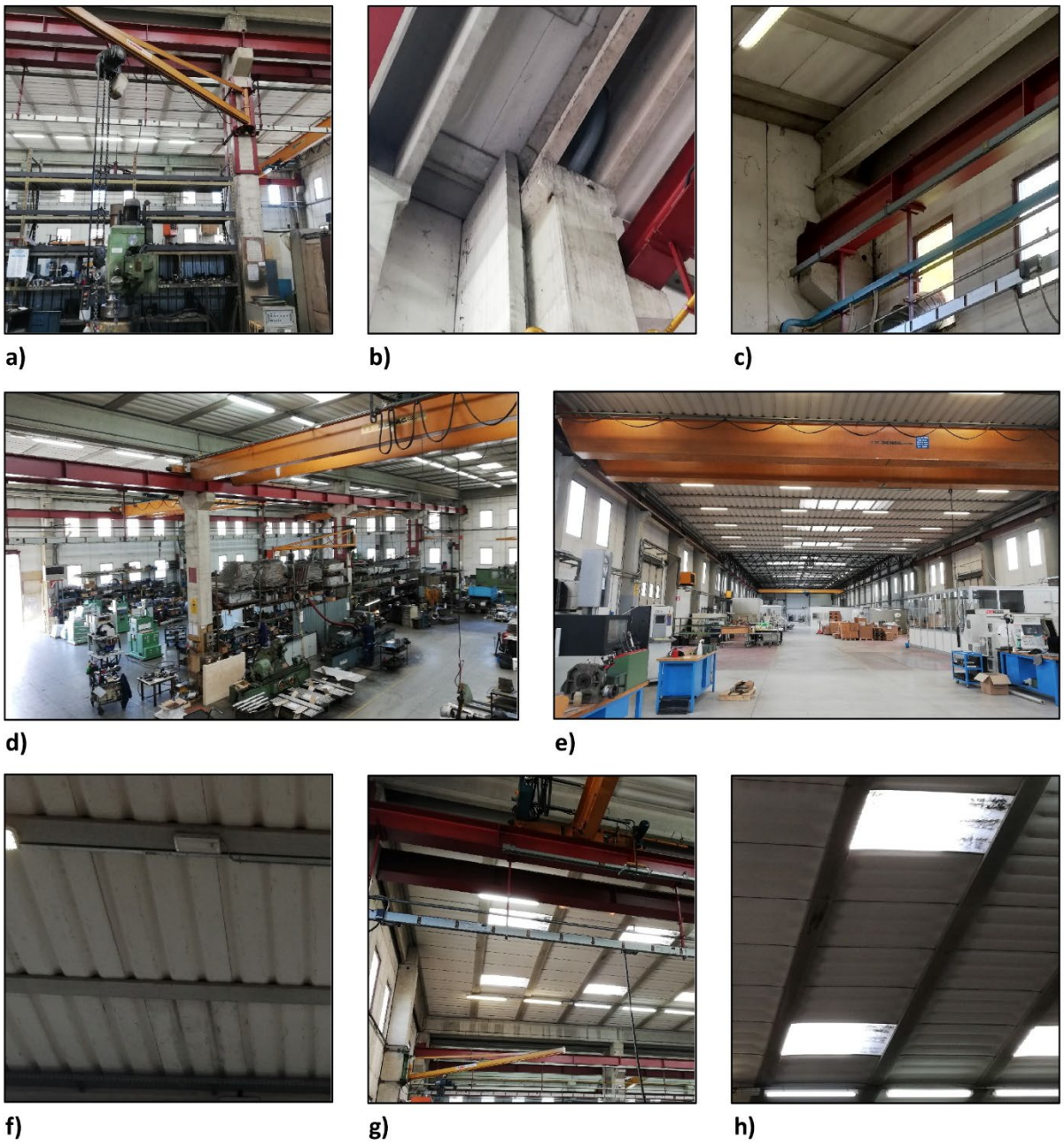


Figure 3.40 Photographical evidence of existing buildings of the P_rc_b variant. Details of the load bearing frames (a) column, b) relation with the central beam and downpipe for rainwater collection, c) relation between roofing beams, side beam and column); internal views of a double nave structure (d) and a single nave building (e); details of roofing completion elements (f, g, h).

3.3.3.5 Variant P_rc_t

The evolution of roofing solutions in industrial buildings has seen a significant transition towards the use of prestressed tiles with alar sections, marking a departure from the previously predominant prefabricated beams. Starting from the 1990s, precast roofing tiles have demonstrated advantages such as the ability to span larger distances, streamline installation processes, offer improved resistance to environmental factors, facilitate integration of skylights, and ameliorate the overall aesthetic and environmental quality of indoor working spaces. As a result, this variant is representative of 17% the total building stock but this value significantly arises considering the 1988-1996 period up to 34% in Casentino and 41% in the structures built after 2007 in Mugello. Multistorey structures have not been detailed in the analysis because of their reduced representativeness.

An evolution of roofing completion elements has been retraced also within this typological variant as illustrated in Figure 3.41. In older facilities, roof pitch was obtained by simply juxtaposing the tiles and covering the gaps with small, vaulted elements, both opaque and translucent to create skylight portions. In more recent structures, the interaxis between tiles tended to enlarge reaching up to 7 meters in structures built after 2007. In addition, emerging skylights with shed configurations and self-supporting metal frames emerged in the last decades and will be hence detailed in a dedicated typological variant. At the same time, both energy and environmental performances of roofing components progressed. At first, modern completion elements are asbestos-free, being realized with fibre cement cupels or sandwich panel components. In addition, tiles featuring integrated insulation layers in the core of the precast elements were developed and gained popularity on the market.

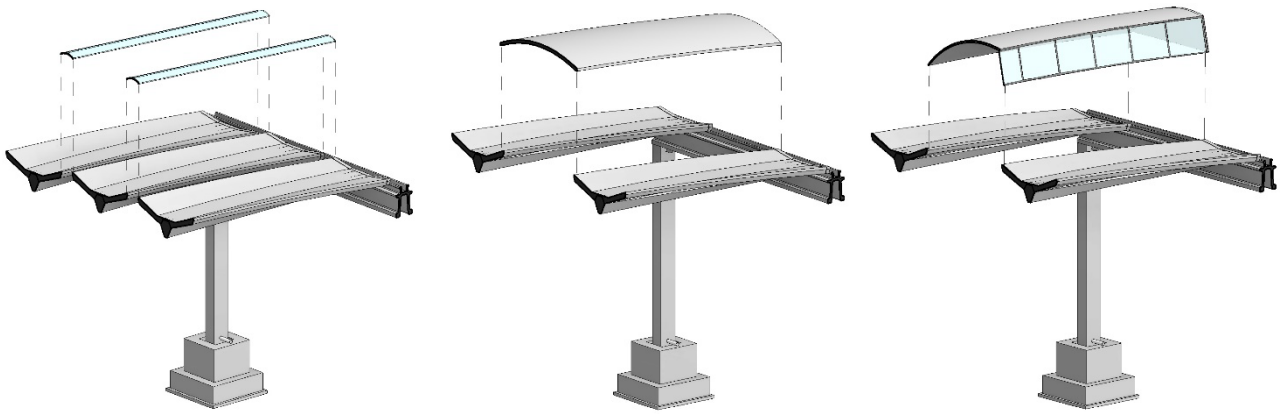


Figure 3.41 Evolution of roofing completion elements in Variant P_rc_t buildings.

Notably, the replacement of beams with prefabricated tiles has not altered the fundamental structural organization, which still relies on longitudinal frames with H-section beams atop pillars with tenon heads as depicted in Figure 3.42. However, the introduction of tiles has enabled coverage of larger spans while reducing installation components due to their wider section that also prevent from installing counter ceiling layers. Considering the average gross area, the number of naves and their dimensions, a trend toward larger buildings can be registered when compared to the ones of the P_rc_b variant.

Perimeter walls consist of vertical panels connected via metal joints to the outer wing of the perimetral beams, ensuring structural integrity and continuity throughout the building envelope.

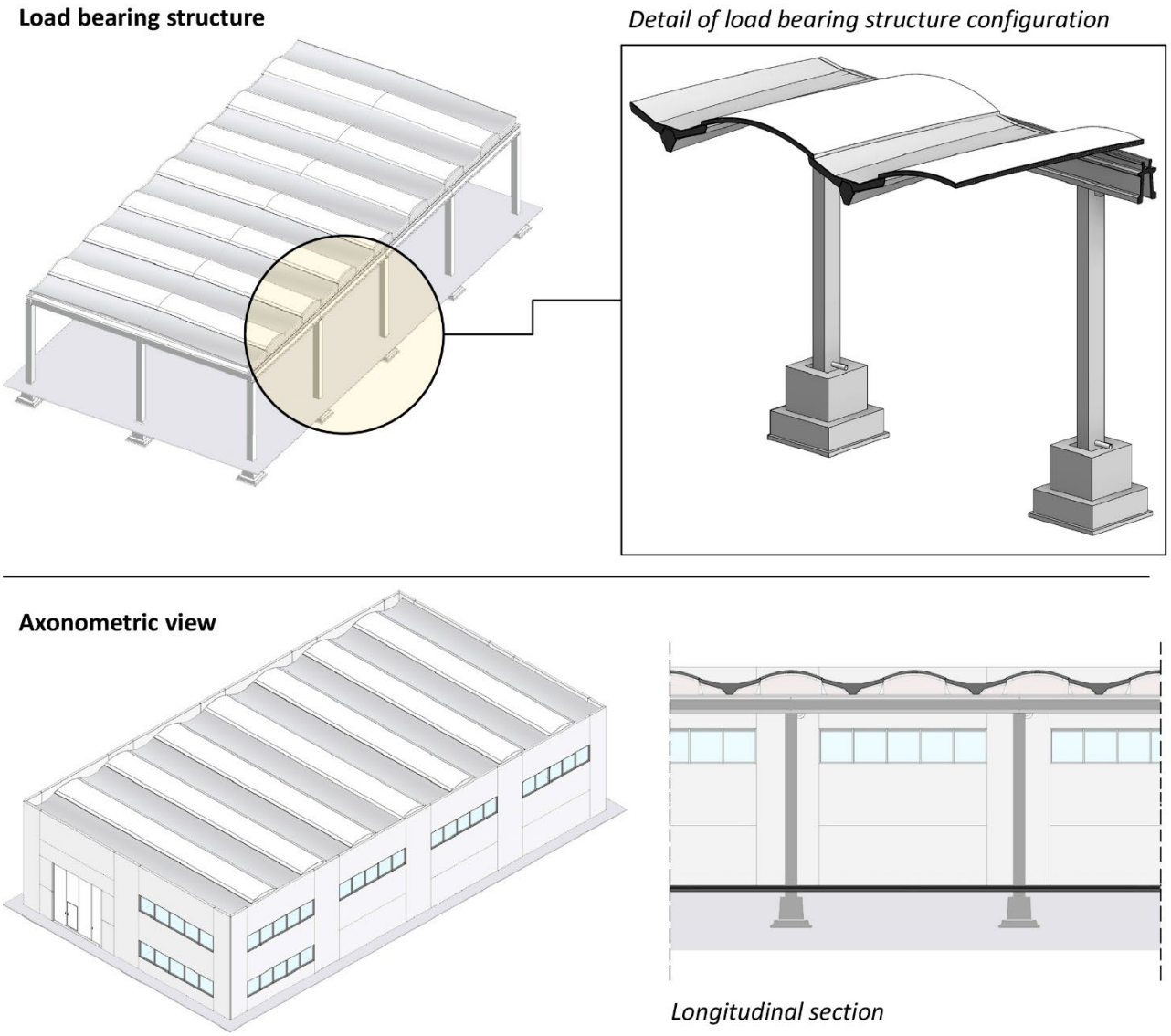


Figure 3.42 Variant P_rc_t: graphical representations of the main distinguishing features.

Figure 3.43 collect images of existing buildings referring to the typological variant described.

Figure 3.43 Photographical evidence of existing buildings of the P_rc_t variant. Aerial views of existing buildings featuring different roofing tiles layout and completion elements (a, b, c); internal views (d, e); details of roofing tiles, completion elements and interaction with the load bearing structure (f, g, h).

3.3.3.6 Variant Sh_rc_t

The typological variation with shed roofs is based on the same structural configuration and the distinguishing factor simply lies in the completion element used for the roofing pitch. A vaulted element is installed inclined using self-supporting metal frames on one side of the tile, which accommodate emerging skylights. Skylights are installed facing north direction to prevent direct solar radiation and mitigate overheating risks while ensuring natural lighting in the workspaces, which are generally single-story to maximize the benefits provided. Moreover, roof openings can improve ventilation and heat management, contributing to more sustainable, energy-efficient buildings. This type of buildings, being a more recent technological solution, features a significant gross covered area due to the use of lightweight tiles capable of covering significant widths, up to 30 m. Notably, examples of similar configurations were also assessed among older facilities, recurring to roofing tiles with different sections and using lower quality openings and windows frames.

In Figure 3.44 the main distinguishing characteristics are illustrated and in Figure 3.45 photographical evidence of real case study buildings are reported.

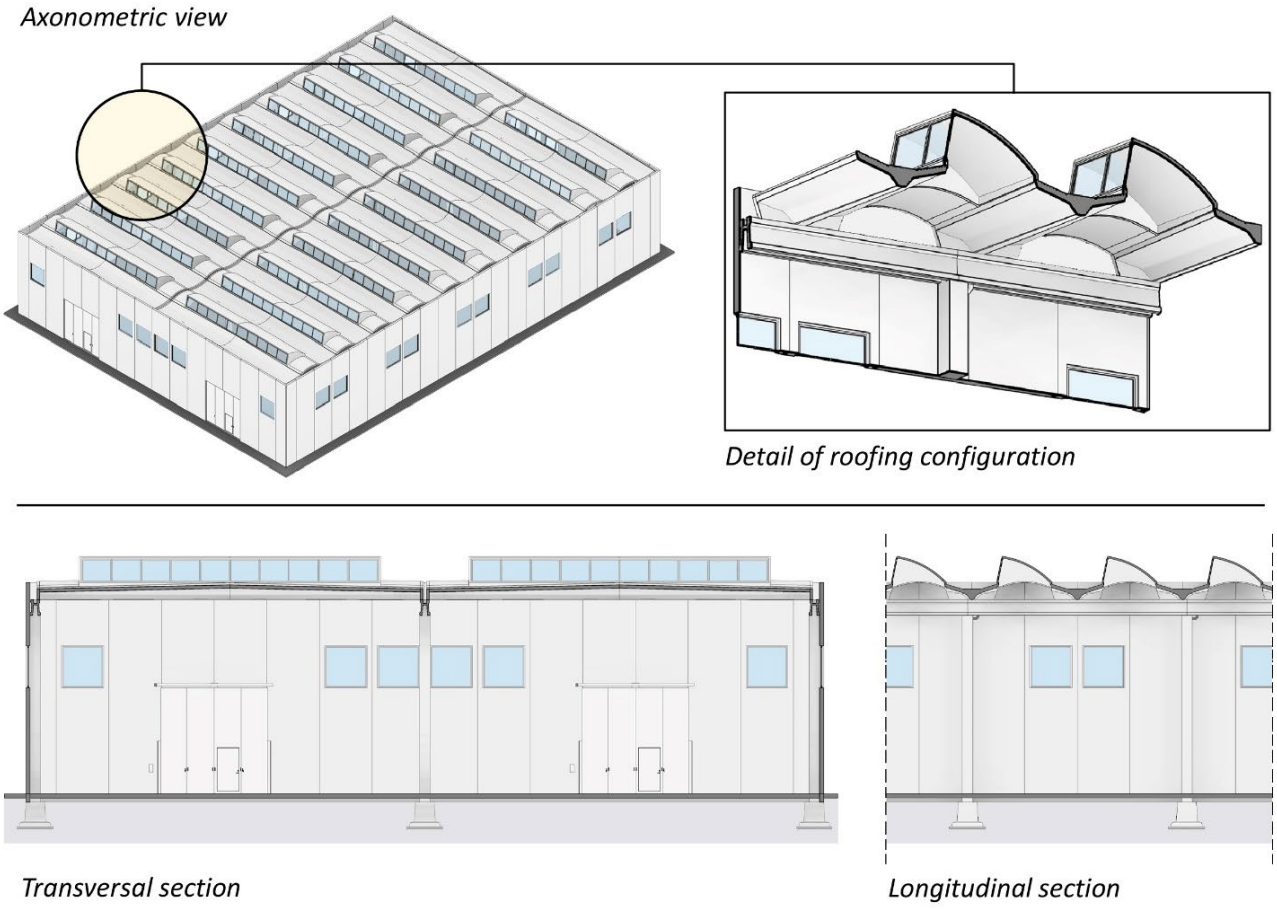


Figure 3.44 Variant Sh_rc_t: graphical representations of the main distinguishing features.

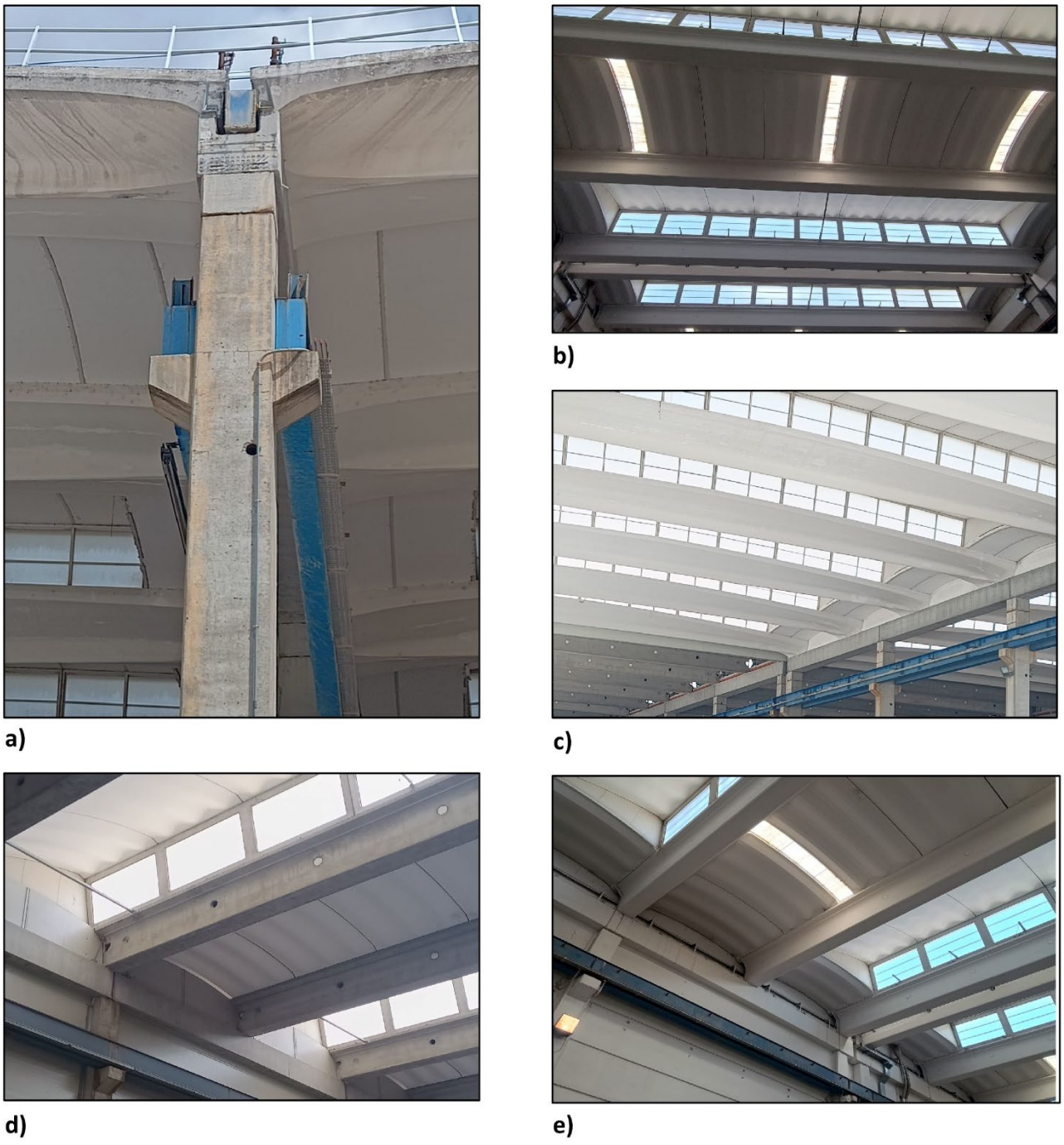


Figure 3.45 Photographical evidence of real existing buildings belonging to the Sh_rc_t variant: details of the load bearing frames (a); internal views (b, c) and details of the roofing completion solutions (d, e).

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ANNEX 3.A.

Casentino typological variants for precast industrial buildings - Statistical data sheets

Variant V_m_a

TYPOLOGICAL VARIANT V_m_a

ROOF	ROOF SHAPE	ROOF MATERIAL
	Vaulted	Steel
STRUCTURAL ELEMENT	Arch beams	

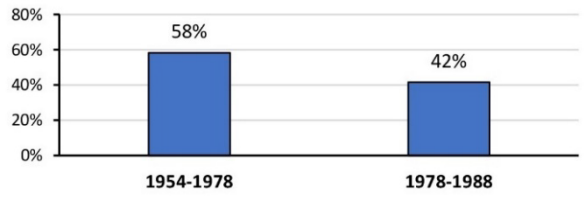
NUMBER OF FLOORS	N. A.	0%	Single Storey	100%	Multistorey	0%

Number of buildings	12	Gross area [m^2]	57'276.52	Volume [m^3]	394'283.19

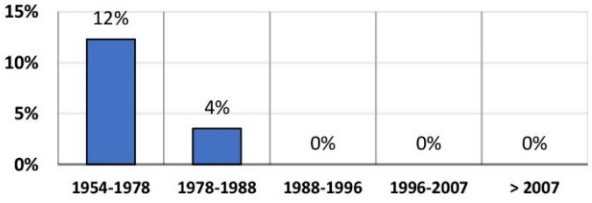
Representative of **3%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

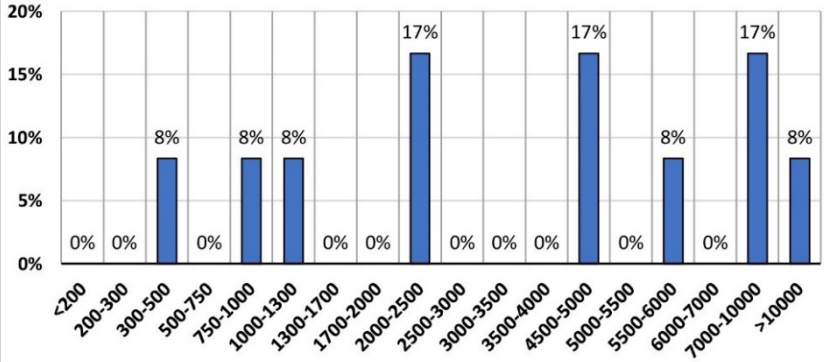


Representativeness in the different periods

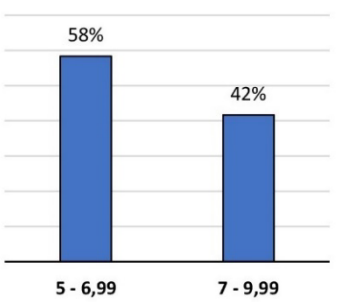


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

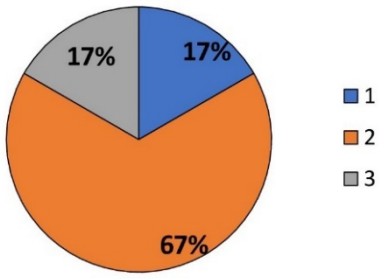
Floor area [m^2]



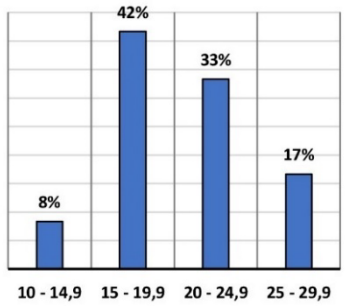
Total building height [m]



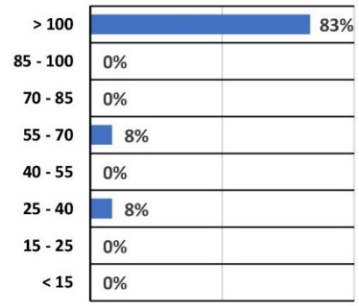
Number of naves



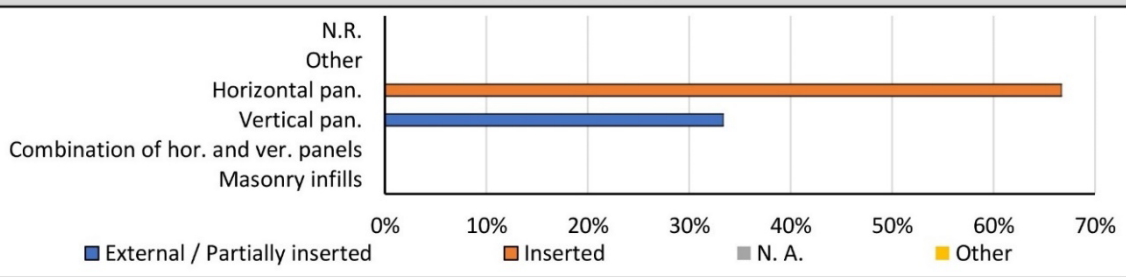
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Variant Sl_m_tr

TYPOLOGICAL VARIANT Sl_m_tr

ROOF	ROOF SHAPE	ROOF MATERIAL
	Sloped Roof	Steel
STRUCTURAL ELEMENT	Truss Beams	

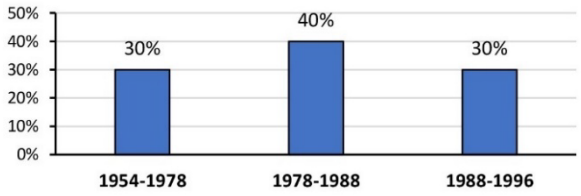
NUMBER OF FLOORS	N. A.	0%	Single Storey	100%	Multistorey	0%

Number of buildings	20	Gross area [m^2]	24'215.75	Volume [m^3]	169'339.09

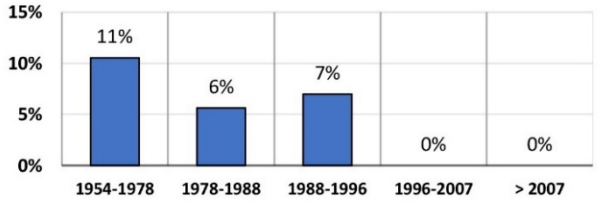
Representative of **5%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

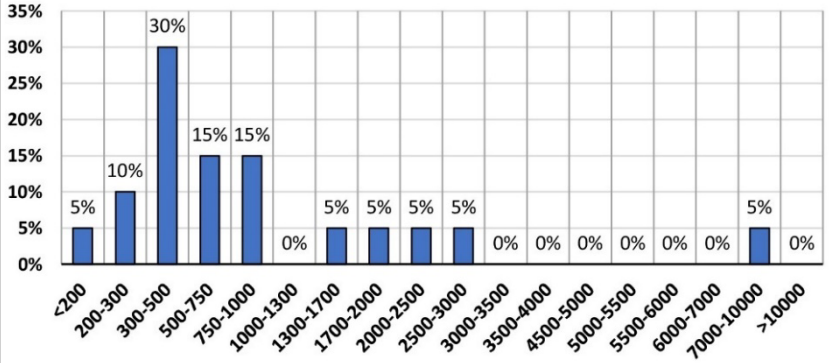


Representativeness in the different periods

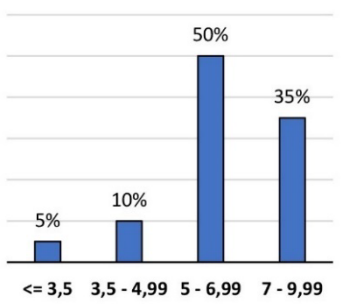


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

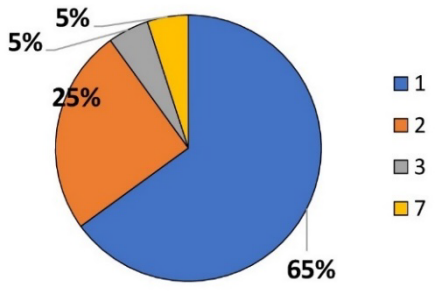
Floor area [m^2]



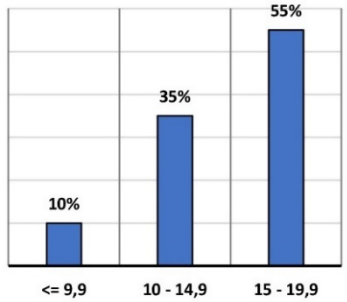
Total building height [m]



Number of naves



Nave width [m]



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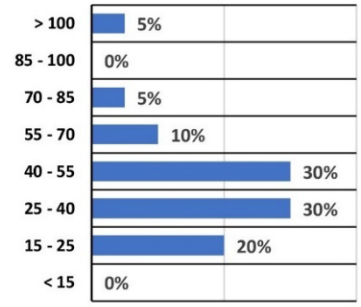
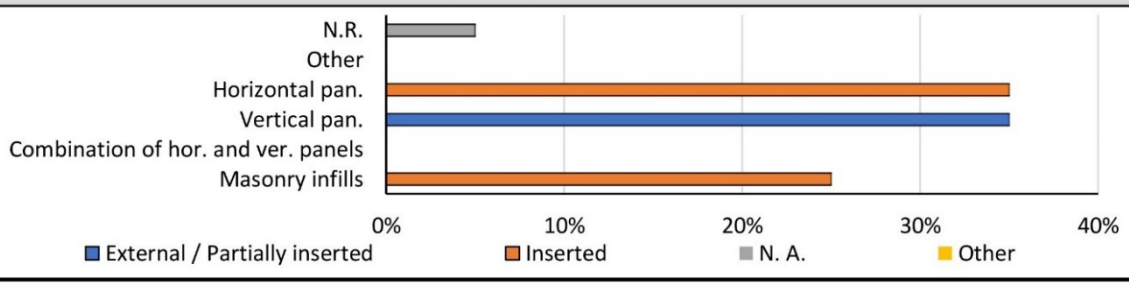


ENVELOPE CHARACTERISTICS



Variant P_rc_b

TYPOLOGICAL VARIANT P_rc_b

ROOF	ROOF SHAPE	ROOF MATERIAL
	Plain	Precast R. C.
STRUCTURAL ELEMENT	**Beams**	

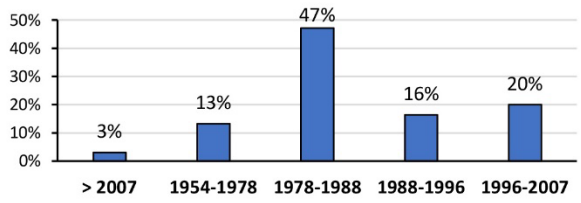
NUMBER OF FLOORS	N. A.	2%	Single Storey	78%	Multistorey	20%

Number of buildings	195	Gross area [m²]	178'211.49	Volume [m³]	1'191'336.41

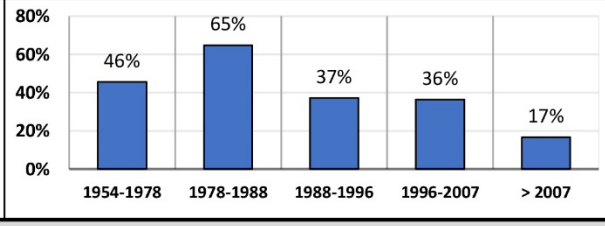
Representative of **46%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

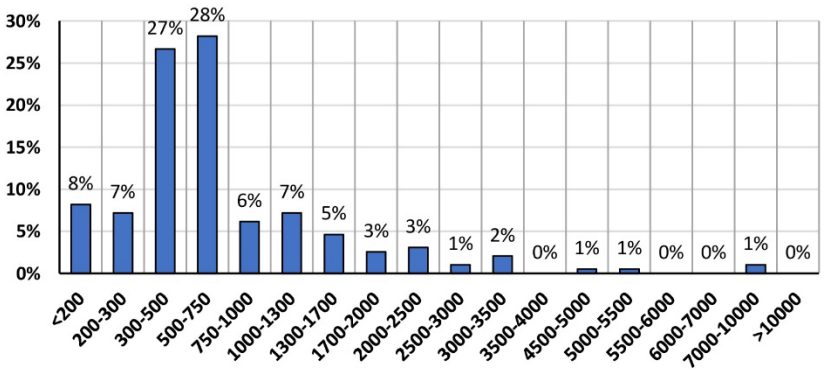


Representativeness in the different periods



DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

Floor area [m²]



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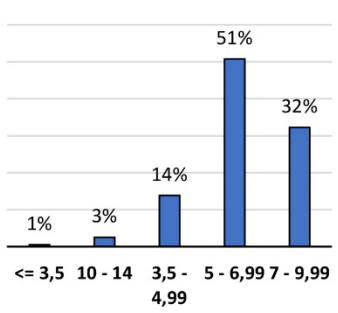
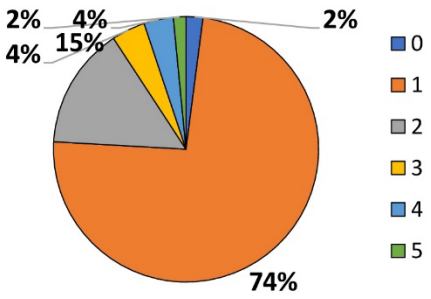
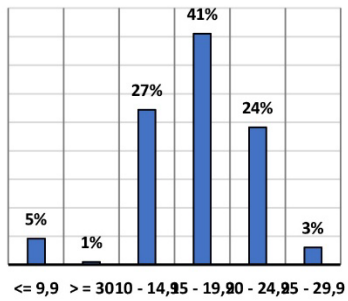


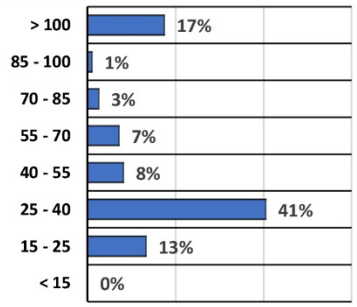
Number of naves



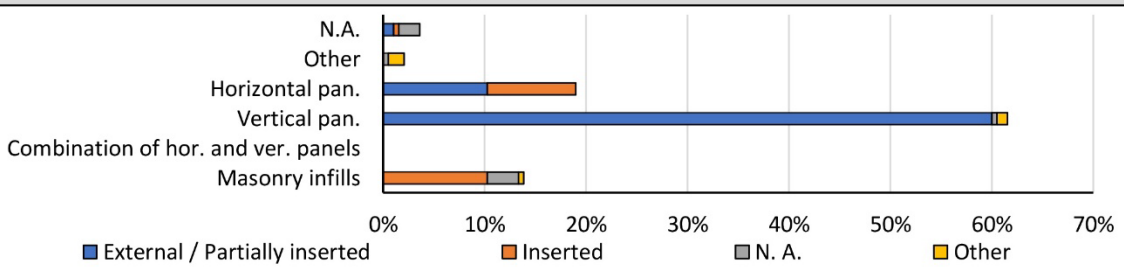
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Subvariant P_rc_b_s

TYPOLOGICAL VARIANT P_rc_b_s

ROOF	ROOF SHAPE	ROOF MATERIAL
	Plain	Precast R. C.
STRUCTURAL ELEMENT	**Beams**	

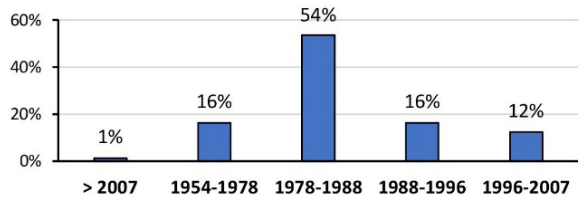
NUMBER OF FLOORS	N. A.	2%	Single Storey	78%	Multistorey	20%

Number of buildings	153	Gross area [m^2]	149'136.71	Volume [m^3]	951'075.00

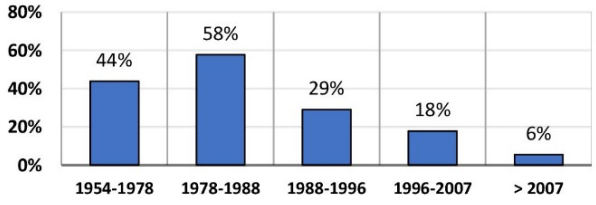
Representative of **36%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

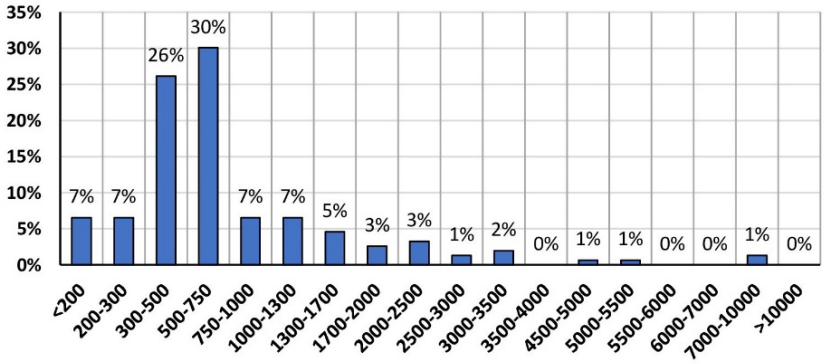


Representativeness in the different periods

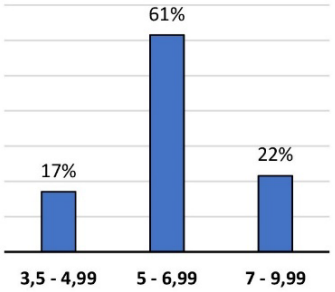


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

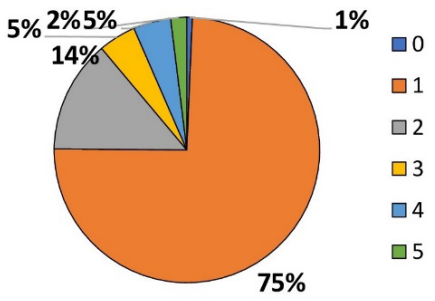
Floor area [m^2]



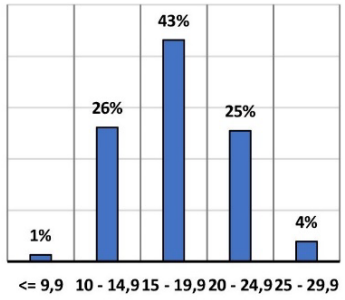
Total building height [m]



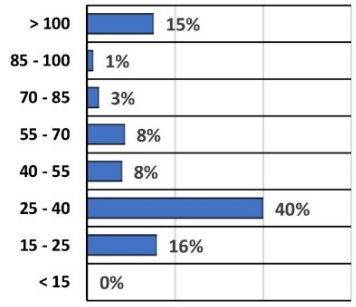
Number of naves



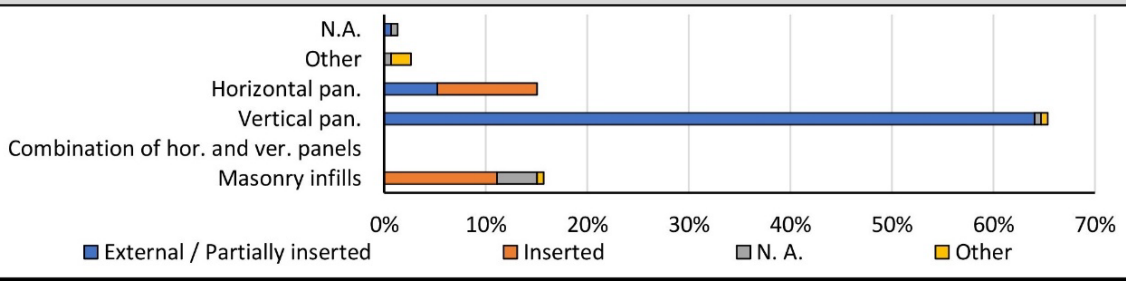
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Subvariant P_rc_b_m

TYPOLOGICAL VARIANT P_rc_b_m

ROOF	ROOF SHAPE	ROOF MATERIAL
	Plain	Precast R. C.
STRUCTURAL ELEMENT	**Beams**	

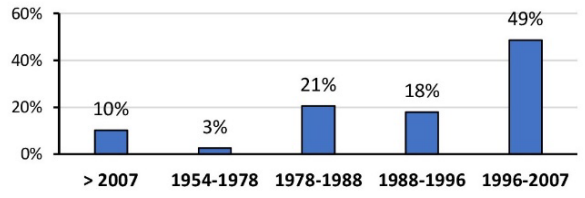
NUMBER OF FLOORS	N. A.	2%	Single Storey	78%	Multistorey	20%

Number of buildings	39	Gross area [m^2]	28'137.61	Volume [m^3]	233'426.80

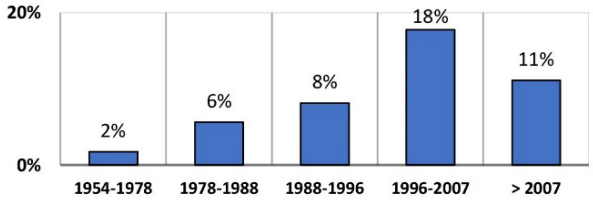
Representative of **9%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

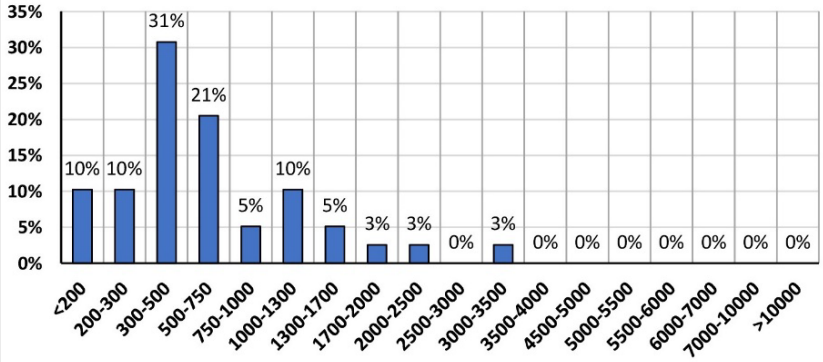


Representativeness in the different periods

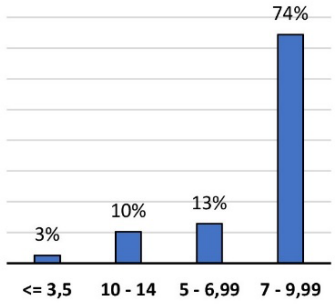


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

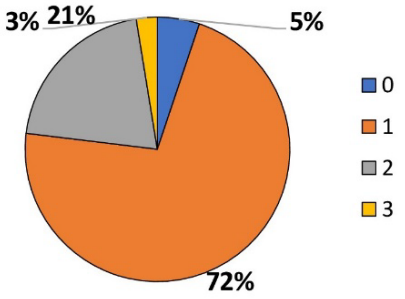
Floor area [m^2]



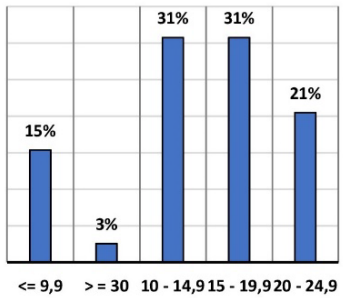
Total building height [m]



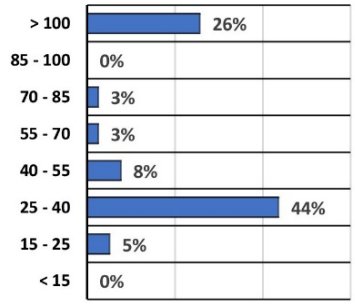
Number of naves



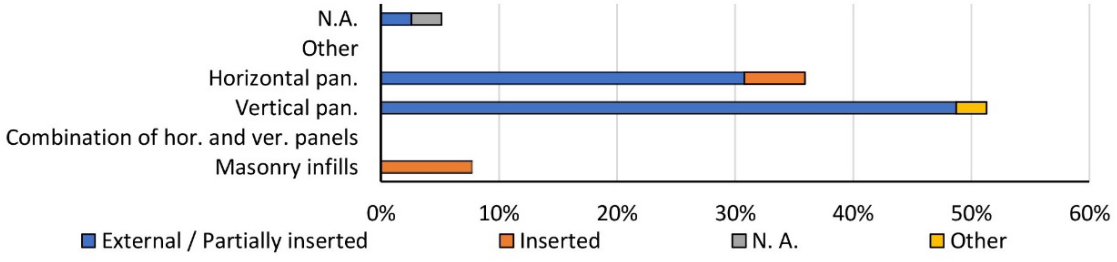
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Variant P_rc_t

TYPOLOGICAL VARIANT P_rc_t

ROOF	ROOF SHAPE	ROOF MATERIAL
	Plain	Precast R. C.
STRUCTURAL ELEMENT	**Wing tiles**	

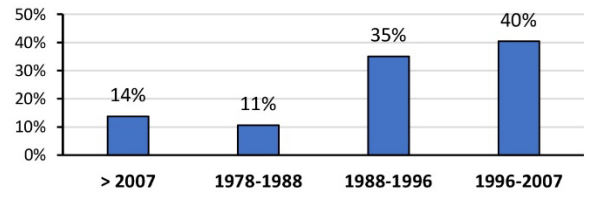
NUMBER OF FLOORS	N. A.	0%	Single Storey	76%	Multistorey	24%

Number of buildings	94	Gross area [m²]	111'342.29	Volume [m³]	768'457.08

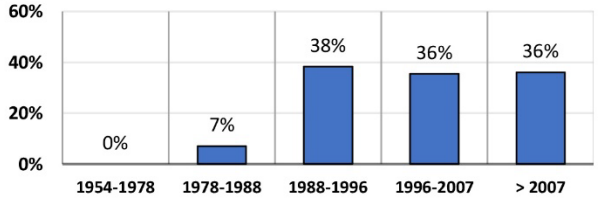
Representative of **22%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

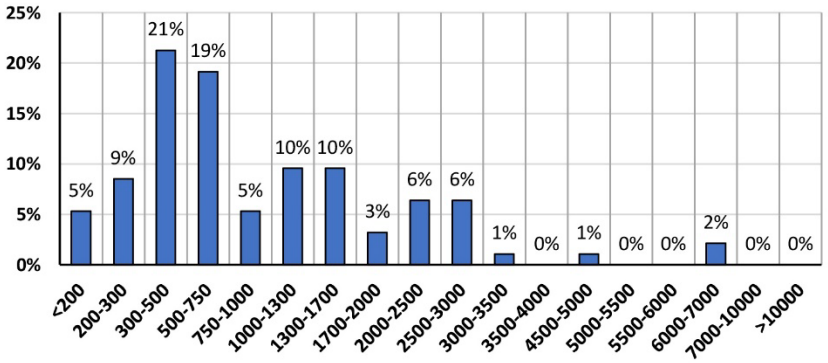


Representativeness in the different periods

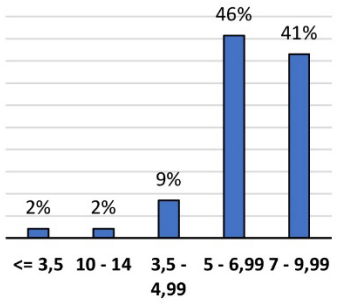


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

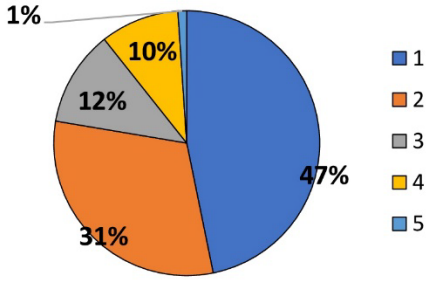
Floor area [m²]



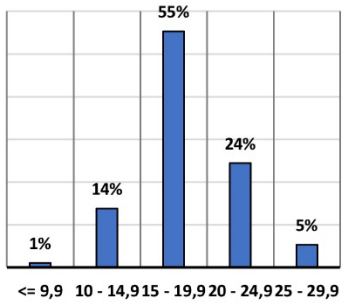
Total building height [m]



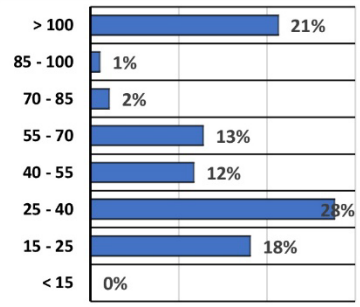
Number of naves



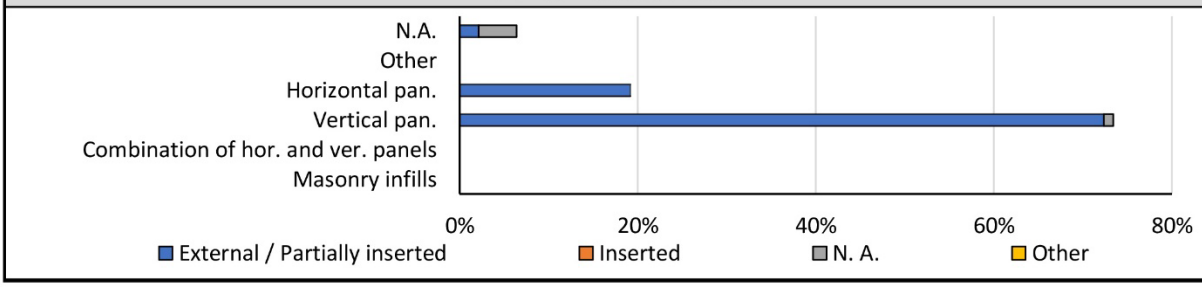
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Variant Sh_rc_t

TYPOLOGICAL VARIANT Sh_rc_t

ROOF	ROOF SHAPE	ROOF MATERIAL
	Shed	Precast R. C.
STRUCTURAL ELEMENT	**Wing tiles**	

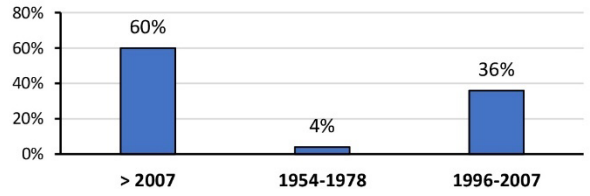
NUMBER OF FLOORS	N. A.	0%	Single Storey	84%	Multistorey	16%

Number of buildings	25	Gross area [m²]	70'666.00	Volume [m³]	496'615.95

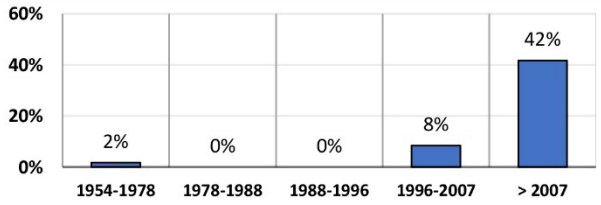
Representative of **6%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

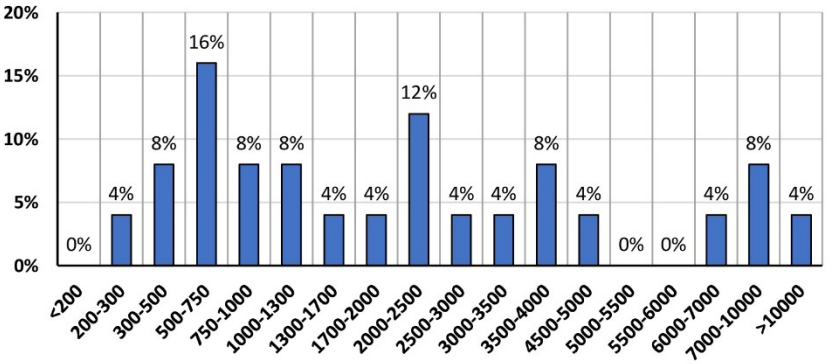


Representativeness in the different periods

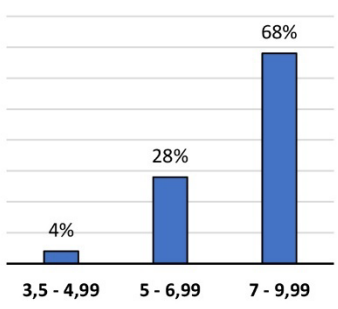


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

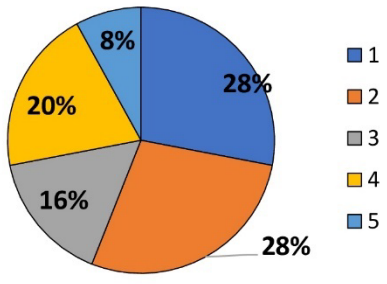
Floor area [m²]



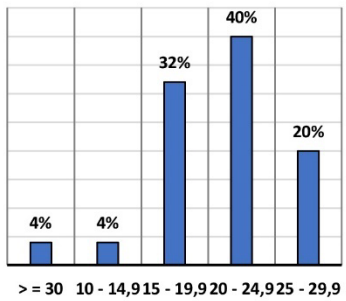
Total building height [m]



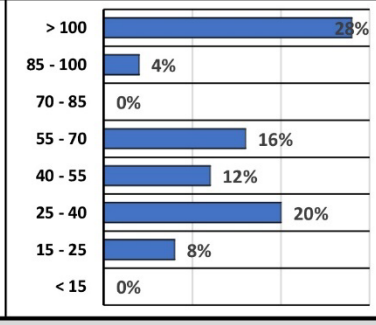
Number of naves



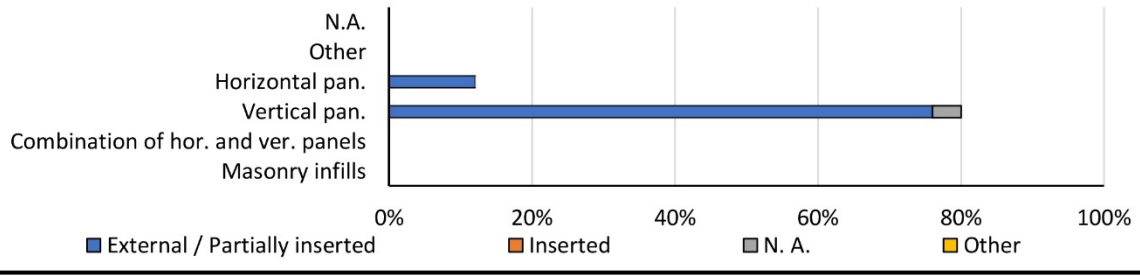
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



ANNEX 3.B.

Typological variants for precast industrial buildings in Mugello- Statistical data sheets

Variant Sl_rc_slb

TYPOLOGICAL VARIANT Sl_rc_slb

ROOF	ROOF SHAPE	ROOF MATERIAL
	Sloped Roof	Precast R. C.
STRUCTURAL ELEMENT	Sloped beams	

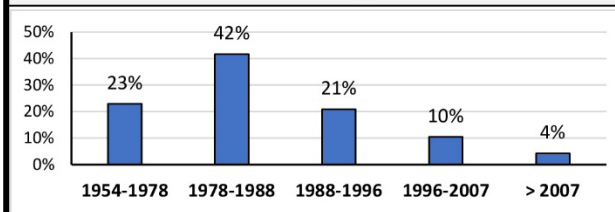
NUMBER OF FLOORS	N.r.	8%	Single storey	81%	Multistorey	10%

Number of buildings	48	Gross area [m²]	58'559.11	Volume [m³]	429'042.72

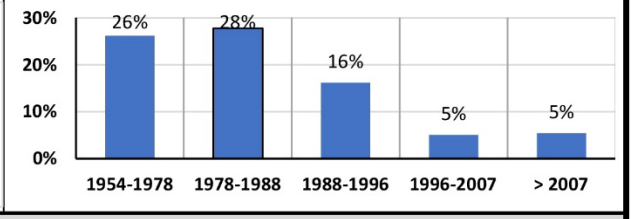
Representative of **15%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

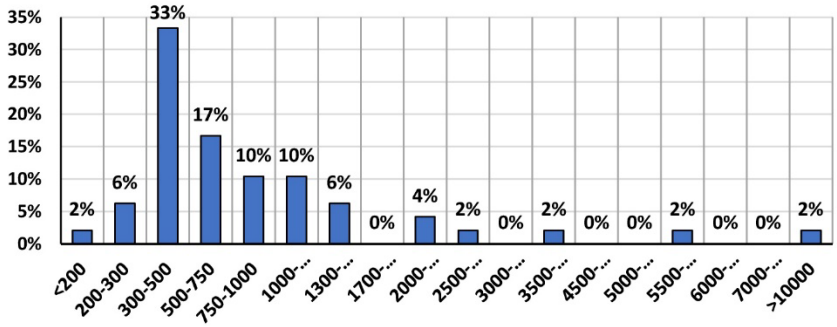


Representativeness in the different periods

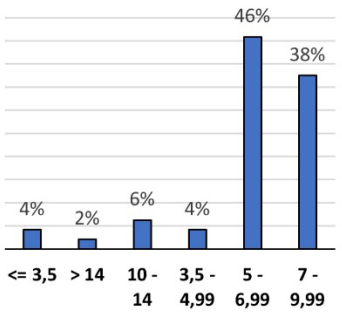


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

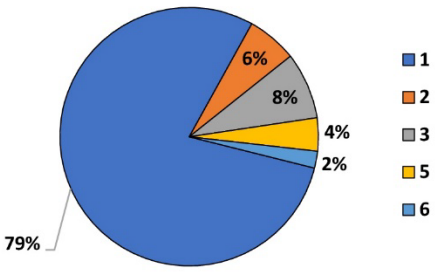
Floor area [m²]



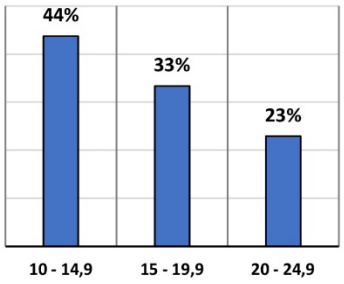
Total building height [m]



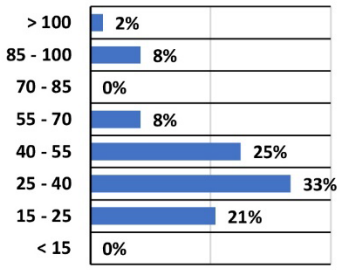
Number of naves



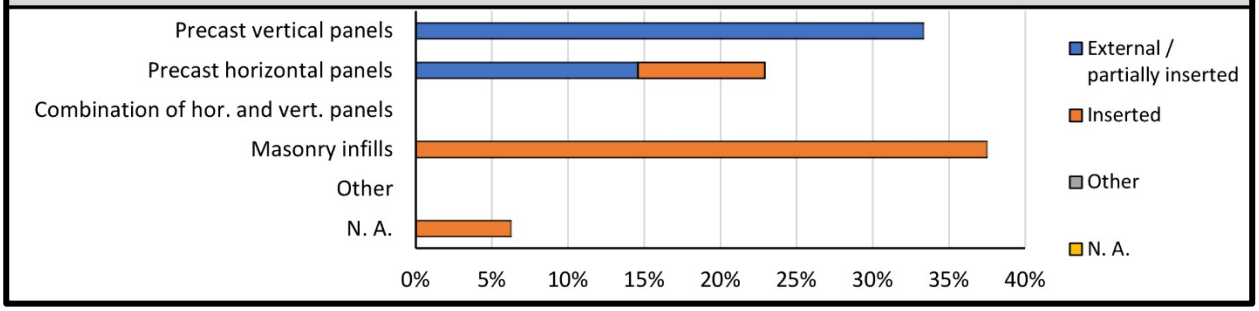
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Variant Sl_m_tr

TYPOLOGICAL VARIANT Sl_m_tr

ROOF	ROOF SHAPE	ROOF MATERIAL
	Sloped Roof	Steel
STRUCTURAL ELEMENT	Truss Beams	

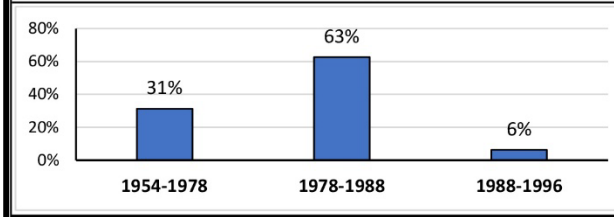
NUMBER OF FLOORS	N.r.	0%	Single storey	100%	Multistorey	0%

Number of buildings	16	Gross area [m²]	21'706.00	Volume [m³]	116'495.69

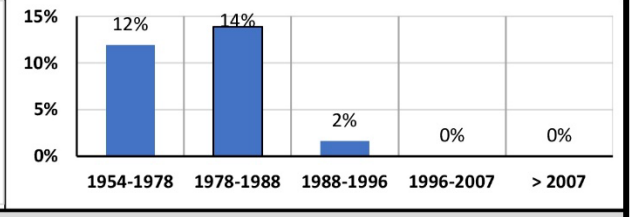
Representative of **5%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

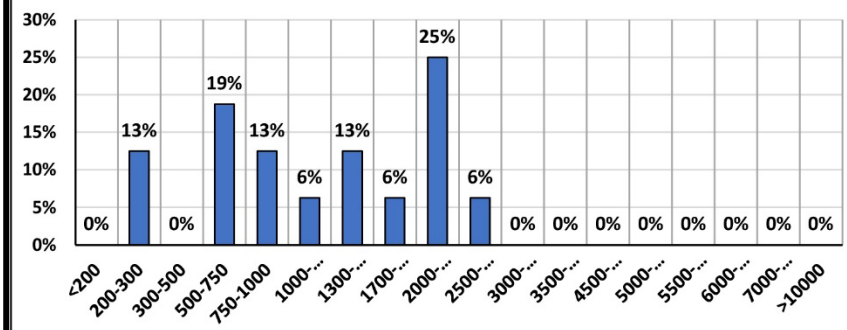


Representativeness in the different periods

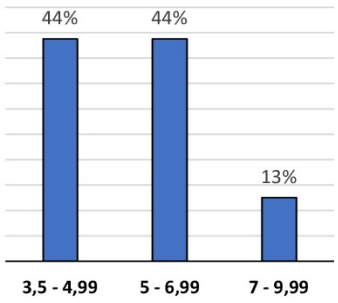


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

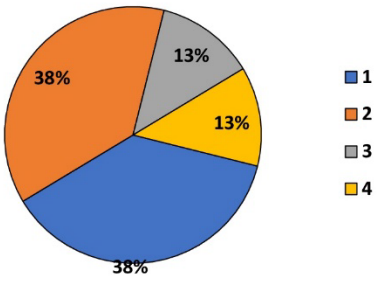
Floor area [m²]



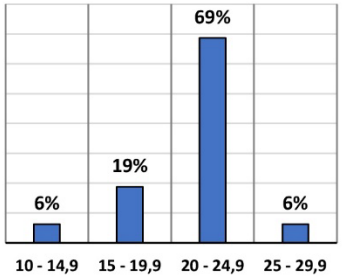
Total building height [m]



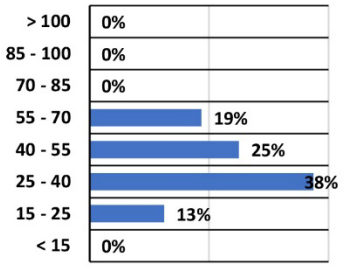
Number of naves



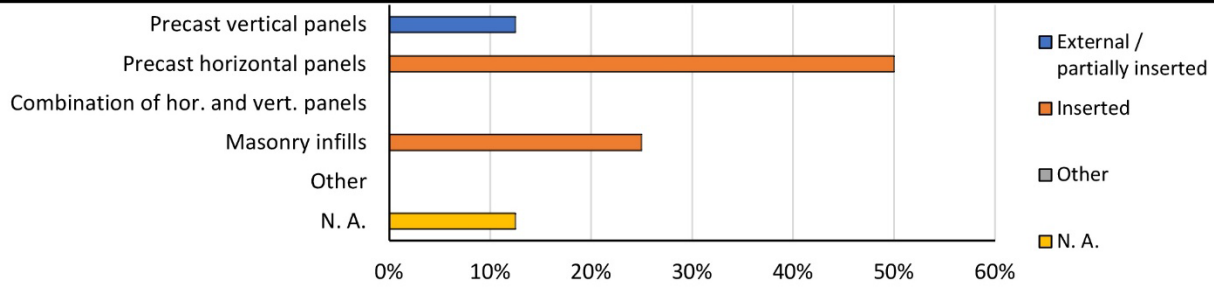
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Variant P_rc_b

TYPOLOGICAL VARIANT P_rc_b

ROOF	ROOF SHAPE	ROOF MATERIAL
	Plain	Precast R. C.
STRUCTURAL ELEMENT	Beams	

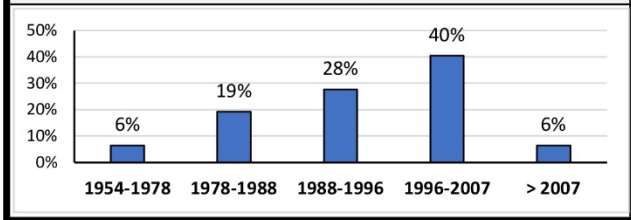
NUMBER OF FLOORS	N.r.	6%	Single storey	65%	Multistorey	29%

Number of buildings	141	Gross area [m²]	185'003.20	Volume [m³]	1'389'208.28

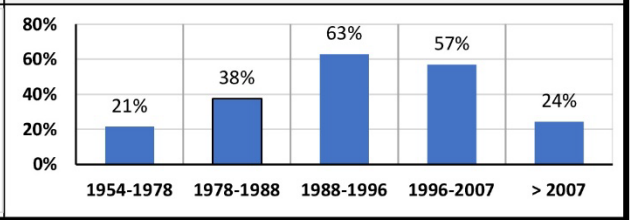
Representative of **45%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

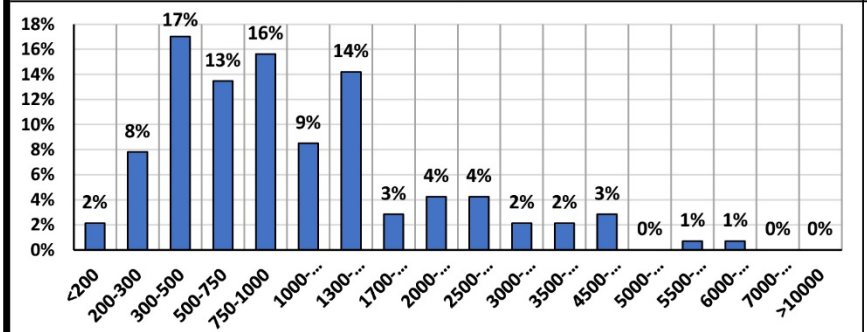


Representativeness in the different periods

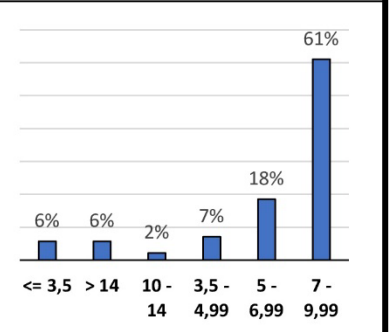


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

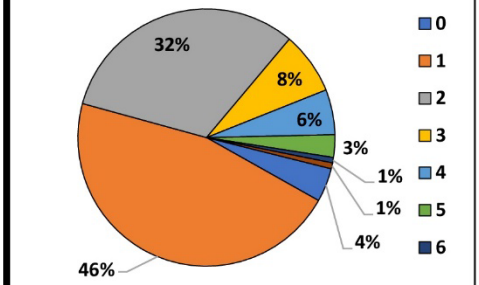
Floor area [m²]



Total building height [m]



Number of naves



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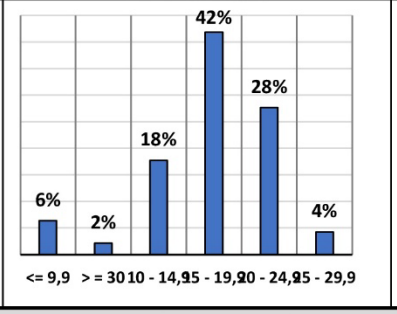

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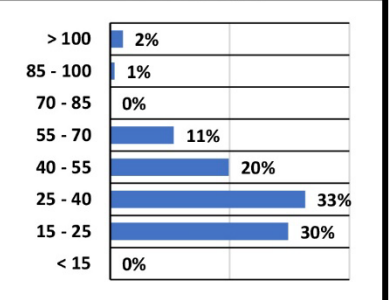
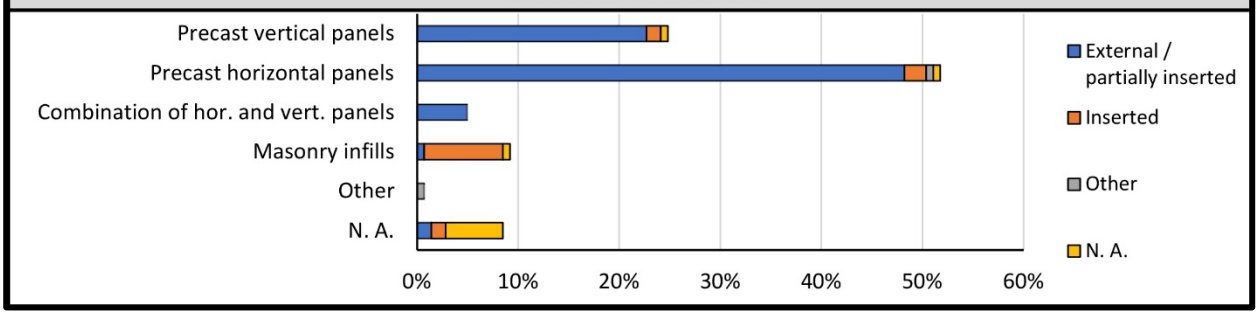


ENVELOPE CHARACTERISTICS



Subvariant P_rc_b_s

TYPOLOGICAL VARIANT P_rc_b_s

ROOF	ROOF SHAPE	ROOF MATERIAL
	Plain	Precast R. C.
STRUCTURAL ELEMENT	Beams	

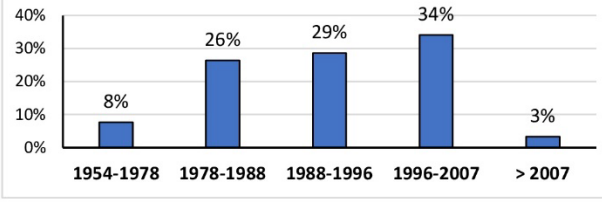
NUMBER OF FLOORS	N.r.	6%	Single storey	65%	Multistorey	29%

Number of buildings	91	Gross area [m²]	102'345.26	Volume [m³]	752'261.14

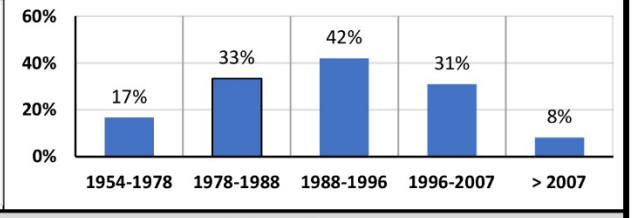
Representative of **29%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

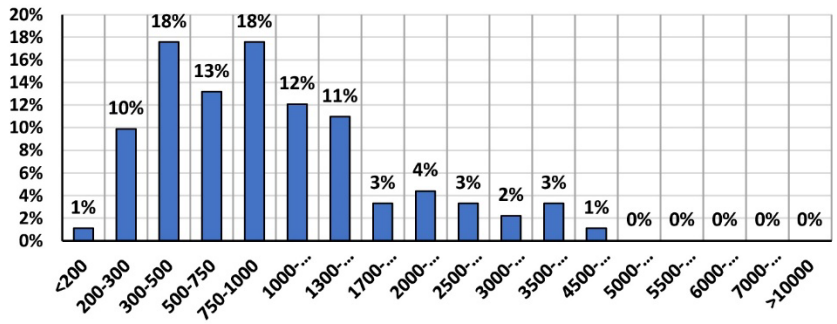


Representativeness in the different periods

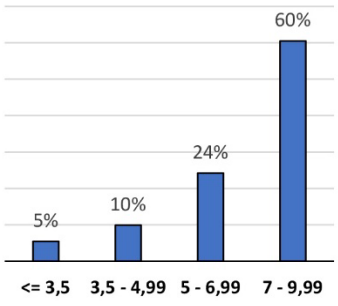


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

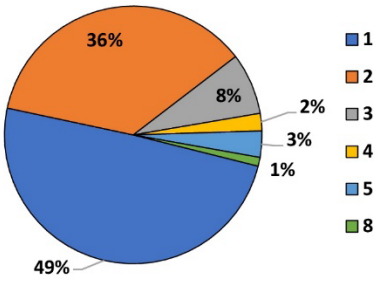
Floor area [m²]



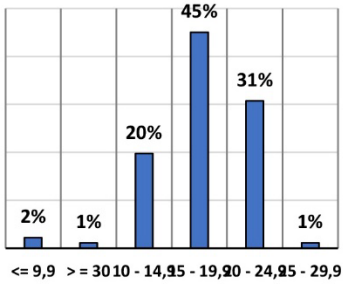
Total building height [m]



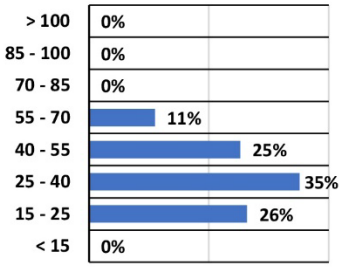
Number of naves



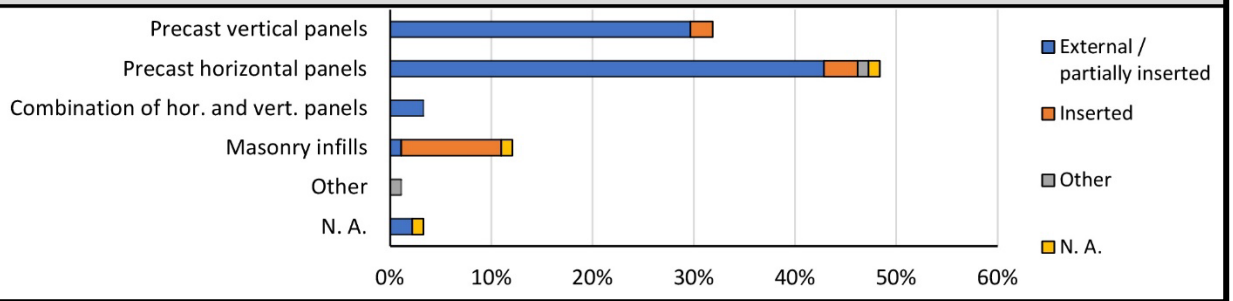
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Subvariant P_rc_b_m

TYPOLOGICAL VARIANT P_rc_b_m

ROOF	ROOF SHAPE	ROOF MATERIAL
	Plain	Precast R. C.
STRUCTURAL ELEMENT	Beams	

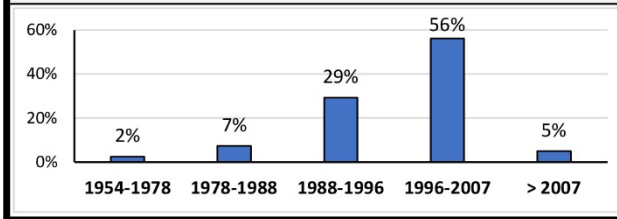
NUMBER OF FLOORS	N.r.	6%	Single storey	65%	Multistorey	29%

Number of buildings	41	Gross area [m²]	67'748.22	Volume [m³]	534'317.39

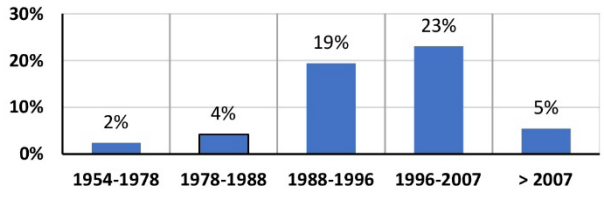
Representative of **13%** *of buildings*

DIFUSSION AND DISTRIBUTION OVER TIME

Distribution of buildings over time

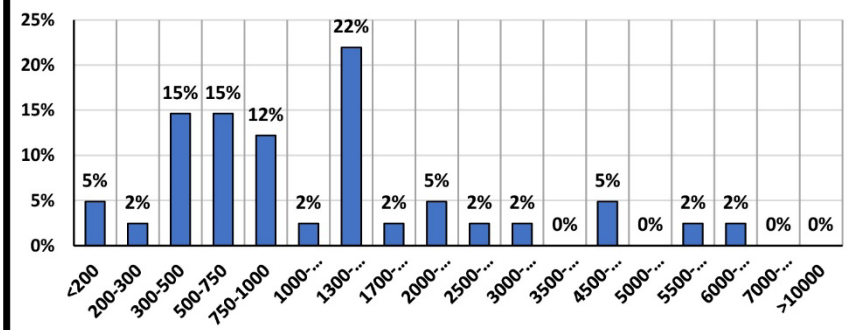


Representativeness in the different periods

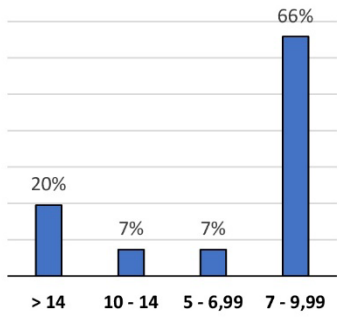


DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution

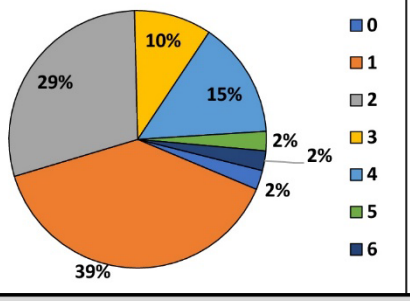
Floor area [m²]



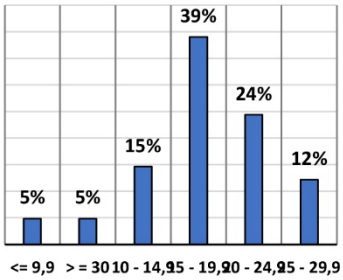
Total building height [m]



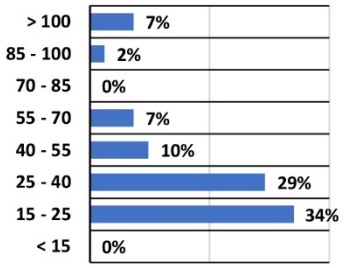
Number of naves



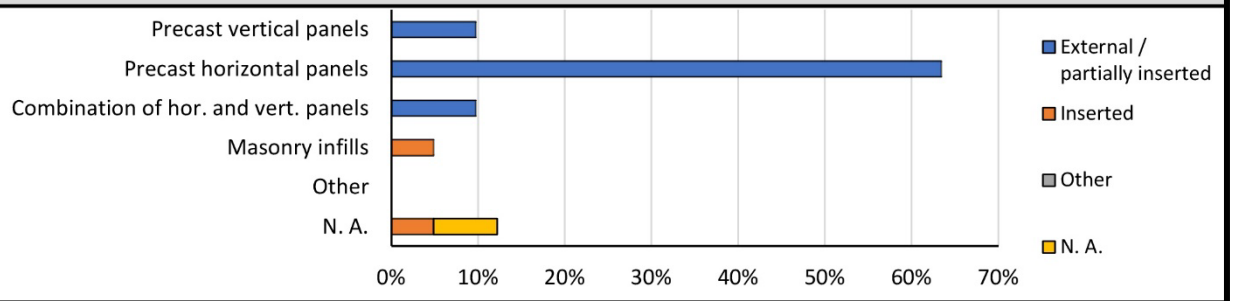
Nave width [m]



Nave lenght [m]



ENVELOPE CHARACTERISTICS



Variant P_rc_t

TYPOLOGICAL VARIANT P_rc_t

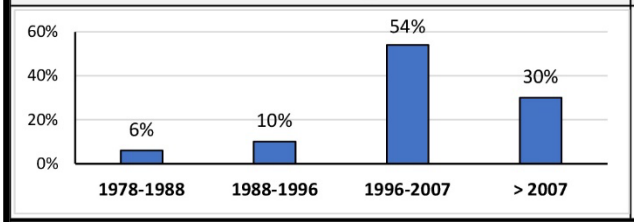
ROOF	ROOF SHAPE	ROOF MATERIAL
	Plain	Precast R. C.
STRUCTURAL ELEMENT	Wing tiles	

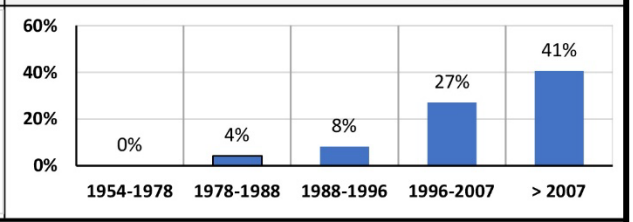
NUMBER OF FLOORS	N.r.	2%	Single storey	68%	Multistorey	30%

Number of buildings	50	Gross area [m²]	58'960.08	Volume [m³]	491'204.37

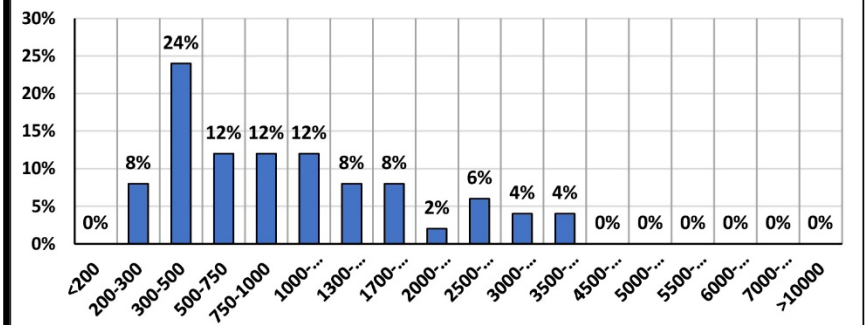
Representative of **16%** *of buildings*

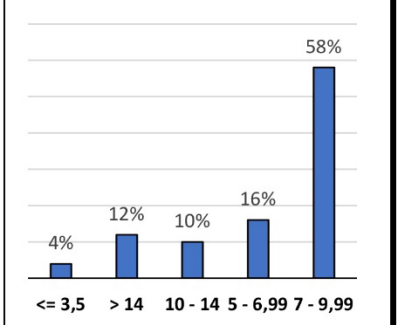
DIFUSSION AND DISTRIBUTION OVER TIME

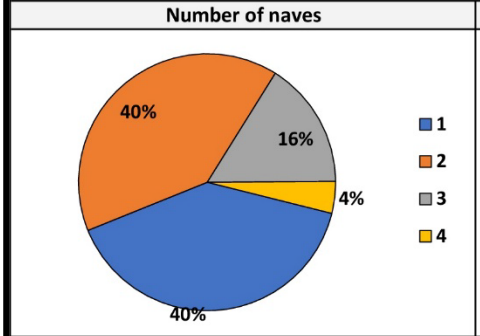


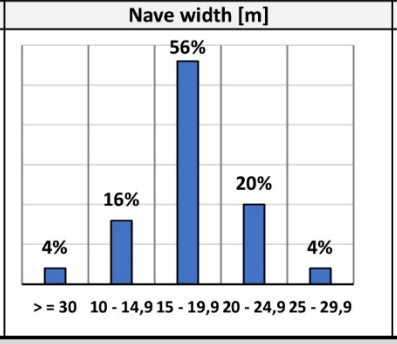


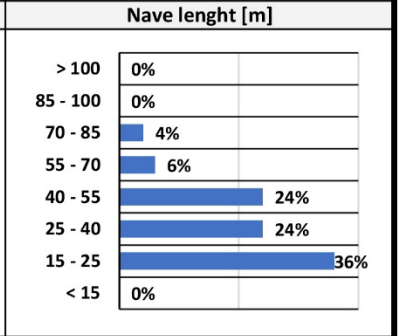
DIMENSIONAL DATA AND STRUCTURAL ORGANIZATION - statistical distribution



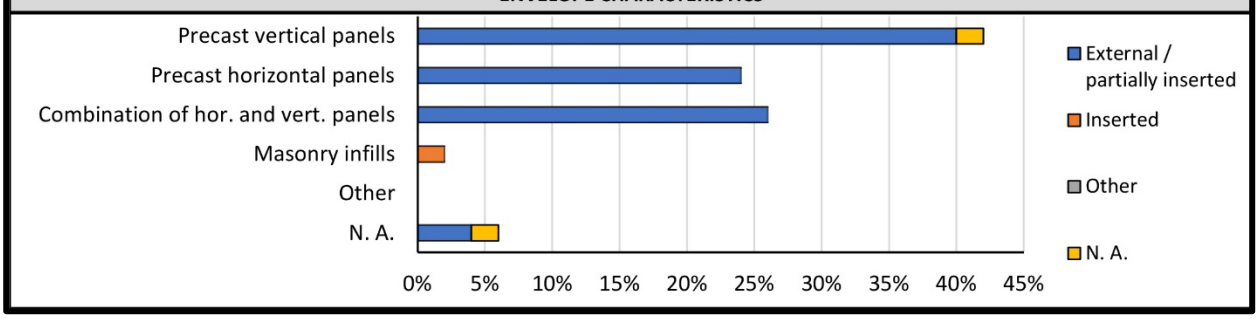




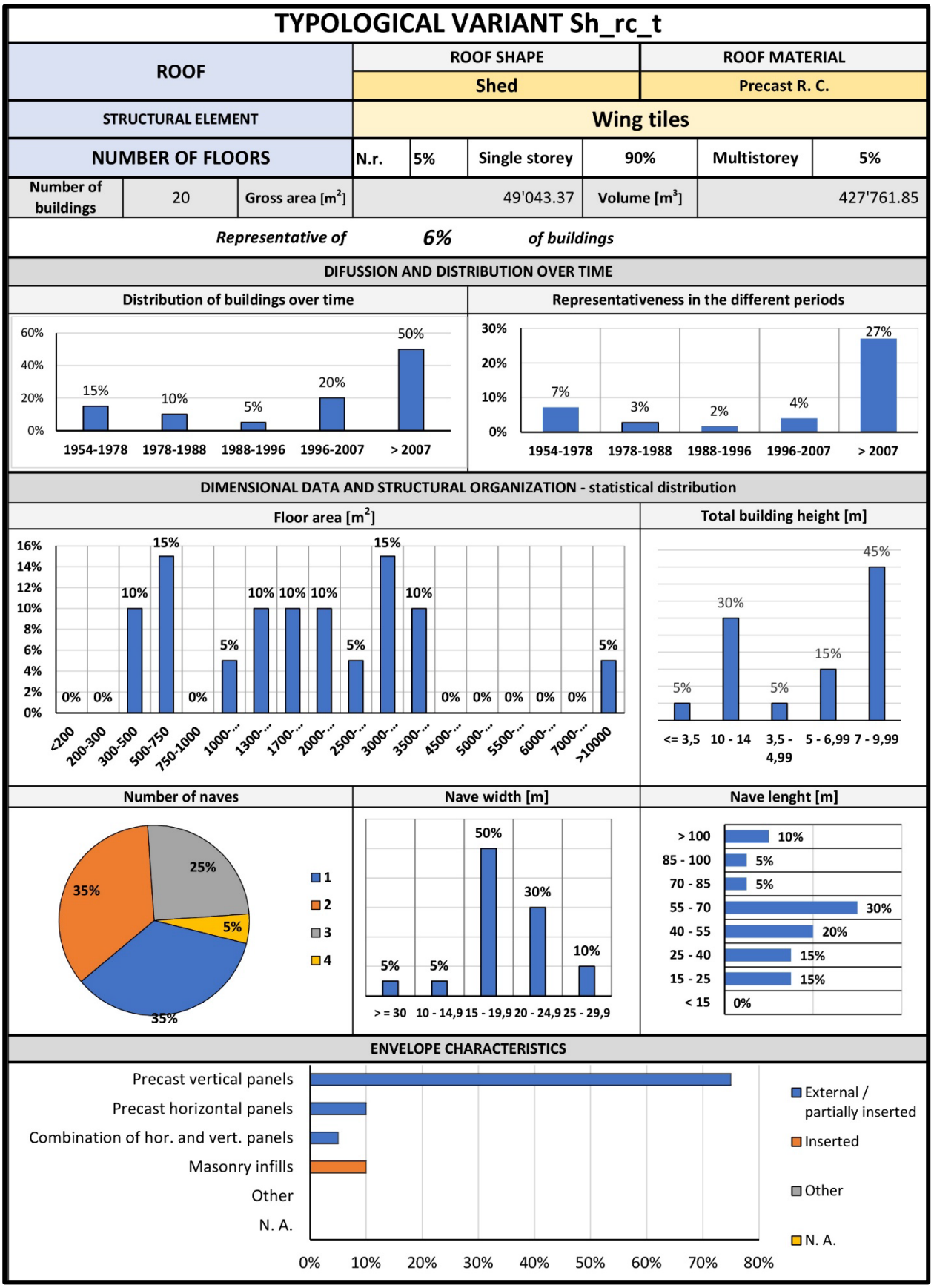




ENVELOPE CHARACTERISTICS



Variant Sh_rc_t



4 ISSUES AND CRITICALITIES

In this chapter, the main critical issues affecting industrial buildings are introduced. The insights presented are derived from the comprehensive survey of the existing structures introduced in section *3. Territorial building stock analysis*.

As previously introduced, the current existing industrial building stock of Tuscany region has been investigated through both digital and on-field recognitions. On-site inspections enabled a thorough evaluation of the conditions of structural elements, vertical closures, roofing elements, and the mechanical systems of the buildings. These allowed to assess decay phenomena of building components or bad maintenance conditions.

Furthermore, on-site visits allowed to establish direct interactions with the companies operating in the buildings. This offered valuable insights into usage conditions, system installations, and any issues or discomfort experienced. Some of the companies interviewed also provided data on monthly energy consumption, crucial to evaluate energy intensive facilities as the industrial ones and to validate in energy models in a subsequent phase of the research.

In addition to the on-site inspections, an extensive review of documentary material was conducted. This review encompassed a wide array of resources, including design documents from municipal technical offices, documents from the State Archives and from the Genio Civile office. These sources provided a wealth of original project information on building materials, construction techniques, structural integrity, and technical-executive details that were indispensable for a deeper understanding of the crucial aspects impacting building performance. These documentary sources complemented the on-site inspections by providing a comprehensive background on the design, construction, and operational history of the buildings.

The in-depth analysis carried out following this approach allowed for a detailed assessment of the condition and performance of the existing industrial buildings, with particular interest towards the precast concrete structures building stock. At this regard it must be specified that the analysis has been extended to comprehend not only exclusively building related aspects but also the ones connected to peculiarities of the industrial districts, as it will be later discussed.

Globally, 4 main topics were identified to categorize the issues assessed, providing a thematic breakdown that allows for a systematic and comprehensive examination of the condition of the industrial building stock in the region and potential solutions for improving its overall performance.

The organization of the chapter reflects the approach adopted in the research and will be hence articulated into 4 distinct sections:

- 41. District-scale and urban layout related issues
- 4.2 External walls and vertical closures
- 4.3 Roofing, structures and completion elements
- 4.4 Mechanical system installations for air conditioning, lighting and energy from renewables.
- 4.5 References

Notably, some of the issues identified are shared and common across multiple typological variants, particularly those related to external walls and building systems. This indicates that there are structural and functional problems that go beyond the specificities of different configurations and can be addressed proposing standardized solutions or uniform approaches for their maintenance and improvement.

Conversely, the scenario for the technological solutions for roofing is more complex. The various typological variants found in different contexts lead to a greater variety of approaches and technologies used. This necessitated a detailed and targeted analysis that considers the peculiarities of the alternatives assessed to produce intervention proposals suitable for the unique characteristics.

4.1 District-scale and urban layout related issues

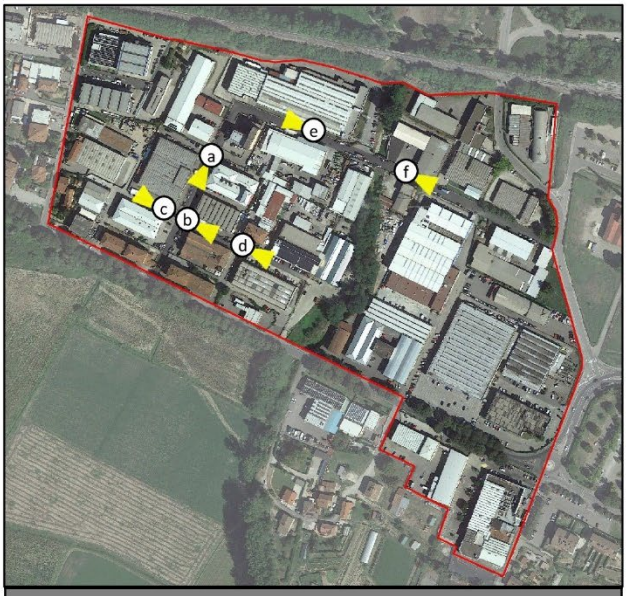
In Italy, industrial buildings are located in specifically intended urban districts, located in peripherical areas outside the urban settlements and close to the main road arteries of communications (e.g. motorways, infrastructural hubs, logistic centres, etc.).

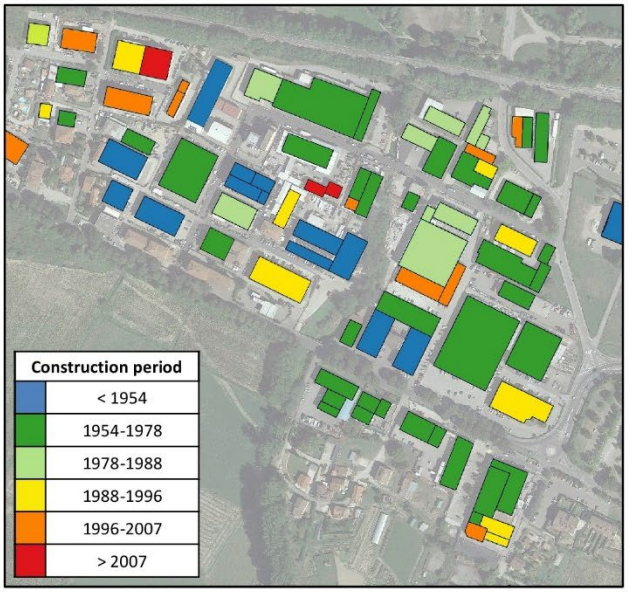
Considering the two areas of Tuscany investigated, this topic was deepened with relation to the Mugello region. In this case, 19 industrial districts were identified and 70% of the manufacturing buildings included in the analysis were assessed to be located in these specific urban clusters. The specifically oriented studies conducted, allowed to derive common features and trends helpful for the definition of the main characteristics of such peculiar urban environments.

In several cases an original nucleus of aged buildings can be recognized with structures generally built before 1978 and subsequent developments over time. The different periods of construction clearly affect the internal layout and configurations of the districts. In the older ones, the absence of clear regulatory plans can be observed resulting in an irregular and dense distribution of buildings leading to a fragmented urban fabric. Consequently, public roads within these districts are often narrow and not designed to accommodate modern vehicles that usually require significant manoeuvring areas for material handling operations. This issue can moreover imply logistical inefficiencies and potential safety hazards, worsened by the lack of open spaces or areas designated for shared functions such as parking and storage.

Conversely, starting from the 1980s, the layout of manufacturing sites in Italy has evolved to feature a more regular and well-defined geometry. Building lots, typically rectangular in shape, are arranged with the shorter side facing the main road, making them easily identifiable and accessible and with areas for loading and unloading raw materials and finished products are separated from public pathways, enhancing safety and efficiency. The main façade of the facilities is generally oriented toward the main road hosting the administrative and representation headquarters, often organized on a two-level distribution. The wider road sections and the reduced urban density also allowed to accommodate spaces for public parking and green areas, even if the latter are still not sufficient in many cases.

In Figure 4.1 and Figure 4.2 two different industrial districts, in Borgo San Lorenzo and Barberino di Mugello respectively, are presented as exemplary sites using thematic maps, quantitative data derived from GIS elaboration and photographic material acquired during on-site inspections.





VIA ROSSA– Borgo San Lorenzo	
District area [m²]	179'207
Total number of buildings	87
Surface covered by buildings [m²]	64'791
% of built surface	36%

Material of load bearing vertical structure	
Masonry	-
Steel	4.3 %
Reinforced Concrete	4.3 %
Precast Reinforced Concrete	85.7 %

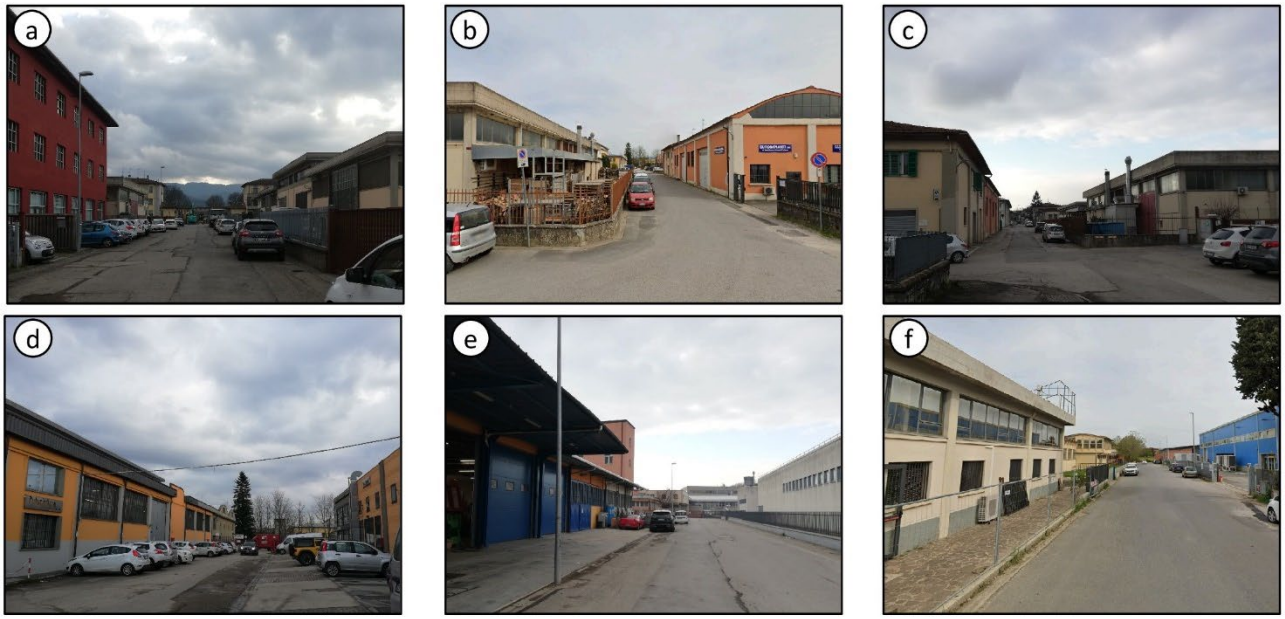
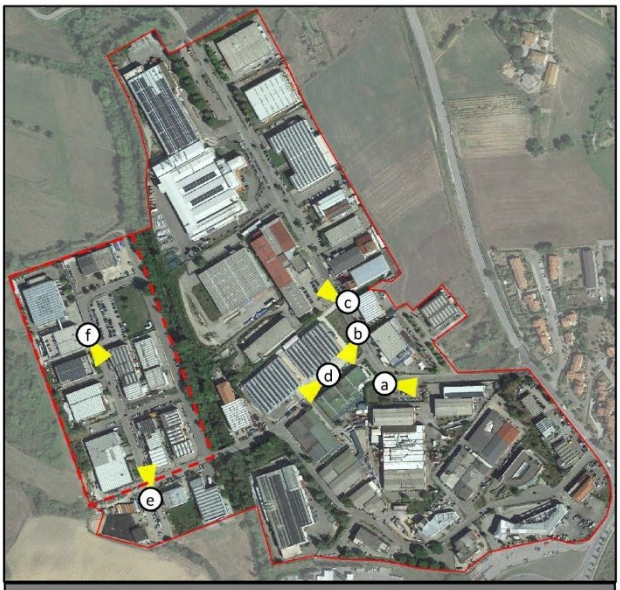
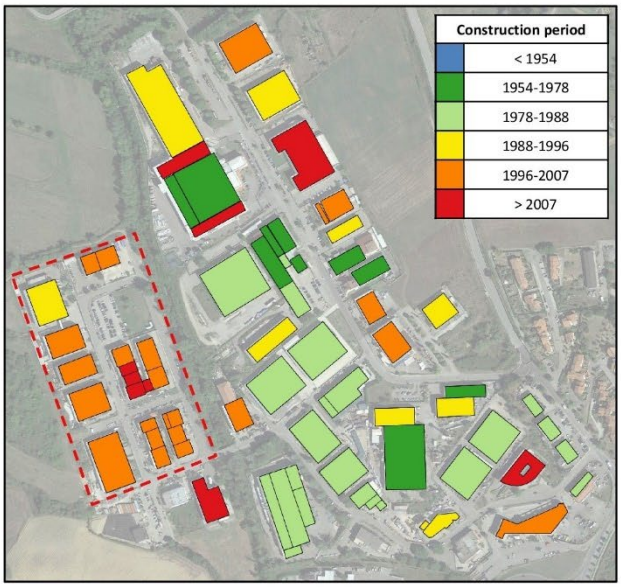


Figure 4.1 Analysis of the Via Rossa industrial district in Borgo San Lorenzo. *Source: elaboration of the author.*





PIAN DELLA LORA – Barberino di M.llo	
District area [m²]	318'842
Total number of buildings	75
Surface covered by buildings [m²]	93'992
% of built surface	29%

Material of load bearing vertical structure	
Masonry	-
Steel	4.3 %
Reinforced Concrete	4.3 %
Precast Reinforced Concrete	85.7 %

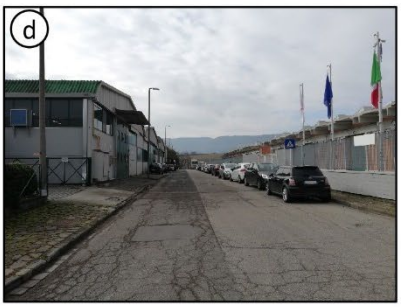


Figure 4.2. Analysis of the Pian della Lora industrial district in Barberino di Mugello. The dashed line in the aerial views encircle the most recent urban expansion of the district, originated starting from the 2000s. *Source: elaboration of the author.*

The industrial districts addressed were chosen because representative of the key features previously introduced. The one located in Borgo San Lorenzo mostly dates back to before the 1980s and it hosts a considerable amount of cast-in place concrete structures. As expected, it is characterized by a greater percentage of built surface, accounting for 36% of the total area of the district. Conversely, the industrial district in Barberino di Mugello presents an original dated nucleus but has experienced new development since the 1980s. In this case, precast concrete systems represent by far the most common construction solution, adopted in about 85% of the facilities. Notably the most recent urban expansion is clearly recognisable by the well-defined urban layout and clear distribution of the buildings in the portion of the district highlighted by the dashed line in Figure 4.2.

As appearing from the photographical evidence reported in the previously introduced figures, these urban areas are generally characterized by a low architectural quality conveyed by the recurs to standardized precast construction technologies leading to uniform and non descriptive environments. The visual quality of external finishing surfaces was disregarded in case of precast cladding panels leading to homogeneous and aesthetically unappealing facilities.

The excessive amount of paved and building surfaces along with the lack of green areas can negatively contribute to worsen outdoor overheating conditions during the hottest months. These factors are in fact universally recognized as responsible for the Urban Heat Island (UHI) effect. This topic is becoming constantly more relevant in view of the changing climatic scenarios connected with the ongoing global warming that induces more frequent and prolonged heatwaves and extreme meteorological phenomena. At this regard, the absence of draining surfaces can be a potential issue in case of intense raining events acting as a detrimental factor in inducing flooding risks.

In addition, industrial districts are often affected by low air quality levels as recognized in the scientific literature [1] [2]. These can be caused by both dust and particulate dispersion connected with production processes, highly emitting machinery, and heavy vehicles traffic. The inadequate share of green areas and the lack of vegetation represent, also at this regard, a detrimental factor.

The main criticalities affecting industrial or manufacturing districts can be hence synthesized as it follows:

- Dense construction density, especially in case of older settlements;
- Inadequate manoeuvring areas for heavy vehicles;
- Lack of opens spaces and areas for shared functions (parking, storage, etc.);
- Low architectural and aesthetic quality of the built environment;
- Excessive paved and built surfaces and absence of green areas or vegetation, detrimental factors worsening the risk connected with UHI;
- Inadequate share of draining surfaces potentially contributing to flooding events;
- Low air quality induced by industrial processes, system installations, and heavy vehicles traffic.

It is important to note that most studies in the scientific literature focus on the cited topics but exclusively addressing residential urban districts and a significant research gap about industrial and manufacturing areas can be also highlighted.

4.2External walls and vertical closures

External walls are crucial for the building performance from a multidisciplinary perspective as they affect the visual-aesthetic quality and the annual energy demand of facilities. As previously mentioned, external walls were proven to differ in terms of position with respect to the load bearing structure and technological solutions adopted. In Figure 4.3 the alternatives assessed are recalled and graphically synthesized.

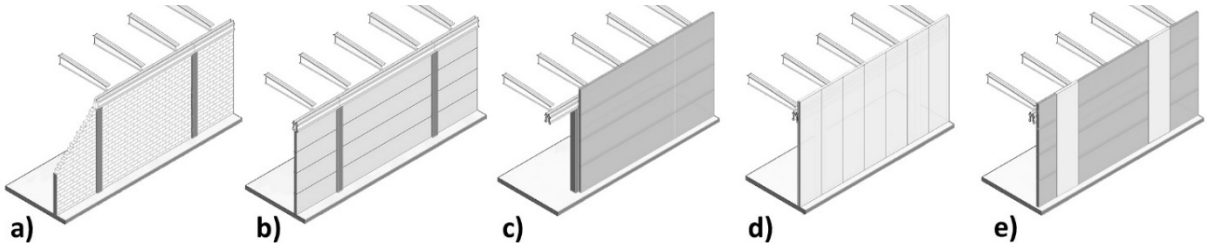


Figure 4.3 Alternative configurations assessed for external walls in industrial buildings: a) masonry infills; b) precast inserted horizontal panels; c) precast external horizontal panels; d) precast external vertical panels; e) combined precast vertical and horizontal panels. *Source: elaboration of the author.*

Masonry infills represent the most dated solution, adopted in both cast-in place concrete structures and precast ones. In this case the infills, made up using ashlar masonry, traditional bricks or aerated concrete blocks, are arranged within subsequent columns, intercluded in the load bearing structure. As for the external finishing, a simple plaster layer even if un-finished walls or exposed bricks solutions can be encountered. Therefore, the architectural quality of buildings is poor and often compromised by bad maintenance over time, with decays and detachments of plaster portions. The absence of an adequate thermal insulation layer, usually not foreseen in the original design phase, results in insufficient thermal transmittance and inadequate thermal inertia. In Figure 4.4 photographic evidence of existing buildings with masonry infills is provided.

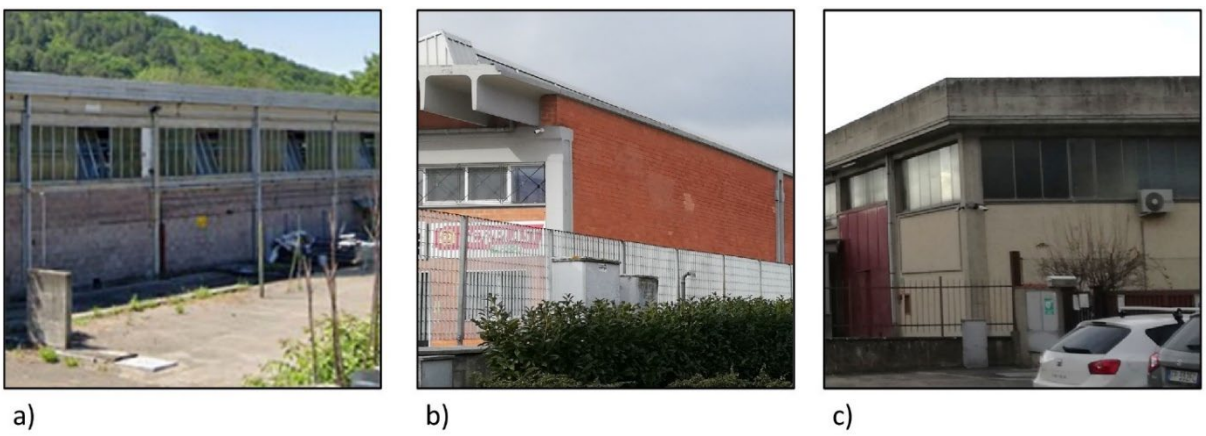


Figure 4.4 Masonry infills: a) aerated concrete blocks; b) exposed bricks; c) plastered masonry. *Source: elaboration of the author.*

Precast concrete cladding panels are the most frequently adopted solution, using both horizontal and vertical elements. The former can be arranged in both internal and external positions with respect to the columns, while the latter are almost exclusively installed outside the load bearing structure. Different geometries and external finishing can be found, as reported in Figure 4.5 and Figure 4.6.

Figure 4.5 Different types of horizontal precast concrete panels: a) plain inserted panels; b) external panels. *Source: elaboration of the author.*

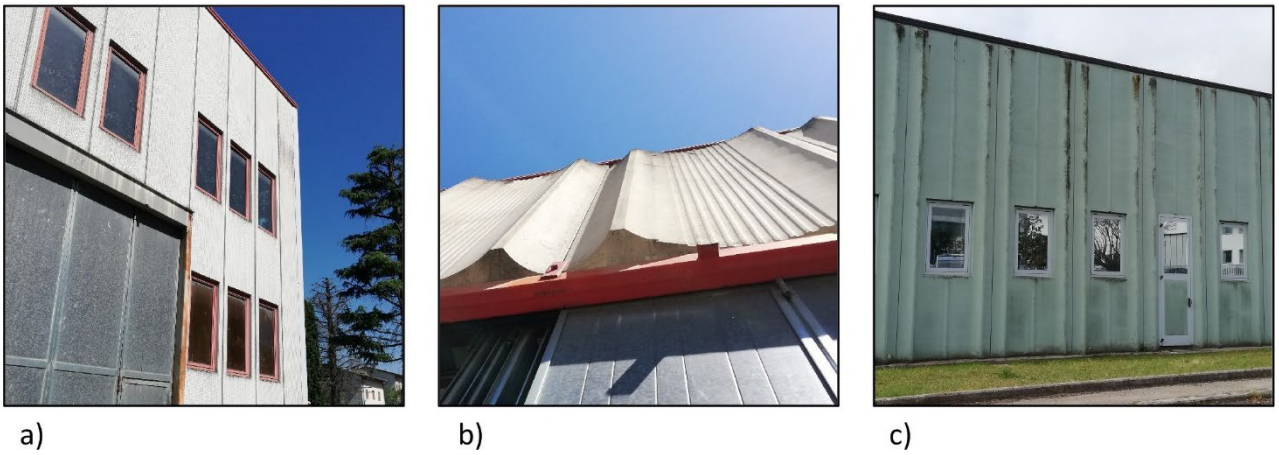


Figure 4.6 Different configurations of vertical precast concrete cladding panels: a) plain narrow panels; b) panels with undulated geometry; c) panels with vertical ribs. *Source: elaboration of the author.*

In case of precast cladding panels, the considerable mass of the elements can influence the overall seismic response of the structure. The relation and connection between the panels and the structural frames is a key aspect to be carefully analysed given their rigidity and weight. The interactions between cladding elements and building's structure proved to be particularly relevant in case of precast industrial facilities during the recent earthquake events. Rocking effects and detachments of the panels were registered for both vertical and horizontal external panels, while precast inserted elements caused shear failures because of the presence of ribbon windows leading to the insurgence of short column and soft story mechanisms.

From an energy performance point of view, the stratigraphy of precast panels fosters an internal insulation layer, usually realized using EPS elements. In the oldest applications, these were mainly used for a lightening purpose and their thickness (usually below 0.10 m) was not sufficient for an adequate thermal insulation. Moreover, the presence of internal concrete ribs connecting the two external slabs results in distributed thermal bridges over the facades. As the panels have been exposed to external atmospheric agents, ageing and decay, the actual conditions and the effectiveness of the EPS layers are difficult to be predicted when analysing the thermal performance of facades. The portions in correspondence of the juxtaposition of panels, often not adequately protected, can furthermore be subjected to air and water leakages. Only in recent buildings these criticalities have been overcome thanks to advancements in production technologies and materials' properties.

Bad maintenance compromises the visual appeal of many industrial buildings, with efflorescence, condensation and damp stains retraceable on the facades. The different properties of the internal concrete ribs and the lightening and insulating panels led also to differentiated ageing of the surfaces. Similarly, cracks and breakages can be detected. These criticalities are illustrated in Figure 4.7.

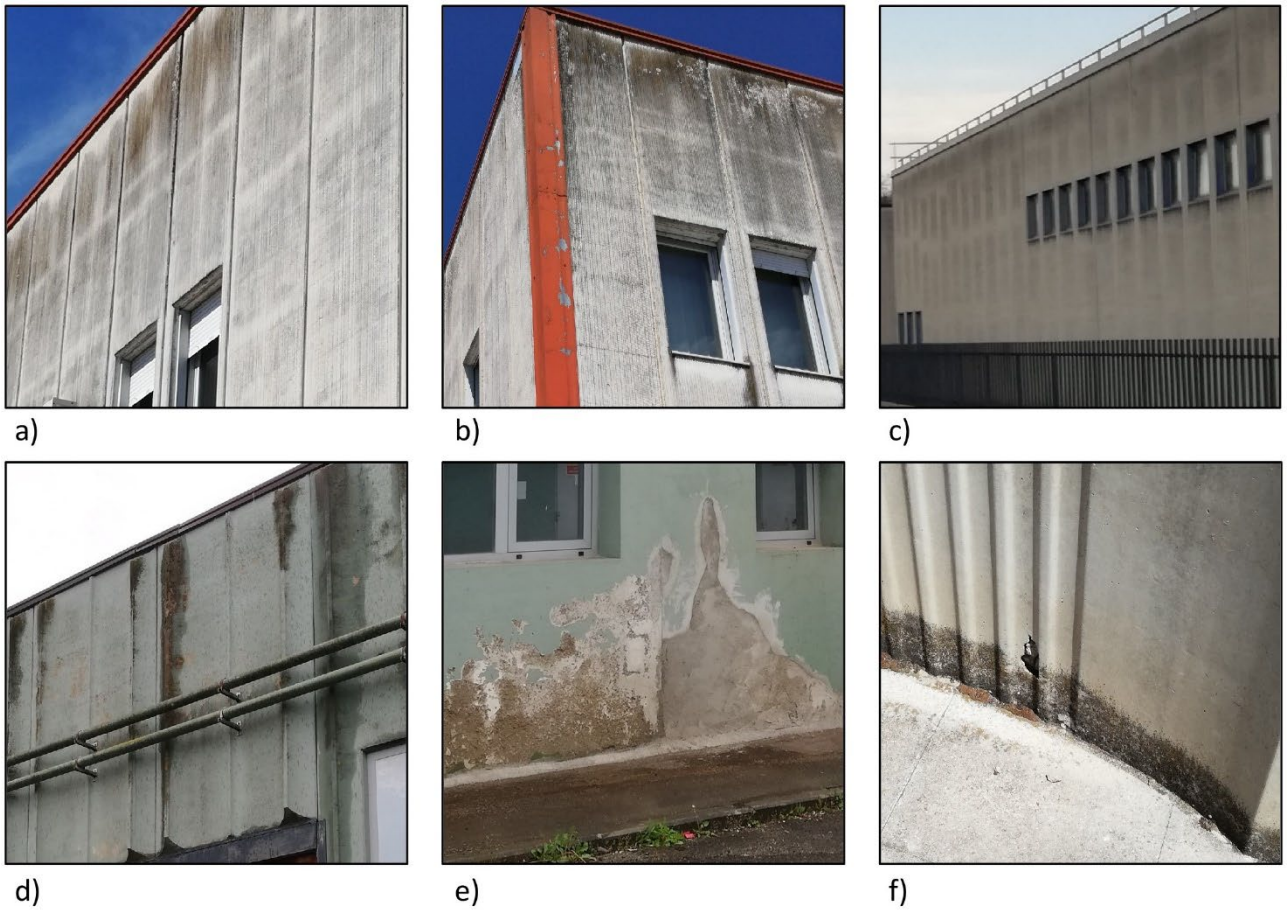


Figure 4.7 Decays phenomena: a), b), c) differentiated ageing; d), e) condensation and damp stains; f) cracks. *Source: elaboration of the author.*

Windowed portions and openings in the external walls are another possible source of localized criticalities. As for windows, deficiencies can be highlighted relating to the bad preservation status of both frames and glazed portions. Moreover, due to the dated construction technologies, no thermal break frames were adopted while the glazing is usually characterized by a single wired float pane with low standards for both energy, visual, and acoustic properties. Frequently, cracks can be also registered in the openings on workshop halls. To ensure easy procedures for both loading and unloading operations, wide sectional doors are usually installed in industrial facilities. However, also with reference to these components, the outdated technological solutions adopted result nowadays in inadequate thermal resistance, airtightness and watertightness standards. The current conditions assessed following on-site surveys are illustrated in Figure 4.8.

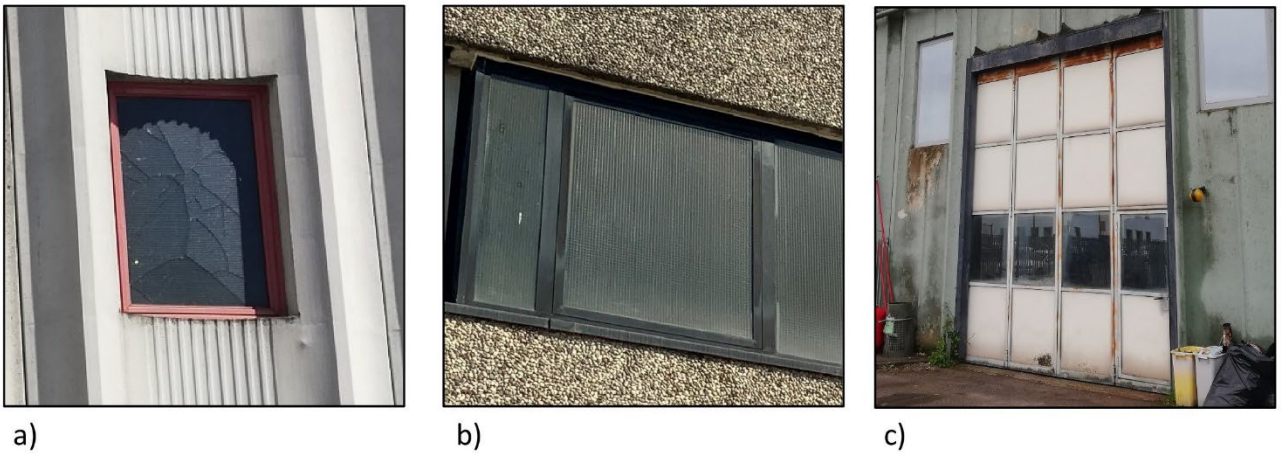


Figure 4.8 Windows and openings in existing buildings: a) cracked window inserted in a vertical precast panel, b) ribbon window in horizontal precast panels cladding, c) sectional outdoor door. *Source: elaboration of the author.*

In conclusion, the main criticalities affecting external walls and vertical closures can be synthesized as it follows:

- Visual-Aesthetic Quality and Maintenance:
    - Poor architectural quality and aesthetic appeal;
    - Decay and detachment of plaster portions in masonry infills;
    - Efflorescence, condensation, damp stains, and cracks on precast panels;
- Energy Performance:

- Inadequate thermal insulation and thermal inertia of masonry infills;.
- Uncertainties about the condition and effectiveness of EPS insulation layers in precast panels;
- Presence of thermal bridges in precast panels;
- Possible air and water leakages at panel junctions;

- Seismic Response:
  - Significant influence of the mass of precast cladding panels on seismic response;
  - Connections subjected to possible failures and breakages;
  - Rocking effects and detachments of panels during earthquakes;
  - Shear failures and collapses due to short column and soft story mechanisms.

- Windowed Portions and Openings:
  - Single float panes with low energy, visual, and acoustic standards except for recently built facilities;
  - Poor preservation of frames and glazed portions;
  - Low airtightness levels for both windows and external sectional doors.

4.3 Roofing structures and completion elements

As emerging from the previous sections, the roofing construction solution and stratigraphy are key elements affecting the overall performance of the building from a multidisciplinary point of view. Given the prevalent horizontal development of industrial facilities, with plan surface much more significant compared to building height, roof is the widest dispersing component of the external envelope.

The solutions fostering metal arches or trusses as main load bearing elements may suffer from inadequate connections with the vertical load bearing structures resulting in collapses under seismic actions. Moreover, in these kind of configurations, fibre-cement panels or cupels are still in place as completion and finishing elements and the presence of asbestos components should be hence addressed as a primary issue. A double layer can be often found with the internal one acting as counter ceiling. However, the presence of a thermal insulation layer should be assessed case by case, even if reasonably ineffective and insufficient to meet the actual performance standards.

A similar approach is also adopted in case of roofing configurations including precast beams as load bearing components. Except for buildings realized starting from the ‘90s, also in this case asbestos can be retraced in completion panels locate on both the intrados and extrados of the beams, usually showing a Y-shaped section. Since they are involved in rainwater collecting and draining, the extrados surface of both roofing and side beams can be subjected to erosion and washout phenomena leading to a progressive decay. Since the roofing system relies on the juxtaposition of different elements (beams, cupels, counter ceiling, side closing panels) mechanically fixed or stuck, the airtightness and waterproofing of the stratigraphy may be compromised especially in the oldest facilities subjected to ageing and being exposed for several years to the atmospheric agents. Thermal insulation is partially guaranteed by the specifically meant layer of rock or glass wool laid over the counter-ceiling. According to the stratigraphy derived from the original design documentation, the thickness of the insulation is however not sufficient to ensure the thermal transmittance required by the current regulations. Moreover, the so realized insulating layer is discontinuous because regularly interrupted by the precast beams that constitute significant thermal bridges because entirely exposed on their extrados.

These limitations were partially resolved in case of the newly designed precast concrete wing tiles, fostering a continuous embedded insulating layer, completion elements with enhanced thermal

properties and airtightness. However, in dated buildings many of these criticalities were still unresolved and pose significant challenges to be addressed nowadays.

The roofing solution with double sloped precast beams is conversely characterised by the recurs to precast slabs, generally with π profile, to realize the roof pitch connecting consecutive portal frames. In this case a more appreciable variety of possible finishing stratigraphy can be assessed and uncertainties about the presence of thermal insulation should be resolved with case-specific assessments via on-site inspections or documentation examination.

Notably, all the precast roofing systems share structure related issues induced by the presence of a considerable seismic mass localized at the top of the buildings. The weight of the elements implemented is in fact not negligible and heavily affect the response of the structure in case of horizontal actions. This aspect is more relevant in case of both wing tiles and double sloped beams because of their masses involved and, for the latter, the additional presence of precast concrete slabs. The consequent failures of connections, inadequate to face the solicitations induced, results in localized or generalized collapses. In Figure 4.9, seismic-related failure mechanisms are illustrated.

Figure 4.9 Collapses after seismic events: a) failure of beam-to-column connection and detachment of the cladding panels; b) collapse of precast roofing tiles. *Source: elaboration of the author.*

Skylights, variably arranged and conceived, potentially represent critical elements to be investigated in detail. At first, their thermal resistance is generally extremely low, especially in dated buildings where polycarbonate or fiberglass elements are still in place without adequate framing to reduce air and water leakages. These are characterized by low visual properties, while the ageing of surfaces led to stains and deteriorations resulting in unpleasant aesthetic effects. In case of windowed skylights of dated facilities, both glass panes and metal frames are no longer providing satisfactory performances.

During summer months and in case of direct solar radiation, skylights on the roofing plane can induce overheating conditions in industrial halls. Figure illustrates different skylights solutions.

Figure 4.10 Details of different skylights configurations: polycarbonate panels in a) π-section slabs and b) precast beams roofing solutions. *Source: elaboration of the author.*

To sum up, the fundamental issues related to roof solutions are reported below:

- Health and environmental risks:
  - Use of asbestos-cement panels or cupels, which often contain asbestos,
- Energy Performance:
  - Inadequate thermal insulation;.
  - Compromised airtightness and waterproofing, especially in older facilities;
  - Presence of thermal bridges caused by precast roofing beams;
- Seismic Response:
  - Considerable seismic mass at the building's top because of precast components;
  - Connections subjected to possible failures and breakages;
- Skylights:
  - Single panes or polycarbonate panels with low energy, visual, and acoustic standards except for recently built facilities;
  - Poor preservation of frames and glazed portions;
  - Low airtightness levels.

4.4Mechanical systems for air conditioning, lighting and energy from renewables.

Systems and installations represent the main source of energy demand in industrial buildings along with the machinery used in manufacturing processes. On site surveys revealed a heterogeneous scenario but some general trends could be derived.

As for the air conditioning purposes, only air heating is guaranteed while the cooling demand is disregarded. Gas unit heaters are the most adopted system solutions, chosen because of the ease of installation, the low thermal inertia and the limited space demand. On the other hand, these generally work following a simple on-off scheme with no heating modulation and the models installed are usually outdated and affected by low efficiency. Hot water unit heaters represent a possible alternative: heat is transferred through copper tubes with aluminium fins through forced convection to the air pushed by dedicated fans. In this case a central boiler is foreseen Alternatively, centralized gas heaters with hot-air distribution system were also encountered. Heating systems fostering heat pumps as generators were registered only in limited applications and for smaller facilities. Similarly, heat recovery units are not installed. In buildings hosting also an administration section with offices, these are heated recurring to traditional solutions like radiators with gas boilers for hot water production and cooling during summer is also provided by heat pumps for air conditioning. No mechanical ventilation systems were usually encountered, and air change rates are ensured relying only on natural ventilation by simply opening windows (where possible) or sectional doors. On the other hand, recirculation vents to avoid warm air stratification towards the upper portions of the working halls were encountered in a few cases. In Figure 4.11 and 4.12 evidence collected during the on-site recognitions carried out are presented.

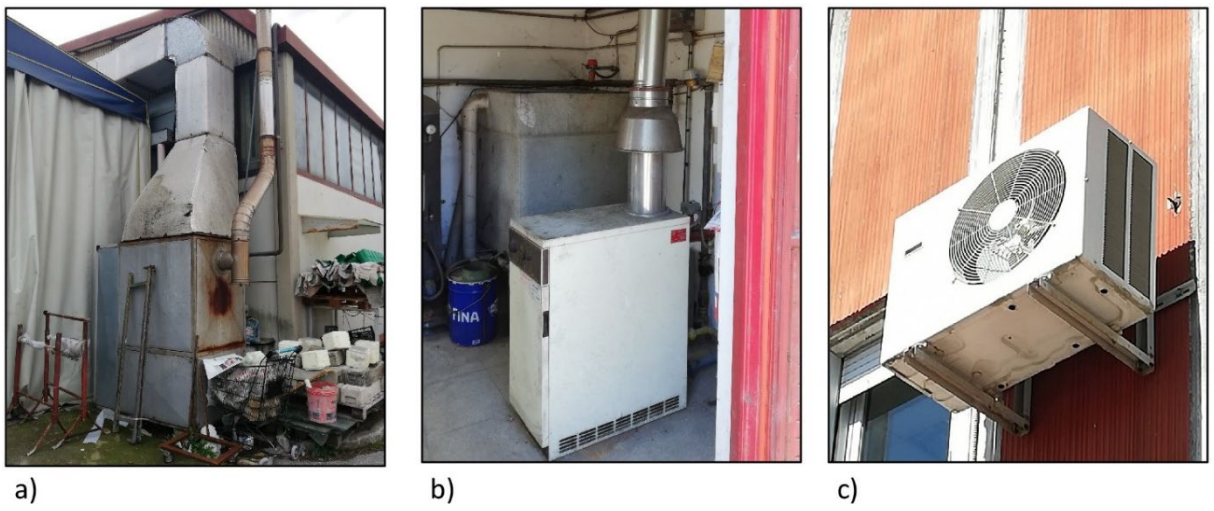


Figure 4.11 Heat generation solutions: a) gas boiler; b) gas boiler for hot water production; c) heat pump. *Source: elaboration of the author.*

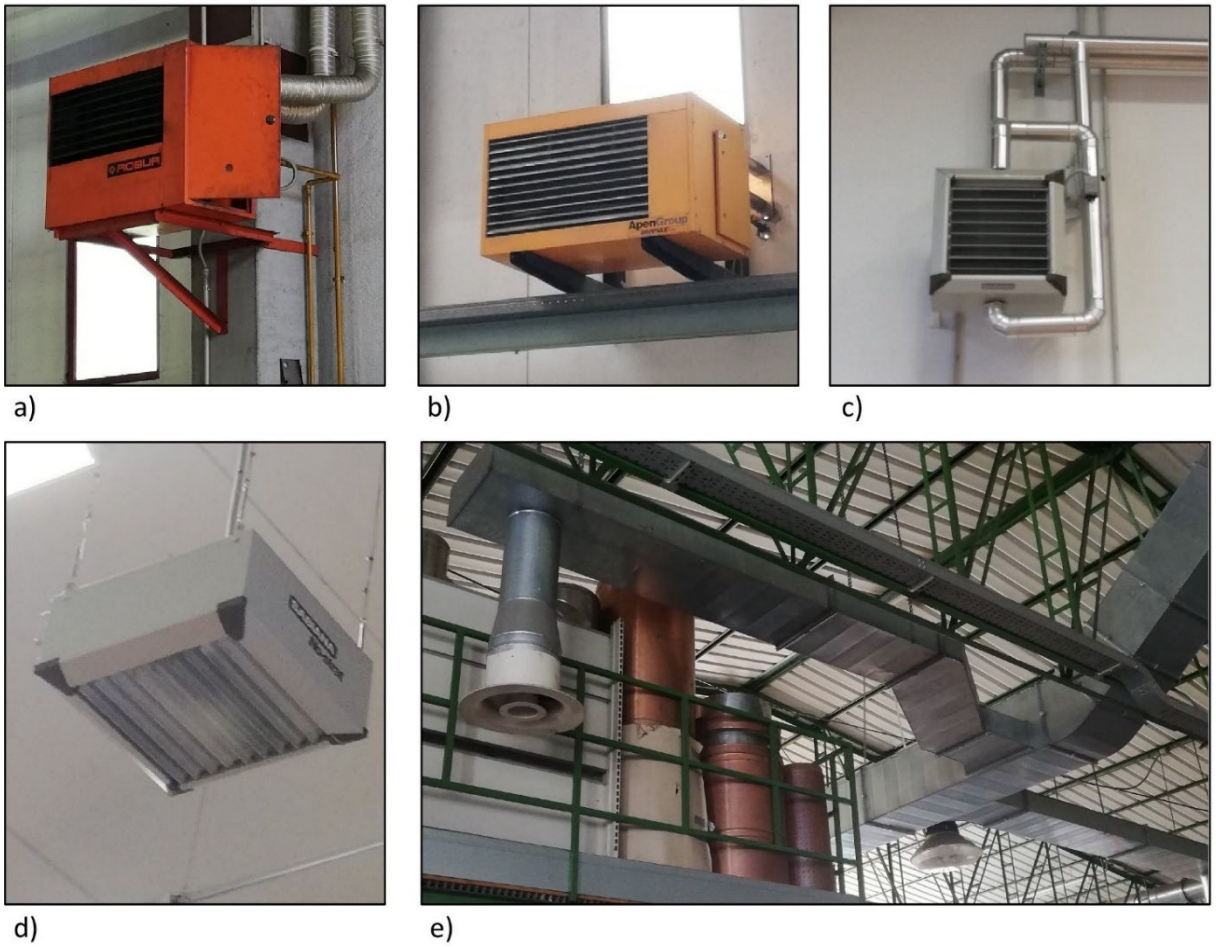


Figure 4.12 Heating systems and terminal alternatives: a), b) gas unit heaters; c) water unit heater; d) recirculation vent for flux optimization; e) hot air distribution pipes and terminals. *Source: elaboration of the author.*

As for lighting systems, LED technology is still not implemented and fluorescent or neon lamps are installed hanging from the ceilings or directly fixed to them, as reported in Figure 4.13. This solution results in scarce lighting effectiveness given the distance from the lighting source to the working plane. Moreover, the lighting system is not equipped with sensors capable of dimming power according to the actual needs and they hence stay frequently turned on for the whole lasting of the working shifts with consequent energy wastes.

Energy supply still largely relies on fossil fuels for heating demand and on energy from the grid considering the electric energy consumption. According to the results of the territorial analyses carried out, 90% of existing facilities have no PV panels or other solutions for energy production on-site from renewables. Aerial and satellite views revealed that these are only implemented in recently constructed buildings or facilities that underwent massive renovations. Similarly, sensors-based automation solutions for systems control or opening operations are not installed.

Figure 4.13 Lighting systems with fluorescent lamps: a) attached to the ceiling; b) fixed to rails; c) suspended from roofing beams. *Source: elaboration of the author.*

The main criticalities relating to systems in industrial buildings can be summed up as below:

- Widespread adoption of outdated unit heaters with low efficiency and control effectiveness;
- No heat recovery solutions adopted;
- Cooling demand generally disregarded;
- Clear prevalence of fluorescent lamps with LED lighting still rare to be adopted;
- No sensor-based automation for system control and operations;
- Energy supply heavily dependent on fossil fuels and electricity from the grid;
- No systems to produce energy from renewables are installed in about 90% of facilities included in the research.

4.5 References

1. Zhu X, Yu W, Li F, et al (2021) Spatio-temporal distribution and source identification of heavy metals in particle size fractions of road dust from a typical industrial district. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2021.146357

2. Cai Y, Li F, Zhang J, et al (2021) Toxic metals in size-fractionated road dust from typical industrial district: Seasonal distribution, bioaccessibility and stochastic-fuzzy health risk management. Environmental Technology and Innovation. https://doi.org/10.1016/j.eti.2021.101643

5 RETROFIT AND INTERVENTION PROPOSALS

In this section, different intervention strategies to enhance the overall performances of industrial buildings are presented. Starting from the framework of issues and criticalities introduced in the previous chapter, a series of energy and technological retrofit solutions to be applied on manufacturing districts and facilities have been evaluated. The mitigation strategies proposed were selected to reflect the peculiarities of the different typological variants assessed on the territory, the related boundary conditions, the limits and opportunities offered by the construction technologies adopted, as well as the different multidisciplinary challenges.

In this chapter the main distinguishing features of each retrofit intervention will be discussed along with the expected impacts, derived by conducting a series of microclimate, energy and environmental simulations as later detailed. These series of assessments are functional to the definition of a comprehensive retrofit protocol which collect the various measures indicating their effectiveness and suitability for the different typological variants.

To provide a more effective presentation of the study, this section will be articulated into three distinct parts addressing the mitigation strategies to be applied and their impacts expected respectively at urban and building scales, with the latter referring to envelope components and internal conditions and system installations.

As detailed in the dedicated sections of this dissertation, industrial facilities are currently affected by a considerable range of criticalities connected with construction components and mechanical installations to ensure adequate running conditions. A series of retrofitting measures are proposed, evaluated, and validated to define a compendium of possible redevelopment solutions. Strategies targeting building envelope are calibrated on the specific needs and requirements of the different typological variants identified, considering the different challenges and multi-disciplinary implications. The outdated technological solutions still in place determine low performance standards for building envelope, requiring retrofit interventions to overcome deficiencies mainly connected with inadequate thermal resistance and poor aesthetic appeal.

On the other hand, the systems installations for space heating, ventilation and lighting can be considered as not directly influenced by the typological variant of interest as all the buildings tend to share the same characteristics for the internal areas to be addressed (large volumes, considerable internal heights, similar window-to-wall ratios, occupancy patterns, setpoint temperatures, etc.).

This section is articulated in different subsections as it follows:

- 5.1 Urban scale
    - 5.1.1 Cool pavements, trees planting and green walls as UHI mitigation strategies
    - 5.1.2 Green roofs and trees planting: focus on UHI mitigation and air quality
- 5.2 Building envelope retrofit
    - 5.2.1 Retrofit measures for vertical closures
    - 5.2.2 Retrofit measures for roofing stratigraphy
    - 5.2.3 Validation of results and quantification of energy saving potential
        - 5.2.3.1 Case study building: plain roof with precast beams category (P_rc_b)
            - 5.2.3.1.1 Envelope retrofit: façade and roof recladding
        - 5.2.3.2 Case study building: Sloped roof with precast beams category (Sl_rc_slb)
            - 5.2.3.2.1 Envelope retrofit: façade and roof recladding
            - 5.2.3.2.2 Green roof installation
- 5.3 Internal conditions and system installations
    - 5.3.1 Skylight configurations and lighting conditions
    - 5.3.2 Summer overheating evaluation
    - 5.3.3 BIPV shading system
    - 5.3.4 Heating systems alternatives
    - 5.3.5 PV energy production and storage potential
- 5.4 References

5.1 Urban scale

As presented in the dedicated chapter previously introduced, industrial districts present low architectural quality and environmental standards connected with both their specific intended use, the urban layout characteristics and the materials adopted. The excessive amount of paved and built surfaces produces a soil sealing effect that significantly arise the risks connected to the UHI insurgence and compromise at the same time rainwater management.

To mitigate these criticalities, it is possible to act on both the public opens spaces and built facilities included in the urban area of interest.

Starting with the analysis of the former, the substitution of asphalt surfaces with cool pavements solutions and the introduction of vegetation with trees planting initiatives were addressed as particularly suitable considering the peculiarities of industrial districts. As universally recognised in the scientific communities, also de-paving actions and subsequent introduction of green areas with flowerbeds are recommended to face UHI at street level. However, this kind of measure may result not applicable because of the need of manoeuvring spaces for heavy vehicles, especially in densely built industrial districts already affected by the presence of narrow streets and the lack of sufficient free areas.

The specific measures implemented are presented in detail:

- **Cool pavements**

Cool pavements are designed to reflect more solar radiation and consequently reduce heat absorption if compared to traditional dark asphalts. These materials allow to reduce the surface temperatures of roads and surrounding areas thanks to their higher albedo and their lower thermal emissivity. From a technological point of view, existing surfaces can be converted into cool ones by adding reflective coatings layers or by painting them with lighter colours. In case of brand-new paving interventions, modified mixes including reflective aggregates can be used to enhance the albedo of the road surfaces. The effectiveness of these solution and their diffusion in recent years has been investigated also in throughout reviews of the existing scientific literature, as the one by Rahman et al. [1] and Morales-Inzunza [2]. The UHI-mitigation potential is underlined by these authors along with the contribution to a substantial decarbonisation of the built environment. Similarly, several studies investigating the potential of acting on surfaces' albedo on microclimate in urban context are available.

- **Trees planting**

Planting trees in urban environments greatly contributes to enhancing the urban environmental quality in city districts. Beyond their aesthetic value, trees and vegetation can significantly mitigate the urban heat island effect through shading and evapotranspiration. As reported in the scientific literature, trees planting is considered as a promising green strategy to also reduce outdoor air pollution in urban districts, with several studies suggesting considerable potential for air quality improvements. However, while come studies highlight these capabilities [3], researchers remark the need for a careful selection of the vegetation species [4] and possible undesired effects connected to local recirculation of winds and shielding effects in narrow urban

canyons [5]. While the introduction of trees and vegetation in residential districts is commonly addressed [6][7], industrial areas are not usually considered for similar applications despite the issues currently affecting them.

When evaluating the feasibility of greening interventions in industrial sites however, the selection of the tree species to be adopted must be based on the compatibility of their size with the available planting space and their ability to survive and thrive in an urban environment. Especially in manufacturing districts in fact the need for watering, the UHI effect during summer, and the high pollutant concentration can seriously endanger vegetation. Evergreen canopies should be preferred to benefit from their shading effect during the summer months shielding solar radiation and to exploit their contribution to improving air quality during winter, when particulate concentrations in the atmosphere are higher. Similarly, also the distribution of the trees within the district should be planned to avoid obstruction to loading and unloading operations essential to business activities and to preserve the manoeuvring spaces for heavy vehicles.

Green infrastructures can be applied not only at urban level in public spaces or private areas adjacent to existing facilities, but also integrated in the external envelope of the buildings recurring to green roof and vertical greenery solutions. Authors in the literature highlight that an extensive application of these vegetation technologies can mitigate both UHI effects reducing air temperature [8] and ameliorating the energy performances of buildings [9] [10].

When evaluating the installation of building integrated vegetation solutions in existing industrial facilities, the typological characteristics must be analysed as they dictate the technological choices for the refurbishment. Many factors need to be considered, including architectural, structural, technological, and construction aspects, as well as the needs and usage patterns of both internal and external spaces. This methodological approach is essential for defining interventions that are practical, sustainable, and effective.

Both green roofs and green facades were investigated as potential retrofit interventions for existing industrial buildings and will be detailed in the following of this section:

- **Green facades/vertical greenery**

  The effectiveness of vertical greening technologies applied on buildings' facades is well documented in the scientific literature, with studies analysing the different technological

alternatives currently available on the market [11][12][13]. Among these, “lightweight” indirect green facades with tensioned steel cables or metal frames and climbing vegetation are the most suitable technologies in case of industrial buildings for different reasons. At first, they do not pose relevant challenges for structural and seismic performances of the building. As previously mentioned, precast concrete panels are commonly in place as external cladding elements and their weight is often critical for connections under horizontal actions. Indirect vegetated claddings with metal wires, contrarily to technological solutions like green living walls with modular cassettes, do not induce a significative additional load on the façade panels and do not exacerbate seismic related issues. Moreover, these kinds of vertical greenery require limited spaces for their installation, reduced maintenance operation, and the vegetation species implemented are generally more resistant to external factors.

Conversely, the indirect green cladding solution considered is not able to improve the thermal transmittance of the external walls since no insulation layer is foreseen. On the other side, the shading effect produced can be beneficial during summer season preventing direct solar radiation on both opaque and glazed portions, depending on the layout adopted.

The configuration of facades should be however considered when evaluating the suitability of green cladding interventions. For instance, in many cases, the presence of distributed extensive ribbon windows, large entrance openings, system pipes and external channels, and the use of the building’s adjacent areas as storage spaces represent limiting factors for the application of green walls.

- **Green roofs**

Green roofs are largely recognised as extremely beneficial for both microclimate conditions and air quality in urban districts, as emerging from the wide scientific literature and the studies carried out by several researchers [14].

Green roofs can lower the outdoor air temperature thanks to evapotranspiration phenomena and their albedo, higher than traditional finishing solutions. At the same time, the effects on environmental pollution are documented and the capability of capturing particulate matters highlighted in several research works [15] [16].

In addition to the effects at district and urban scale, the use of green roofs effectively improves the energy behaviour and performance of buildings throughout the year. In the summer, the

improved albedo and moisture in the layers reduce the surface temperature while a beneficial thermal lag is guaranteed by the mass of the soil layer. The latter also offer additional thermal insulation during winter, along with the presence of a thermal insulating layer usually included in green roof stratigraphy.

Industrial buildings have much larger roof surfaces compared to residential or office buildings, making them particularly attractive for implementing similar technological solutions. Conversely, morphological, geometrical, and structural aspects connected to roofing system currently in place can seriously limit their feasibility on a large extent. Typological variants fostering precast beams or tiles may result inadequate given the increased load induced by the green roof stratigraphy that would require substantial integration or replacement of the structural elements, the presence of vaulted completion elements, and the frequent presence of skylights limiting the surface available. Specifically, the adoption of green roofs could be profitable in case pf precast double sloped beams and π panels: in these cases, the replacement of the current precast slabs with lightweight sandwich panels and the subsequent installation of a green roof stratigraphy enables to lighten the entire roof system, leading to a structural enhancement too.

Considering the different green roofs configurations currently available, extensive vegetation is generally recommendable over the intensive one, given its reduced weight connected with the limited thickness of the soil layer required and the less costly maintenance procedure associated.

To evaluate the effectiveness of the different intervention measures considered in the analyses, their application to a real case-study district was assessed via environmental and microclimate simulations, carried out using ENVI-met as modelling and simulation tool.

5.1.1 Cool pavements, trees planting and green walls as UHI mitigation strategies

An industrial district located in Mugello was selected as case study to evaluate the impact of the possible implementation of the following mitigation strategies:

- Cool pavements in the main public streets;

- Trees planting in the suitable areas in public roads;

- Vertical green cladding on buildings facades according to different configurations, applied at first only on southern fronts prospecting the main road, and then added also in the in-ternal canyons.

Outdoor air temperature [°C], relative humidity (%), mean radiant temperature [°C], external surface temperatures [°C] were referred to as evaluate parameters in assessing the benefits of the measures proposed, with respect to the actual state of the industrial district.

This study is thoroughly reported in the paper "*Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes*" published in Atmosphere [17].

The area selected for the case study is the Pian della Lora industrial district in Barberino di Mugello, highly representative of similar areas both in terms of building and urban typological features as emerging from the analysis of its main characteristics previously provided in the text (4.1). The test site is illustrated in Figure 5.1: specifically, both the whole area and a portion of the district representing the newly built expansion, highlighted in red, have been investigated.

Figure 5.1 Case study district; geographical location, definition of the two portions analysed and photographical evidence. *Source: elaboration of the author.*

The M2 district in particular is characterized by broader public roads and a more homogeneous building stock, because of the standardization of construction systems induced by the evolution of precast industry. This district was analysed considering various vertical sections to assess the

influence of urban canyons configuration on the effectiveness of the different measure proposed. In Figure 5.2 both the plan and section views of the M2 district are illustrated in detail.

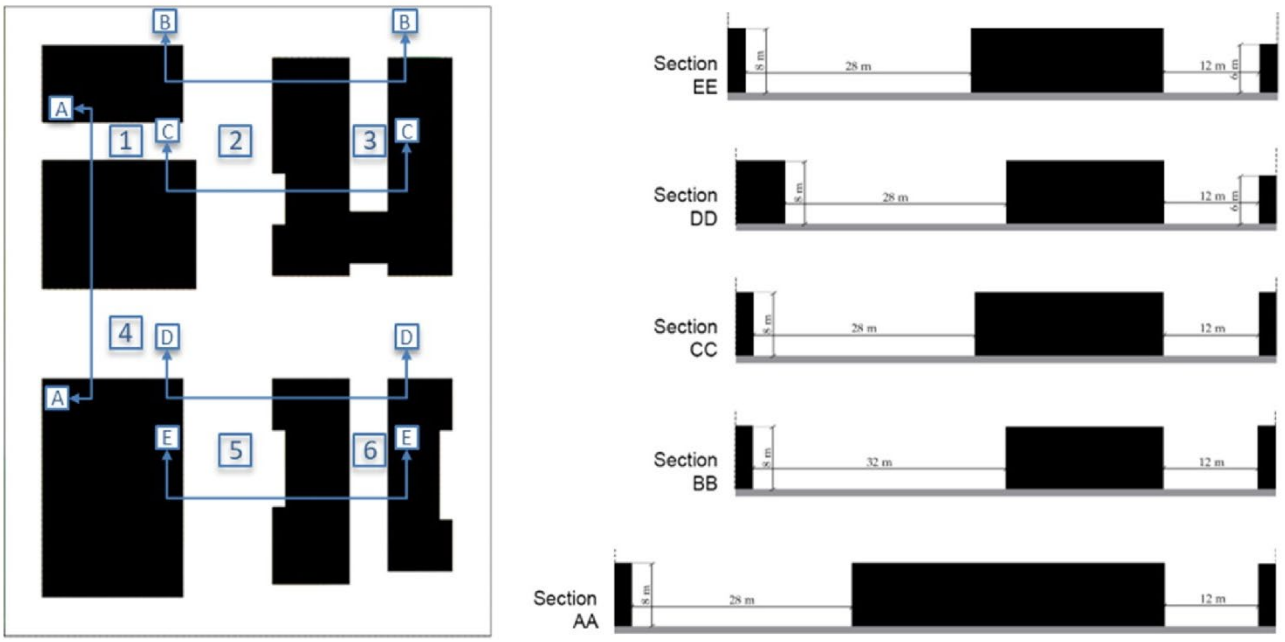


Figure 5.2 M2 district: urban plan layout and sections of the urban canyons investigated. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

The case study area is included in climatic zone E according to the National classification and climatic data from the Bologna Borgo Panigale weather station were imported as .epw file in the simulation environment. The average annual climatic parameters are reported in Table 5.1.

Table 5.1 Annual average climate conditions. *Source: elaboration of the author.*

Climate zone	Heating period	Heating Degree Day [K/d]	Global Horizontal Radiation [kWh/m²a]	Diffuse Horizontal Radiation [kWh/m²a]	Direct normal radiation [kWh/m²a]	Air temperature [°C]	Wind velocity [m/s]
E	15/10 – 15/04	2259	1309	652	1204	14.2	2.6

As for the geometry of buildings and urban roads, the area was modelled starting from aerial views by Google Maps sources and files accessible on regional databases online. Once the geometry of buildings has been recreated, meshing settings were imposed to ensure reliable results but avoiding at the same time unnecessary refined fragmentation of the model to avoid time-consuming simulations procedures. Given the reduced dimensions of the M2 portion, the model meshing was set up to a greater accuracy level.

To simplify the modelling phase, homogeneous properties were assigned to external walls given the wide presence of precast concrete panels while two alternatives were considered for the roofing stratigraphy, including both fibre-cement tiles and the waterproofing membrane as finishing layers. In Table 5.2, 5.3, 5.4, the properties set for the materials in the simulation environment are reported.

Table 5.2 ENVI-met settings for external walls properties and stratigraphy. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808..*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Absorption [%]	Solar Reflection [%]
Precast concrete	0.04	0.85	840	70	30
Expanded Sintered Polystyrene EPS	0.08	0.035	1000	30	-
Precast concrete	0.04	0.85	840	70	30

Table 5.3 ENVI-met settings for roofing properties: stratigraphy featuring fibre-cement tiles. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Solar Absorption [%]
Fiber Cement	0.01	0.60	1000	60
Air	0.70	0.025	1006	-
Rock Wool	0.06	0.034	1000	42
Fiber Cement	0.01	0.60	1000	60

Table 5.4 ENVI-met settings for roofing properties: stratigraphy featuring waterproofing membrane. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Absorption [%]
Elastomeric bituminous membrane	0.004	0.17	1000	60
Expanded polystyrene	0.05	0.035	1000	-
Concrete	0.08	0.85	840	42

Similarly, Table 5.5, 5.6, 5.7, collect the parameters set to introduce the retrofit strategies in the model addressing cool pavement installation, trees planting, and green cladding respectively. For the former, the replacement of asphalt with light coloured concrete pavement was considered. As for three species selection, Tilia cordata “Rancho”, a medium-size deciduous tree, was included as suitable for urban environments. Regarding green façades, indirect ones with climbing plants rooted in the ground and growing on metal wires hanged to the building's external walls were simulated. At least 75% of the available surface on the fronts was assumed to be covered with Hedera, chosen in this case given its resilience toward external agents commonly retrievable in urban context.

Table 5.5 ENVI-met settings for cool road pavements. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

Measure	Pavement	Albedo	Emissivity	Extension	Code
Cool pavement	Light concrete pavement	0.80	0.90	Public roads	CP

Table 5.6 ENVI-met settings for trees planting. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

Measure	Tree	Width [m]	Height [m]	Leaf Area Density [m^2/m^3]	Number of trees	Code
Trees planting	Tilia cordata "Rancho"	4.05 x 5.78	8.63	1.5	345 in M1 district	TP_M1
					68 in M2 district	TP_M2

Table 5.7 ENVI-met settings for green facades. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

Measure	Vegetation	Thickness [m]	Leaf Area Index [m^2/m^2]	Leaf Angle Distribution	Facades involved	Code
Indirect green facades	Elix Hedera	0.30	1.5	0.5	South oriented - prospecting wider urban canyons	GW.1_M1 GW.1_M2
					South oriented - prospecting all urban canyons	GW.2_M2

In Figure 5.3 and Figure 5.4 the application of the mitigation strategies in the case study area is illustrated considering the different configurations in M1 and M2 districts.

Figure 5.3 Configurations of M1 area featuring the different strategies evaluated in the research. *Source: Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

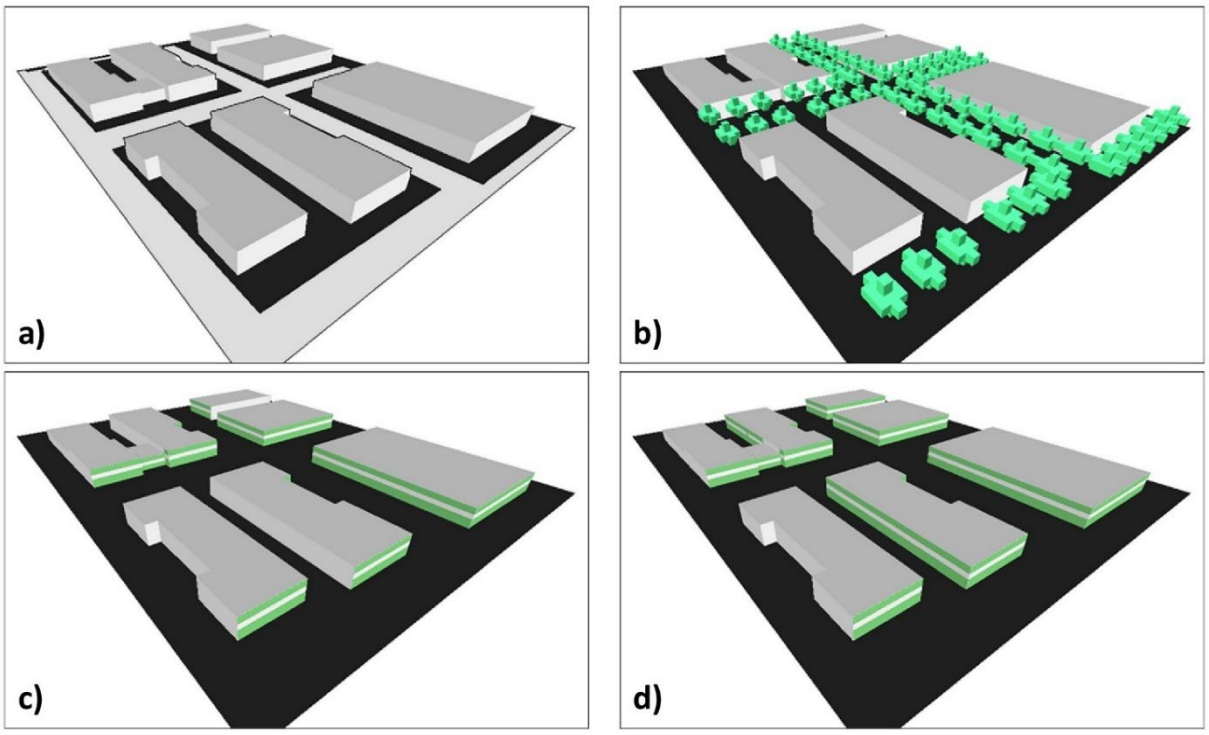


Figure 5.4 Configurations of M2 area: a) Cool Pavement; b) Trees planting; c) Green walls on southern oriented facades and main roads; d) Green walls application extended to cover also narrower urban canyons. *Source: Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

Simulations were conducted assuming central hours (between 11 am and 1 pm) of 21st of June 2020 as reference scenario, with results extracted for noon time at a 1.5 m height. Results will be detailed considering both the district's portions analysed, as obtained after having refined them to exclude all the meshing points not properly pertaining to the manufacturing sites potentially leading to outlier values and altered averages.

Examining the M1 district, all the measures proposed mitigate critical conditions by reducing peak temperatures and shifting the distribution towards lower values. This evidence is particularly clear considering the graph in Figure 5.5, where it can be retraced that TP (Tree Planting) and GW.1 (Green Walls) configurations are characterised by trends substantially replicating the base conditions while CP (Cool Pavement) produces a significant shift with respect to actual state. Solution CP lowers the average air temperature from 28.87°C to 28.42°C. Conversely, TP and GW.1 are less effective, resulting in mean air temperatures of 28.85°C and 28.84°C, respectively.

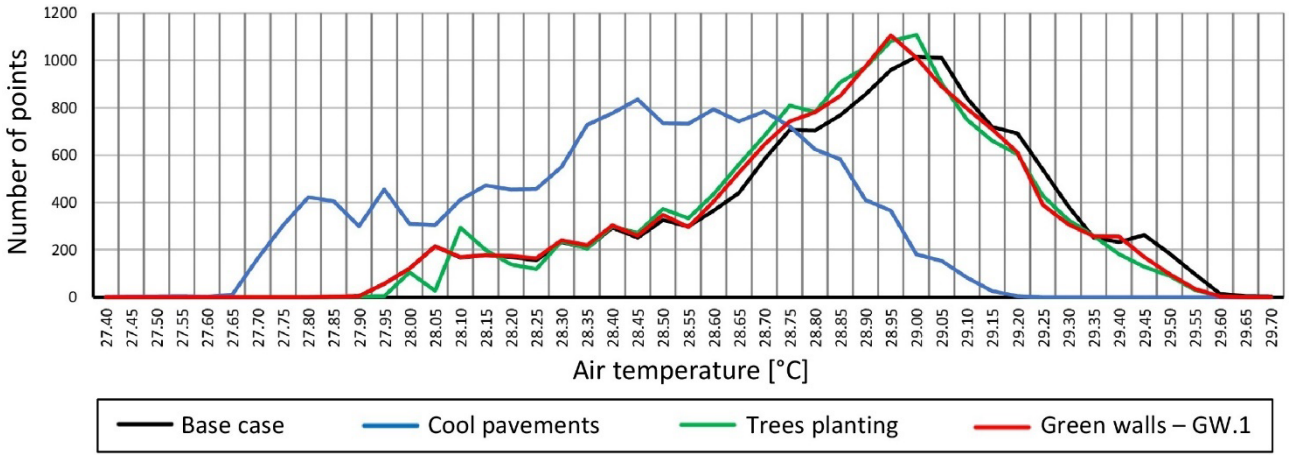


Figure 5.5 Distribution of points in the M1 district associated with the external air temperature under different scenarios. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

The same results, along with insights on mean radiant temperature, are reported in Figure 5.6 showing their distribution in the district. CP (cool pavements) is the most effective solution for reducing outdoor air temperature, resulting in a significant mitigation of external conditions across larger areas of the district. In contrast, TP (tree planting) and GW.1 (green walls) have a less noticeable effect due to their limited coverage area. However, regarding mean radiant temperature, cool pavements increase this parameter due to higher surface reflectivity. Conversely, GW.1 and TP reduce mean radiant temperature significantly: GW.1 lowers it by up to 2°C near external walls with greenery, while TP achieves about a 9°C decrease in shaded areas, making it the most effective measure for this purpose.

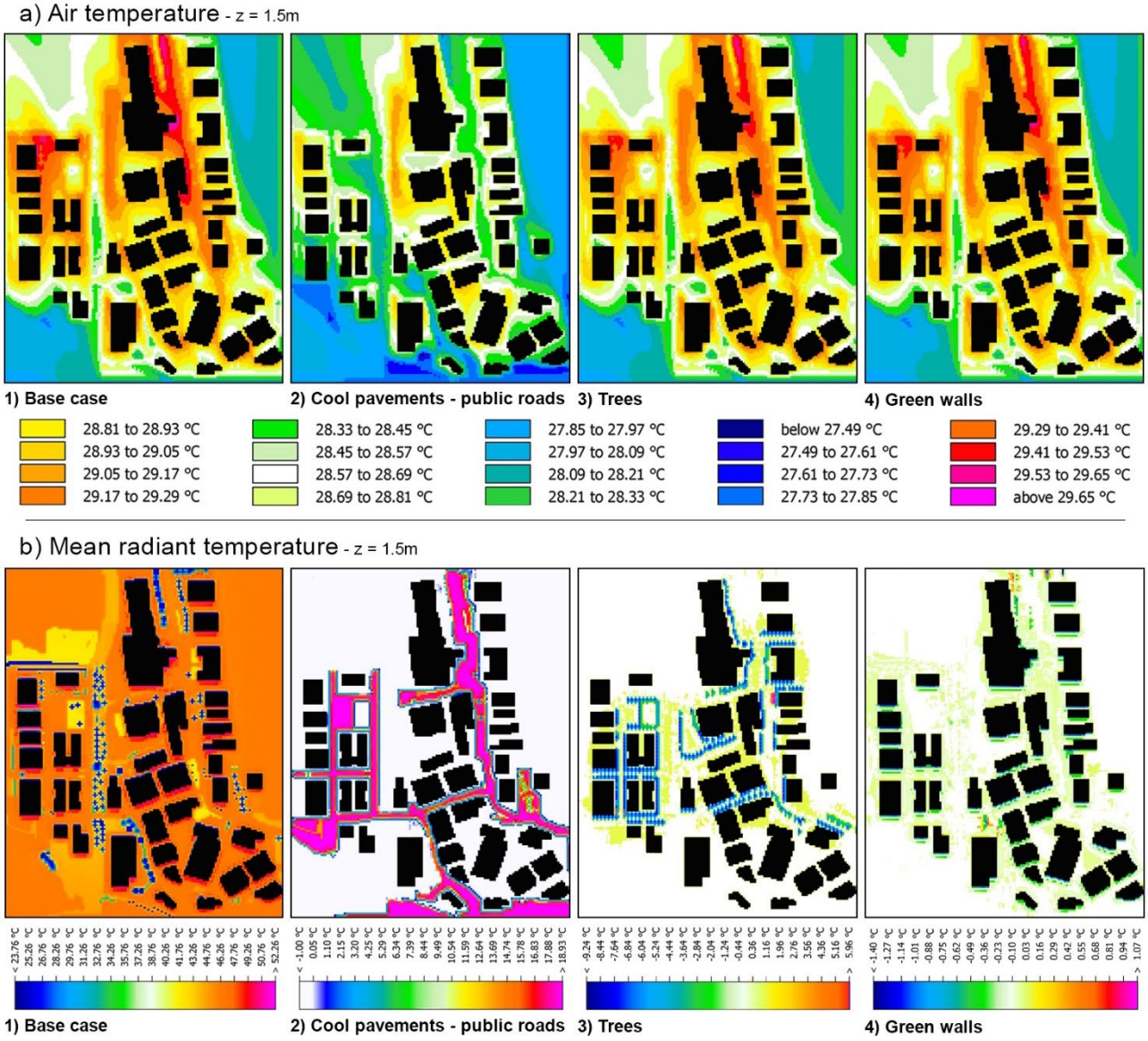


Figure 5.6 Air temperature distribution and mean radiant temperature in Base case, CP, TP, and GW.1 configurations. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

The effectiveness of retrofit measures to be implemented in public urban spaces such as cool pavement and vegetation installation was also investigated in detail considering the M2 districts as expressed in Figure 5.7.

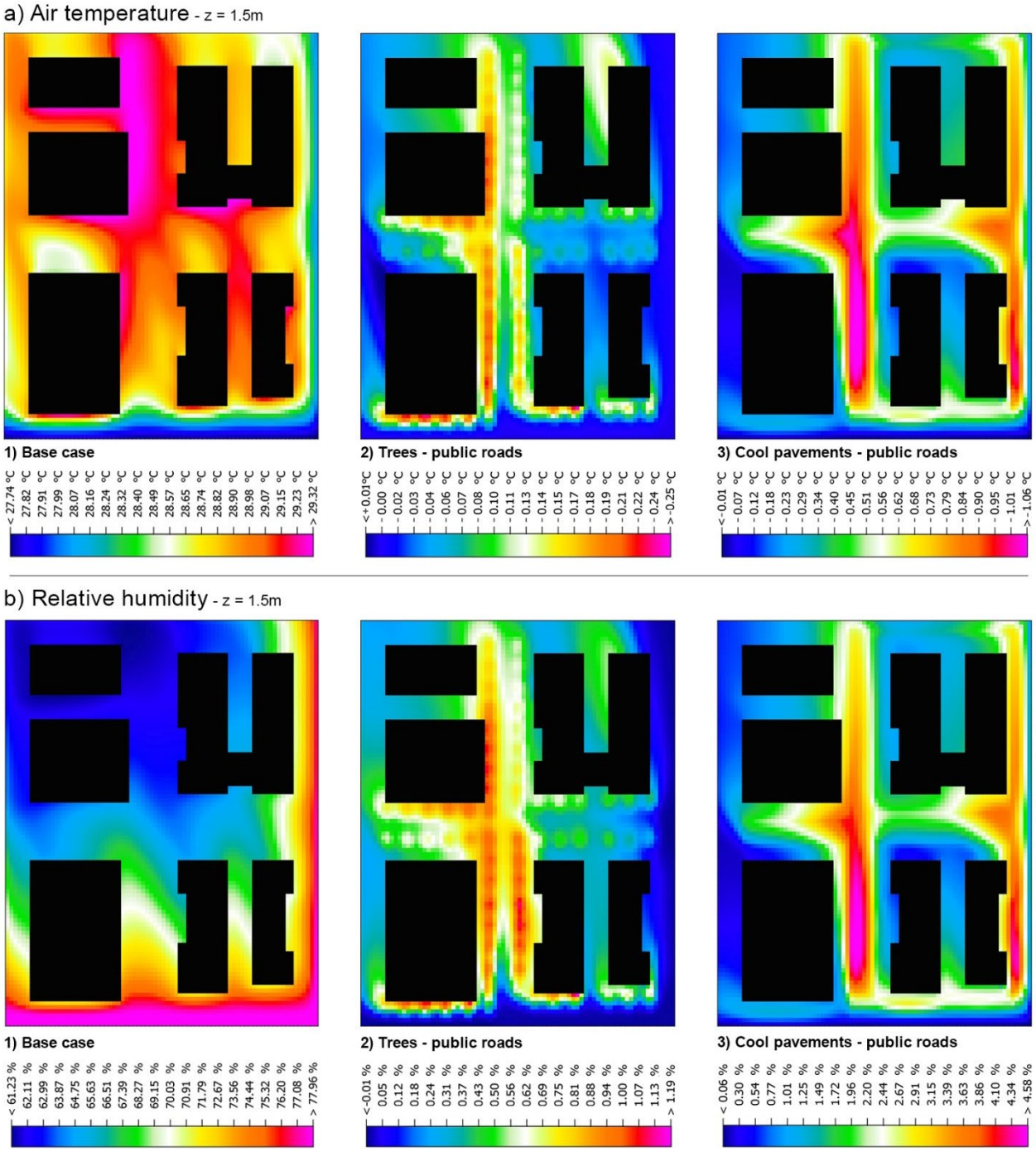


Figure 5.7 Variation of air temperature and relative humidity distribution TP and CP configurations with respect to Base Case conditions for M2 district. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

Trees planting decreases outdoor air temperature especially in correspondence of vegetation crown (> 0.25°C) due to the natural shading effect produced by leaves and branches and, additionally, results in a local relative humidity increase of over 1%. By the way, cool pavements installation proves to be once again the most effective retrofitting measure: in areas exposed to direct sunlight, CP reduces

outdoor temperature by about 1°C and increases relative humidity by approximately 5% compared to the base case.

A comparison between these strategies and the extensive implementation of vertical greenery over facades, according to GW.2 distribution, is presented in Figure 5.8 with reference to the external surface temperature of buildings. Cool pavements have a detrimental effect on these temperatures because of the augmented reflection of solar radiation, while trees can reduce external surface temperatures locally by about 4°C in shaded areas but only marginally at the top or the buildings. Green facades, thanks to extensive shading and evo-transpiration, are the mot effective solution, reducing temperatures by about 8°C for southern façades, and by 1.78°C and 3°C for eastern and western façades, respectively.

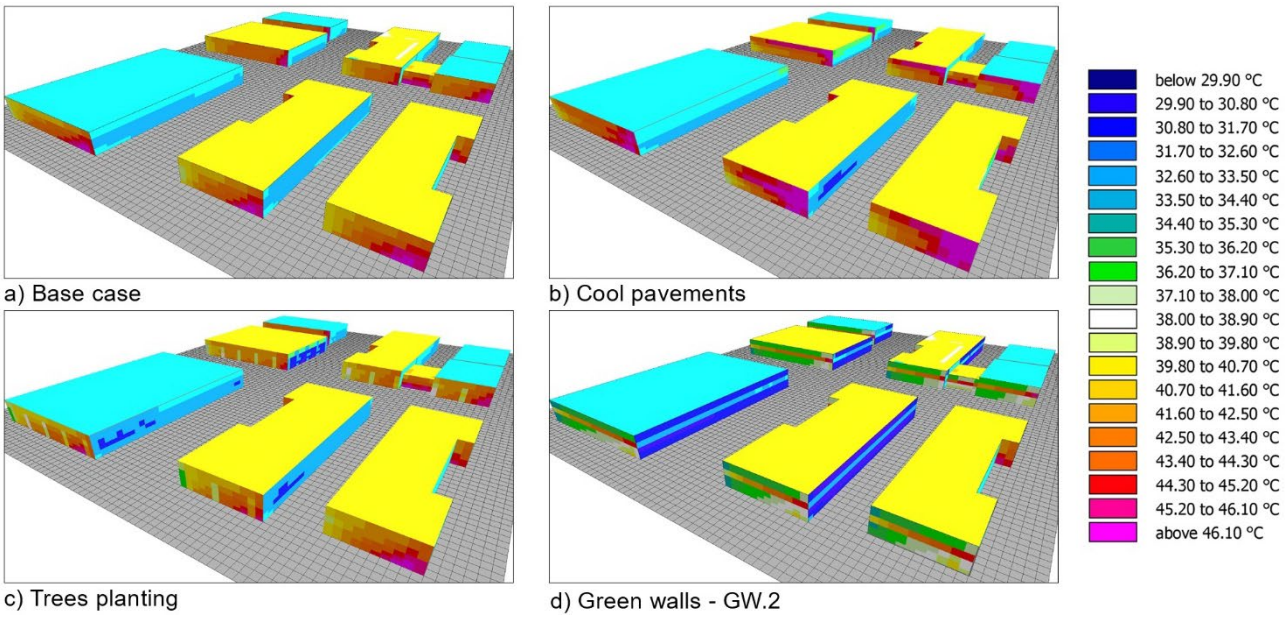


Figure 5.8 Axonometric views of the M2 district with facades' temperatures in the different configurations. *Source: Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

The research let to derive evidence on the influence of both green claddings' extension, considering GW.1 and GW.2 layouts, and the geometry of the urban canyons.

Regarding the former, installing vertical greenery on both the sides of the streets proved to ensure a more pronounced effect in terms of cooling air temperature and increasing relative humidity, guaranteeing at the same time more uniform hygrothermal conditions in the urban canyon under consideration. The maximum temperature reduction occurs in adjacence to green walls exposed to direct sunlight (- 0.17°C), with a noticeable effect even on the opposite side (- 0.13°C). The

effectiveness of green walls decreases progressively towards the edges of the urban canyon and diminishes with elevation towards the top of the buildings.

The influence of urban layout was investigated in detail considering GW.2 green solution and its effects in the different sections of district M2 previously introduced. In Figure 5.9 and Figure 5.10 the results are presented with the graphical outputs obtained after simulations.

Focusing on section AA (Figure 5.9), in the wider urban canyon (number 4), the effectiveness of green walls is less significant, with an average temperature reduction of only 0.04°C since points in the middle of public roads seems to be not affected by the presence of green walls. By contrast, the reduction is more than doubled (0.11°C) in canyon 1, where an average relative humidity increase of about 1.10% is also registered, peaking at 1.4%.

The other sections and urban canyons are illustrated in Figure 5.10. For section BB, unaffected by winds and boundary conditions, the effectiveness of green walls is comparable in both included urban canyons, with a mean external air temperature reduction of about 0.08°C. In section CC, the efficacy of GW.2 in canyon 3 is limited by building shadows. In section DD, a significant reduction in external air temperature (> 0.1°C) is observed in canyon 6, where green facades are more effective than in the wider canyons, in which the effects are noticeable only near building façades. For section EE, this trend is reversed, likely due to prevailing winds at the model's border. The effectiveness of green interventions on external air temperature is reduced but remains appreciable in the narrower streets, while the larger canyons show an increased number of affected points compared to section DD.

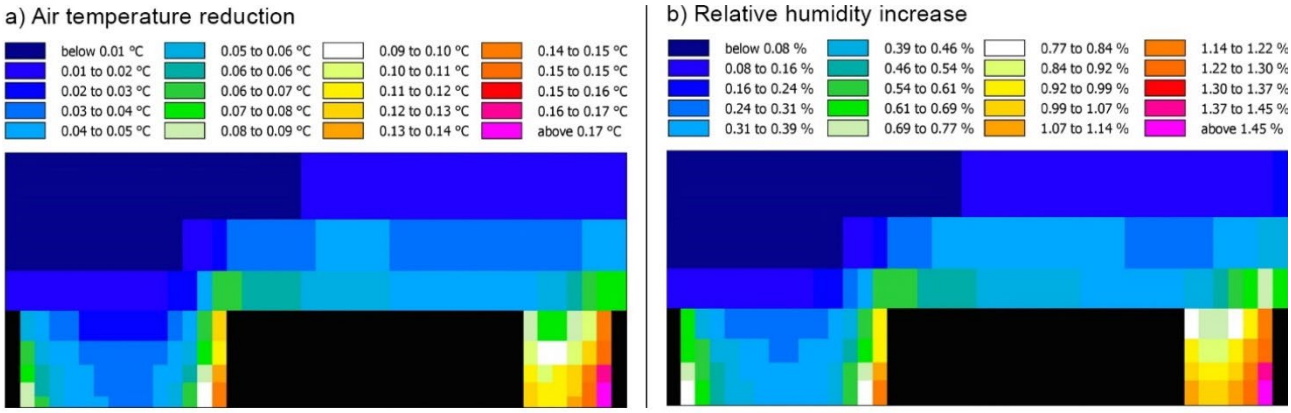


Figure 5.9 Section AA of M2 district: external air temperature [°C] and relative humidity (%) variation following GW.2 solution. *Source: Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

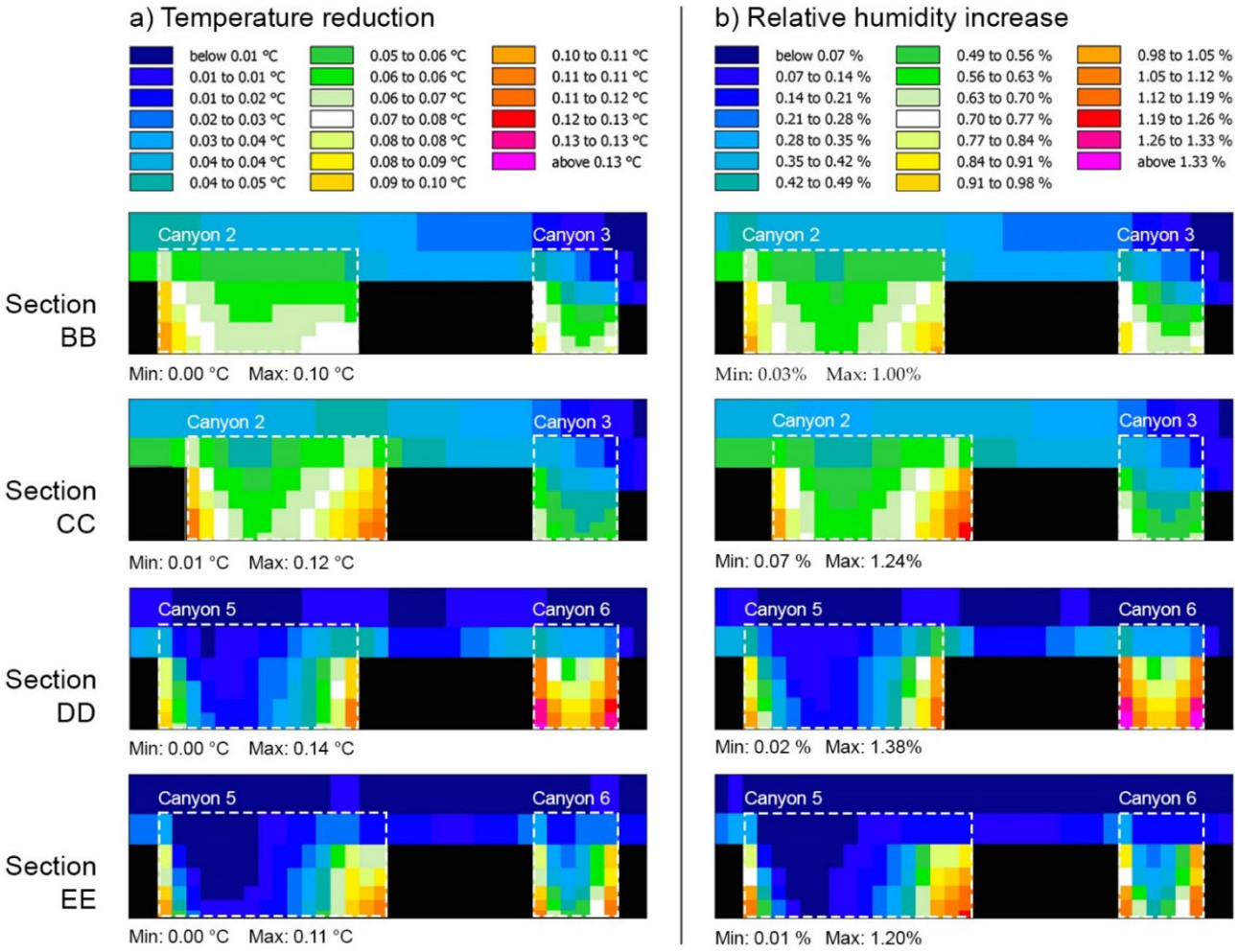


Figure 5.10 Section BB, CC, DD, EE of M2 district: external air temperature [°C] and relative humidity (%) variation following GW.2 solution. *Source: Ciacci C, Banti N, Di Naso V, et al (2022) Experimentation of Mitigation Strategies to Contrast the Urban Heat Island Effect: A Case Study of an Industrial District in Italy to Implement Environmental Codes. Atmosphere 13:1808. https://doi.org/10.3390/atmos13111808.*

The study let to assess that the effectiveness of the different measures, despite being all beneficial, varies significantly based on the urban context. Cool pavements are highly effective for air temperature reduction but may provoke an increase in surface temperatures of the surrounding buildings. Tree planting offers substantial mean radiant temperature reductions through shading but is less effective in air temperature mitigation when considering the average temperature at wide urban scale. Green walls, particularly beneficial in narrow canyons, offer modest improvements in air temperature at urban level but significant reductions in building surface temperatures, highlighting their potential for industrial districts where space constraints limit other forms of greenery.

In conclusion, the following key findings can be outlined for each of the measures analysed:

- Cool pavements:
    - Are the most effective in reducing outdoor air temperatures.
    - Following their installation, the average air temperature in the district can be decreased from 28.87°C to 28.42°C;
    - At the same time however, their implementation can cause an increase in mean radiant temperature and buildings' external surface temperatures due to higher reflectivity of the context;
    - They positively contribute to arise relative humidity at district extent by 1.72%, while green walls and tree planting have minor effects on this parameters (0.25% and 0.06%, respectively).

- Trees planting:
    - Can induce a slight reduction in air temperature and relative humidity if considered at large district scale;
    - Greatly affect local conditions reducing mean radiant temperature by up to 9°C in shaded areas thanks to vegetation crown;
    - Can improve buildings condition by partially shaded façades, depending on solar radiation direction and building orientation;
    - Can partially mitigate the increased reflectivity of the ground in case of cool pavements installation, although less effective in areas with high diffuse radiation.

- Green walls:
    - Have limited impact on a district-level air temperature and relative humidity but are highly effective at local scale;

- Are extremely effective in decreasing buildings' external surface temperatures, by up to 8°C for south-facing façades;

- Effectively shield from direct and diffuse solar radiation;

- Are recommendable to be installed in narrow urban canyons, especially when applied to both opposing building fronts. In this case green walls can lead to a more significant temperature reduction (0.11°C) compared to wider canyons (0.04°C reduction);

- Are influenced by the canyon geometry, wind conditions, and shading from buildings;

- If coupled with cool pavements installation, can partially mitigate the increased reflectivity of the ground.

5.1.2 Green roofs and trees planting: focus on UHI mitigation and air quality

Similarly, a detailed assessment of the influence of green roofs and trees planting as mitigation strategies on micro-climate parameters aims at demonstrating was conducted, by considering the impact on UHI and air pollutants concentration. The research described in this paragraph is extensively addressed in the paper "*Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility*" published in Building and Environment [18].

Following he methodological approach already illustrated in the previous section, a case study industrial district was pointed based un urban and buildings characteristics to evaluate the potential impact of extensive green roof as a retrofitting strategy to be applied on existing roofing stratigraphy. As mentioned earlier, this technological solution it is particularly suitable in case of precast industrial buildings with double sloped beams and precast slabs panel as it can ensure the enhancement of structural, energy, and environmental performance at the same time.

The study evaluated and compared the impact of the possible implementation of the following mitigation strategies:

- Trees planting in the suitable areas in public roads;

- Extensive green roof on existing industrial facilities in the district.

Outdoor air temperature [°C], mean radiant temperature [°C], external surface temperatures [°C], incoming and outcoming longwave radiation [W/m^2], and the deposed mass of PM10 and PM2.5 [μg/m^2] were referred to as evaluating criteria in assessing the benefits of the measures proposed, with respect to the actual state of the industrial district.

A manufacturing site located in Lombardy was considered in this case, featuring analogue characteristics of the ones retrieved in the Tuscany areas investigated. The homogeneous building stock fostering a considerable number of buildings with the desired characteristics and the availability of on-site measurement of outdoor air quality made it particularly suitable for the purposes of the research. The geometry of the urban district of interest was hence modelled in the ENVI-met software, while the evidence of the monitoring campaign carried out in this area by Lombardy Region [19] registering pollutants concentration and microclimate characteristics allowed to validate the

environmental simulations carried out. In Figure 5.11 the methodological workflow adopted is presented.

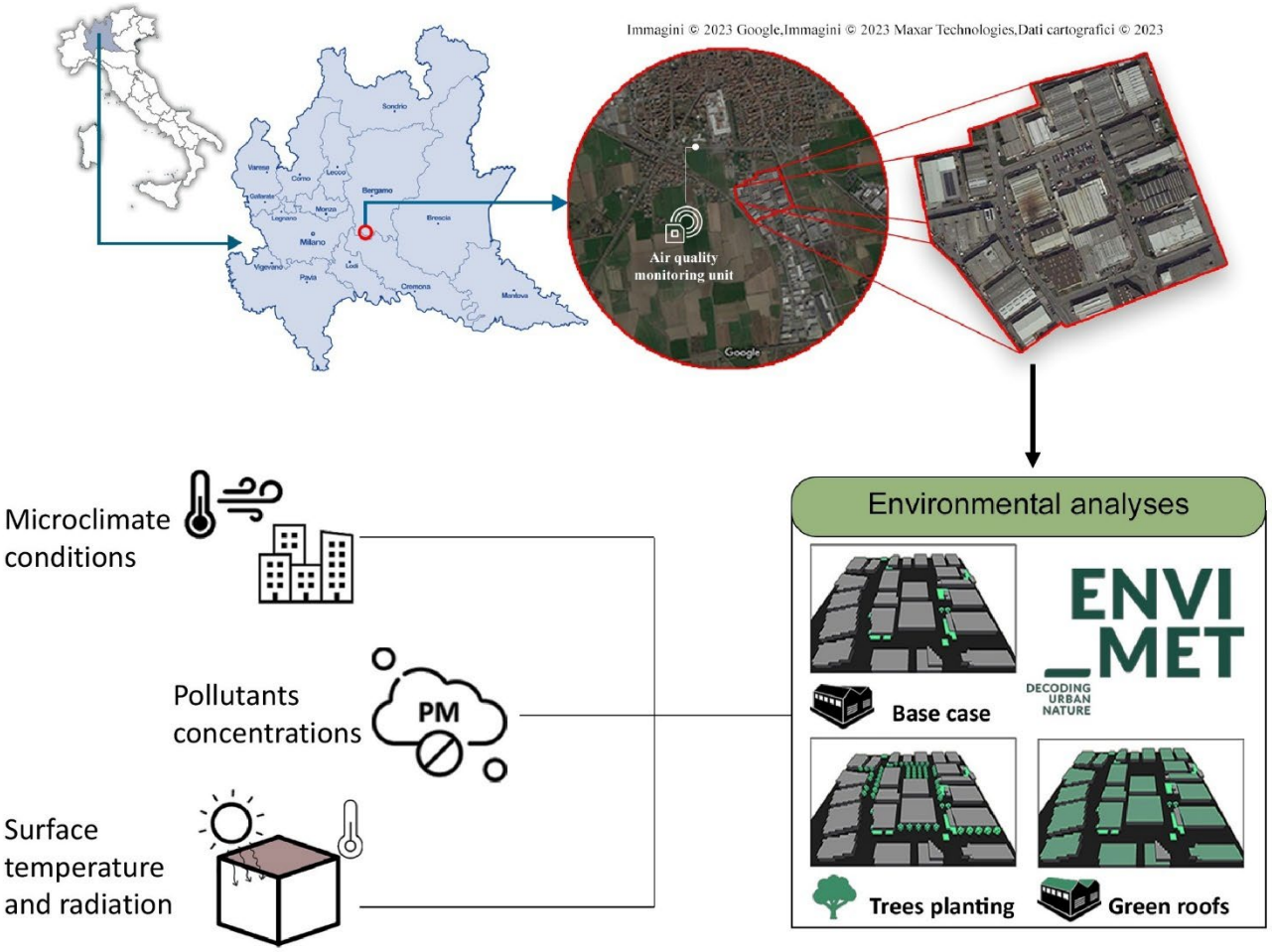


Figure 5.11 Overview of the case study area and methodological framework of the study. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

As for the climatic characterization of the area, it is in climate zone C (temperate climate) according to the Koppen classification and Italian climate zone E, at 111 m above the sea level. Table 5.8 illustrates the average reference parameters for the climate conditions.

Table 5.8 Annual average climate conditions for Caravaggio industrial district. *Source: Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Climate zone	Heating period	Heating Degree Day [K/d]	Global Horizontal Radiation [kWh/m²a]	Diffuse Horizontal Radiation [kWh/m²a]	Direct normal radiation [kWh/m²a]	Air temperature [°C]	Wind velocity [m/s]
E	15/10 – 15/04	2383	1123	630	916	14.4	2.0

Given the uniformity of the building stock typical of the zone investigated, the following properties included in Table 5.9 and Table 5.10 were set for external envelope components.

Table 5.9 ENVI-met settings for external walls properties and stratigraphy. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Absorption [%]	Reflection [%]
Precast concrete	0.06	0.85	840	70	30
Expanded Sintered Polystyrene EPS	0.04	0.035	1000	30	-
Precast concrete	0.10	0.85	840	70	30

Table 5.10 ENVI-met settings for roofing properties and stratigraphy. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Solar Absorption [%]
Fiber Cement	0.01	0.60	1000	60
Waterproof sheet	0.015	0.23	1300	-
Rock Wool	0.04	0.036	1030	-
π precast concrete slab	0.05	2.30	1000	-

Retrofit strategies were evaluated considering trees planting and horizontal greenery on roofs. From a technological perspective, the latter involved the redevelopment of the existing stratigraphy. Specifically, a sandwich panel comprising double metal layers (0.006 m each) and polyurethane insulation (0.10 m) was foreseen to replace the existing precast concrete slab. The green roof stratigraphy chosen, detailed in Table

5.11 also included a water drainage layer and a soil substrate to allow the installation of an extensive vegetation layer.

Table 5.11 ENVI-met settings for green roof properties and stratigraphy. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Material	Thickness [m]	Density [kg/m³]	Conductivity [W/mK]	Specific Heat [J/kgK]
Vegetation (LAD 1.5)	0.01	-	-	-
Soil substrate	0.08	980	0.20	836.8
Filtration (geotextile)	0.00135	-	-	-
Drainage	0.05	25	0.111	1338.9
Anti-root sheet	-	-	-	-
Sandwich panel (polyurethane insulation)	0.10	100	0.022	1450

As for trees installation, evergreen trees species were strategically introduced into both the broader urban canyons and the parking areas., avoiding obstructions for traffic and heavy vehicles. The selection of tree species was guided by their compatibility with the industrial site, taking into account factors such as size, canopy coverage, spacing requirements, as well as the PM10 absorption capacity of various vegetation species [20]. Following these criteria, Quercus ilex, a medium-sized evergreen tree, was chosen. The settings used in the ENVI-met model and are detailed in Table 5.12.

Table 5.12 Tree species properties. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Measure	Tree	Width [m]	Height [m]	Foliage shortwave albedo	Leaves emissivity	Foliage shortwave transmittance
Trees planting	Quercus ilex	6.70 x 8.202	11.32	0.18	0.96	0.30

The spatial distribution of the retrofit measures implemented is presented in Figure 5.12 illustrating the ENVI-met models produced during the research.

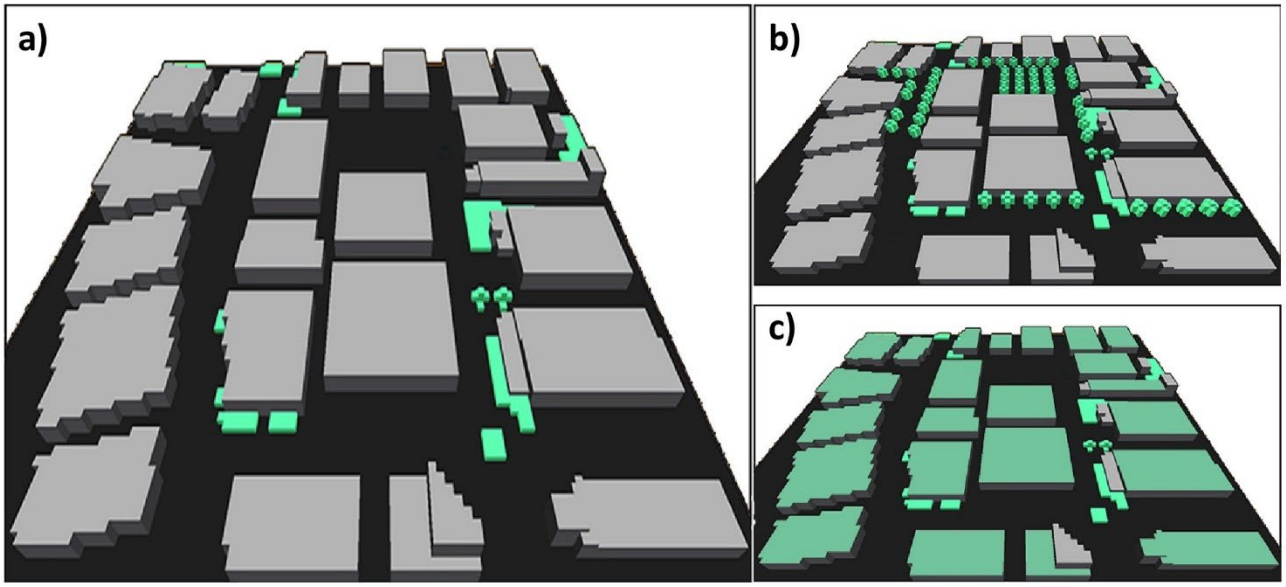


Figure 5.12 ENVI-met models: a) base case; b) trees planting; c) green roofs installation. *Source: elaboration of the author.*

To simulate pollution concentrations (PM10), linear emitting sources were set in the main roads. The average PM10 concentration obtained is 38.6 µg/m³, comparable to the values derived from monitoring campaigns, as shown in Figure 5.13. Additionally, the data present peak concentrations exceeding both daily and yearly threshold values and hence indicating low air quality in the area. According to Italian Law n. 115 of 2010, the daily average limit for PM10 concentration is 50 µg/m³, to be not exceeded more than 35 times per year. Additionally, the law sets a maximum yearly average PM10 concentration limit of 40 µg/m³.

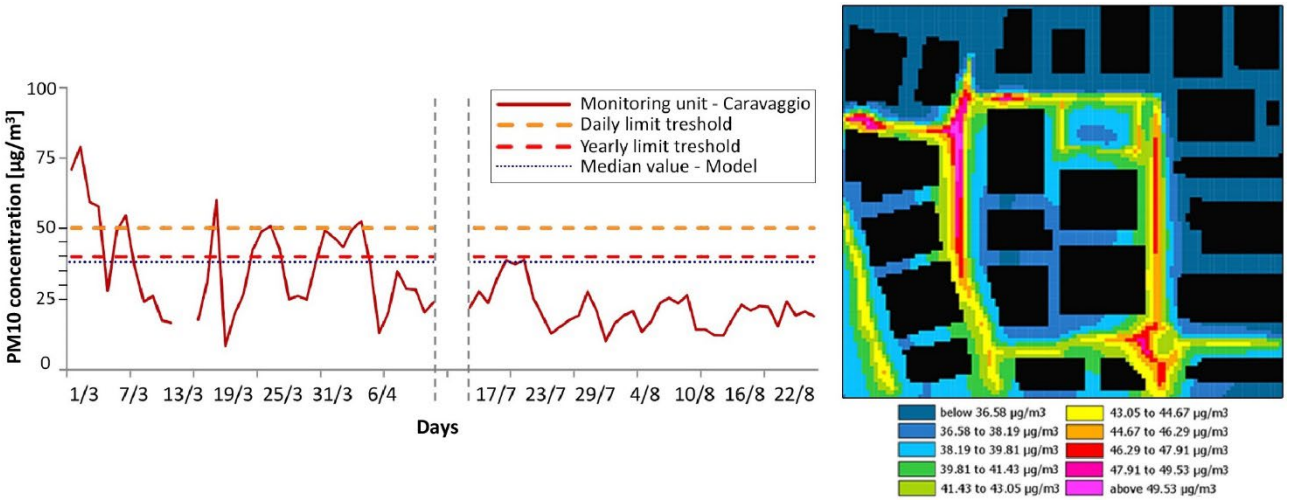


Figure 5.13 PM10 concentration modelling, simulation, and validation in the ENVI-met environment. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Simulations were conducted for two specific dates: March 2nd and July 14th 2021, within the period of 10 a.m. to 4 p.m., with primary results recorded at 3 p.m. The March date was chosen as it

represents the coldest day recorded during the Lombardy Region monitoring campaign, while July 14 was addressed as representative of summer conditions. Results will be presented for both the mitigations strategies illustrated, for both the periods investigated and considering the effects on microclimate conditions and outdoor air-quality.

As highlighted in Figure 5.14, through both spatial distribution analysis and graphical presentation of the data obtained following the simulations carried out, the extensive green roof is an effective mitigation strategy in reducing the average outdoor air temperature, with a drop of approximately 1°C in March. While the base case configuration exhibits a considerable number of points at higher temperatures, the extensive green roof configuration shows a more regular distribution, peaking around 16.65°C. This difference is more evident considering the trends in vertical directions as readable in sections BB and AA, since the influence of green roof becomes more noticeable closer to the roof level (9 m height). Along the vertical development, starting from half the height of the buildings, air temperature decreases from 16.60°C to below 16.05°C.

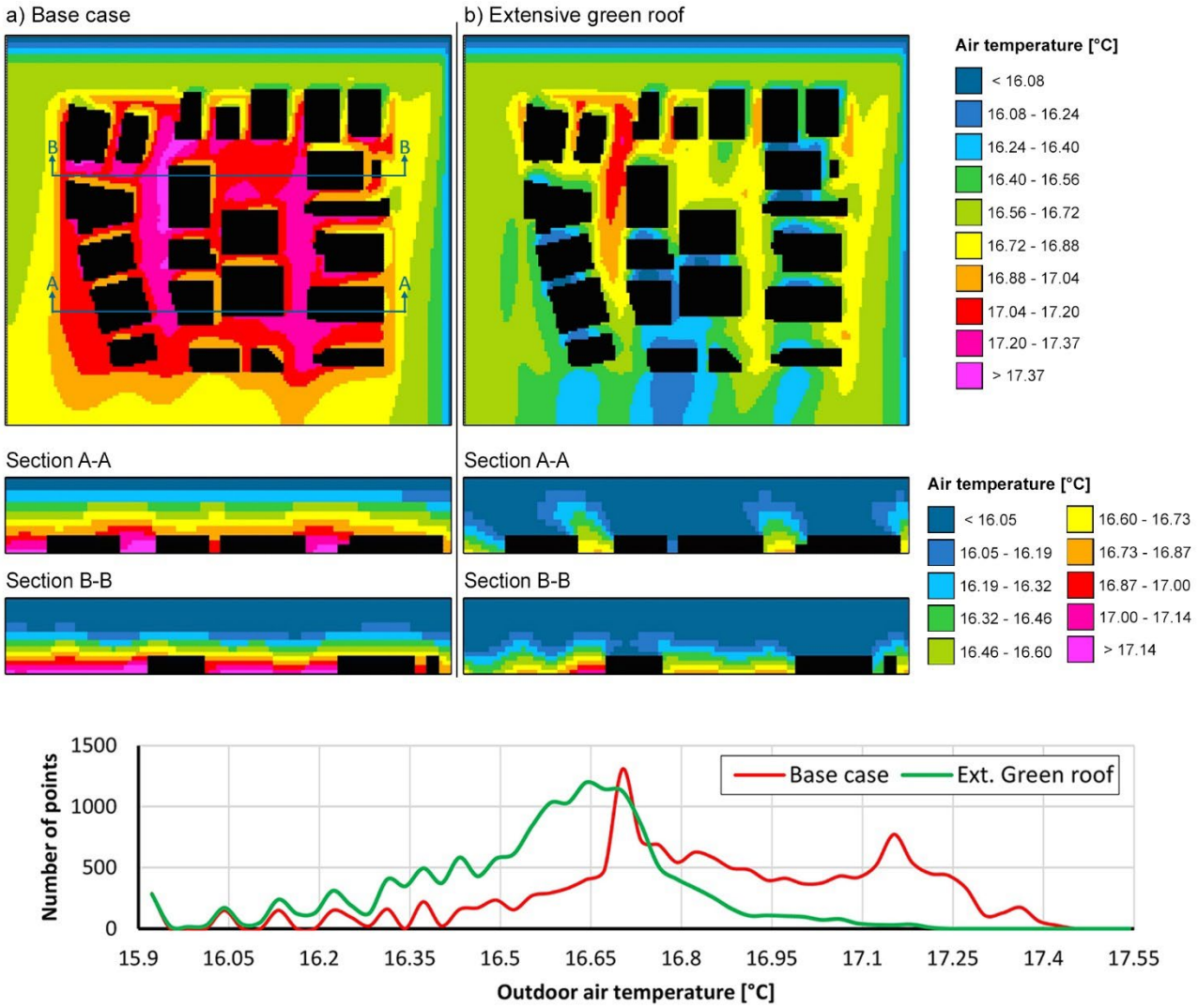


Figure 5.14 Influence of extensive green roof solution on external air temperature in March. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

The impact of green roofs on outdoor air temperature is even more pronounced during the summer season, as shown in Figure 5.15, which illustrates the simulation results from July. In this scenario, the maximum external air temperature exceeds 29.69°C. Consistent with the previous findings, the extensive roof reduces the outdoor air temperature by approximately 1.5°C. Notably, the peak point distribution for the base case is at around 28.63°C with 932 cells, whereas for the green roof layout, it occurs at approximately 28.60°C with 1476 points.

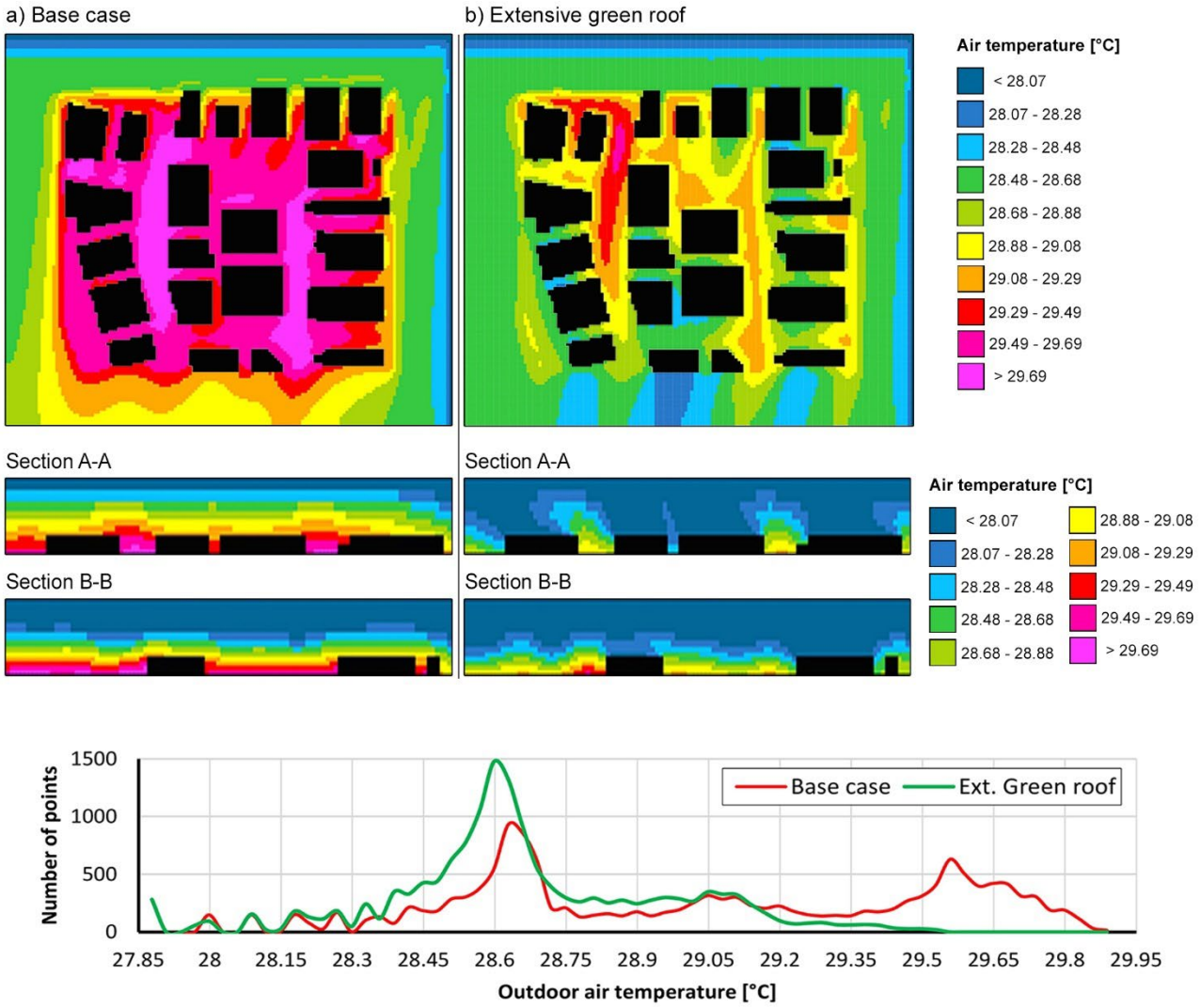


Figure 5.15 Influence of extensive green roof solution on external air temperature in July. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Notably, the characteristics of the vegetation, such as Leaf Area Index (LAI), Leaf Area Density (LAD), and height, can have a major influence on the final effects of the measure proposed and especially on wind speed reduction. This parameter greatly affects both microclimate conditions and pollutant removal. At this regards, two different LAD were considered, and the results are presented in Figure 5.16. The green roof characterized by a higher LAD (1.5 m^2/m^3) results in a reduction in wind speed at the roof level by about 50% compared to the base case. Specifically, wind speeds for the extensive green roof range between 0.31 m/s and 0.76 m/s, while the base case ranges from 0.76 m/s to over 1.36 m/s. In case of vegetation with less reduced growth and a lower LAD (0.3 m^2/m^3), a less significant reduction in wind speed, approximately 0.4 m/s, is observed.

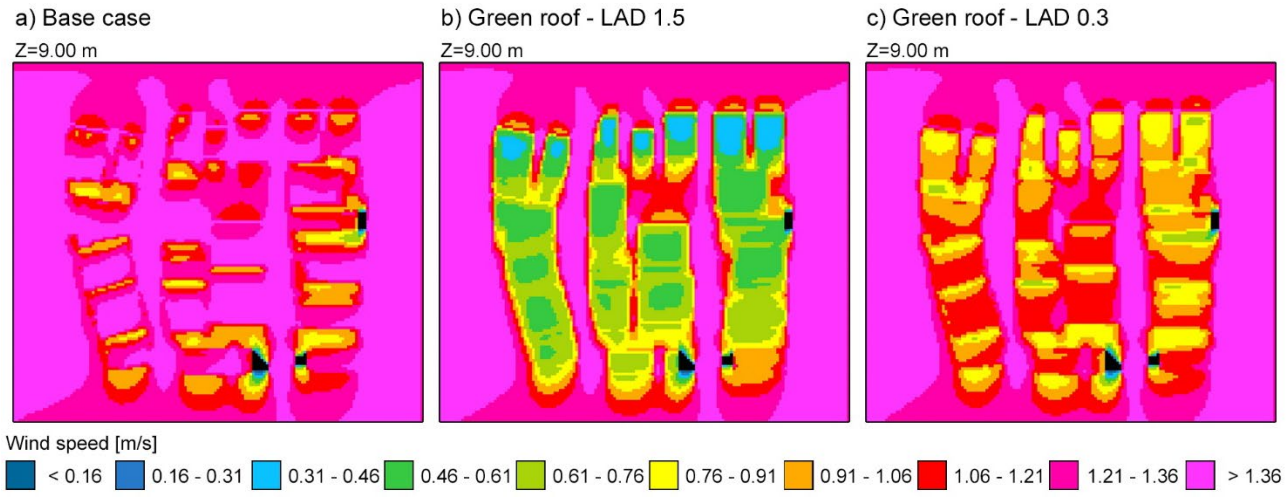


Figure 5.16 Influence of vegetation characteristics in wind speed reduction following green roof installation. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

A similar analysis was produced considering the deposition of particulate matter, specifically evaluating the amount of deposed mass in case of different LAD scenarios. March was considered as reference month in this case given the higher values of pollutants registered in the atmosphere. It is notable in this case that the configuration showing a higher reduction in wind speed associated to higher LAD value exhibits lower values of deposited particulate matter. Conversely, the green roof wit a LAD equal to 0.3 m^2/m^3 exhibits a deposited mass ranging from 35.13 µg/m² to 45.10 µg/m², with a peak at 50.21 µg/m². This configuration can capture particulate matter approximately three times more effectively than the current roofing solutions, which shows deposited mass between 15.03 µg/m² and 20.05 µg/m². Results referring to this aspect are illustrated in figure 5.17.

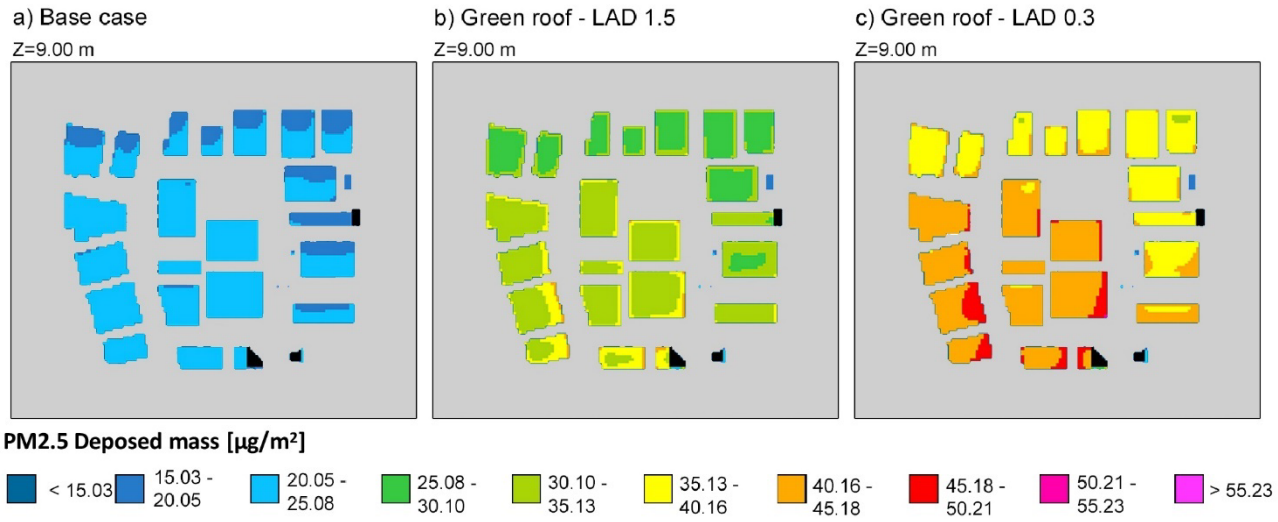


Figure 5.17 Influence of vegetation characteristics in PM2.5 deposition following green roof installation. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving*

urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.

At the building surface level, green roof is beneficial in reducing the external temperature during summer months. In the base case, the external surface temperature typically exceeds 45.12°C, reaching a peak of 52.38°C, while following the green roof implementation a maximum reduction of 15°C is achieved. Industrial buildings usually have larger roof areas than external walls and are exposed to elevated levels of solar radiation during peak hours: by decreasing emitted longwave radiation, the extensive green roof reduces heat flux through the atmosphere, thereby mitigating the Urban Heat Island (UHI) effect. The simulations conducted highlighted an emitted longwave radiation in case of green roof of about 440 W/m², with a 17% reduction with respect to current conditions in case of asbestos finishing.

Figure 5.18 illustrates the results of tree planting interventions, showing the effects on outdoor air temperature and mean radiant temperature for March and July. The results show that this mitigation strategy primarily impacts microclimate parameters at a local scale, with only a minor influence on the broader district conditions. In both March and July conditions, trees planting results in a decrease in outdoor air temperature of approximately 0.2°C and 0.3°C, respectively, particularly in areas with a dense distribution of trees such as the parking lot in the North portion of the district. Changes in temperature within urban canyons with sparsely installed trees are limited, as well as the reduction in the average temperature at the district level. Further analysis of mean radiant temperature reveals notable effects in the vicinity of tree canopies. The simulations show a significant reduction of up to 10°C directly under the tree crowns. In section BB, a decrease of 3°C is observed at the tree crown level compared to the base case, illustrating the localized cooling effect of tree planting interventions. The results of the mean radiant temperature analysis are reported in Figure 5.19.

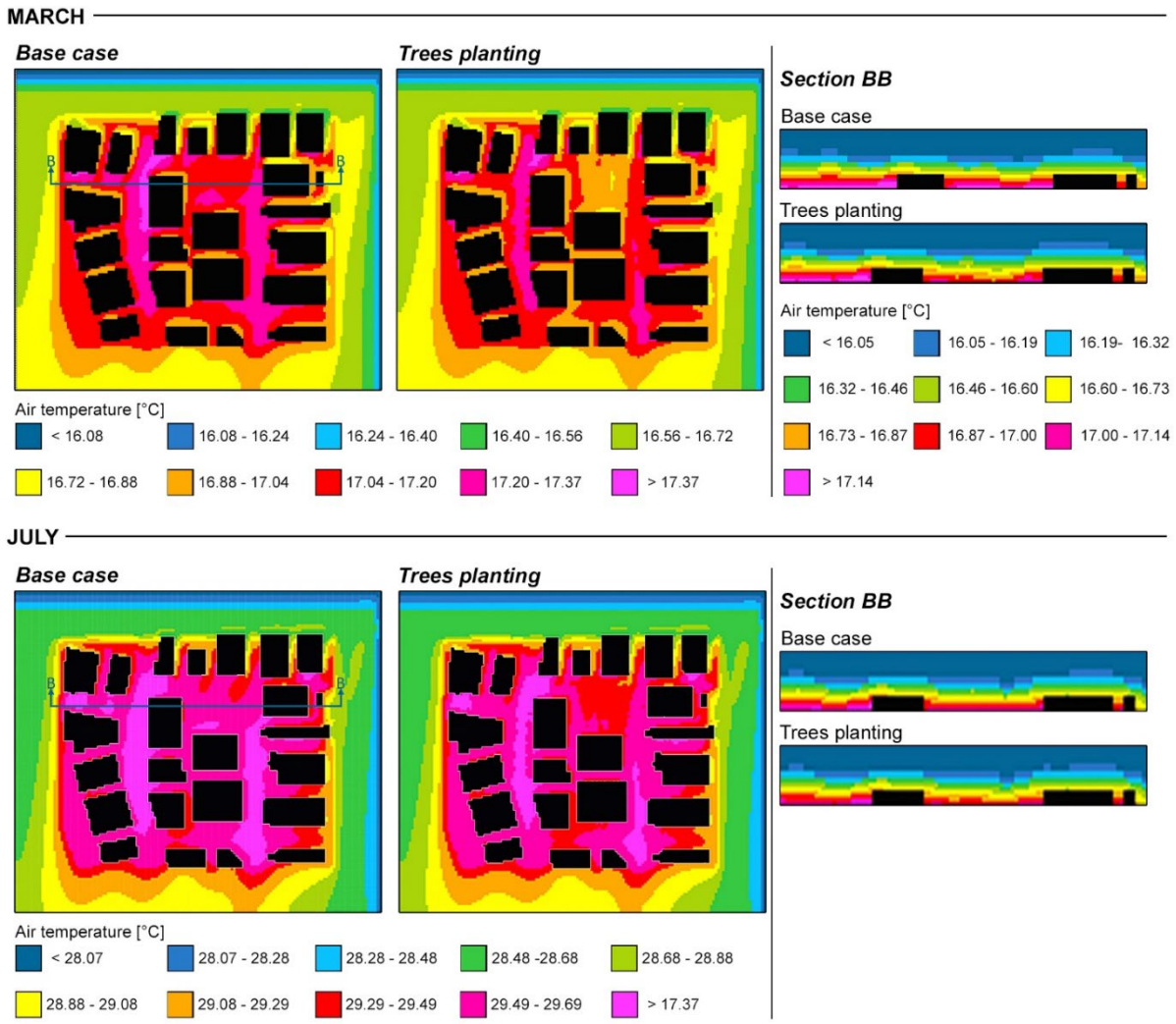


Figure 5.18 Trees planting intervention: results on air temperature in March and July. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Figure 5.19 Analysis of the mean radiant temperature in the district in base case condition and following trees installation considering summer conditions. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an*

Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.

The simulations performed also allowed to assess the role of vegetation in ameliorating outdoor air quality. A slight decrease in PM10 levels can be retraced behind the barrier of trees, as reported in Figure 5.20 through the graphical representation of the results obtained following environmental simulations. This phenomenon relates to the vegetation's ability to concentrate pollution along main roads, thereby reducing pedestrian exposure on adjacent paths. Similar findings have been reported in the literature and urban road greenbelts can be hence evaluated as promising solutions to be deployed in case of industrial districts, especially where narrow roads can result in high pollution concentration. Parking areas, despite having a higher density of trees, do not show a significant reduction in PM10 levels. This can be explained by the lower presence of pollutant sources in these areas during the modelling phase, as vehicular traffic was primarily concentrated on public roads. This observation aligns with the hypothesis that the distribution of pollution sources plays a crucial role in the effectiveness of vegetative barriers in mitigating airborne pollutants.

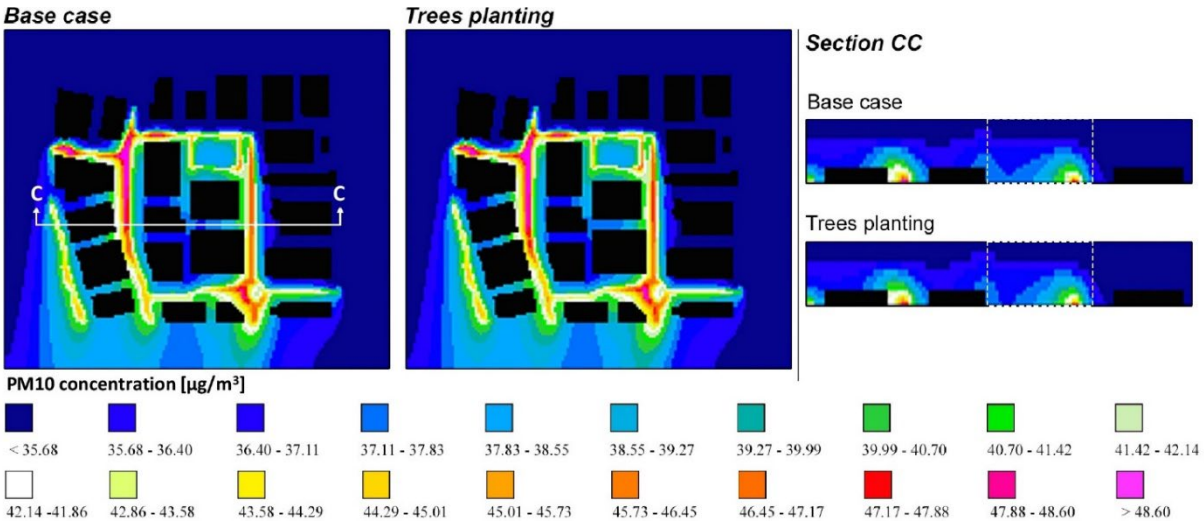


Figure 5.20 Pollutants concentration in the district: comparison before and after trees installation for the March reference date. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

In conclusion, the research highlights that both green roofs and tree planting can improve the urban microclimate conditions, reducing pollutant concentrations, and enhancing the liveability of industrial districts. The strategic integration of these green solutions in urban spaces can lead to improved environmental and aesthetic quality, guaranteeing results at both urban and building scales. The following key findings can be outlined for each of the measures analysed:

- Green roofs:

    - Significantly reduce the external air temperature by up to 1.5°C at a district level;

    - Decrease outer surface roofings' temperature by up to 15°C ameliorating the energy performance of the buildings;

    - Beneficially tackle the UHI consequences by reducing the share of heat re-emitted by the built surfaces;

    - Effectively capture particulate matter (PM2.5), with deposition rates significantly higher than the base case;

    - Should be carefully examined in terms of vegetation species as the characteristics of the greenery highly affect their performances considering for instance wind speed reduction and particulate deposition.

- Trees planting:

    - Primarily influences microclimate parameters at a local level, with remarkable decreases in mean radiant temperature by up to 10°C, ameliorating pedestrian comfort;

    - Results in slight reductions in outdoor air temperature at wide scale, approximately 0.2°C to 0.3°C, but effects are more appreciable in case of areas with a denser plant layout;

    - Effectively reduce pollutant exposure for pedestrians by keeping pollution concentrated on main roads;

    - Should foresee evergreen species for their effectiveness in capturing pollutants during winter when concentrations are higher;

    - Can partially mitigate the increased reflectivity of the ground in case of cool pavements installation, although less effective in areas with high diffuse radiation.

5.2 Building envelope retrofit

To identify a set of redevelopment strategies to properly act on envelope deficiencies, preliminary considerations are necessary to introduce a general distinction between vertical and horizontal opaque closures.

The roofing stratigraphy is closely linked to the building's typology, requiring detailed analysis and case-specific solutions to address the unique components and issues connected. Along with the essential upgrades to thermal performance and insulation, the presence of asbestos in pre-1990s structures poses urgent challenges for removal and replacement.

On the other hand, the technological solutions for external walls have proven to be largely independent of the typological variations found in the analysed area. As a result, retrofitting strategies can be developed and applied for various cases and building configurations, allowing for a generalization of the findings and the replication of similar interventions in a wider set of buildings.

5.2.1 Retrofit measures for vertical closures

When defining retrofit solutions to be applied to existing external walls, particular attention should be given to thermal properties related criticalities, architectural and visual appeal, and their influence on the global structural behaviour of the facility.

For the former, as remarked throughout the text, a general inadequacy in meeting state-of.-the-rt performance standards can be registered. For this reason, except for newly designed buildings, the introduction of an additional thermal insulation layer must be generally foreseen.

Beyond the functional aspects, external walls of manufacturing facilities exhibit a uniform, industrial appearance that diminish the aesthetic quality of buildings, given also the bad preservation state of finishing surfaces. In the current architectural landscape, a growing emphasis on integrating both functionality and visual appeal can be registered: contemporary construction practices prioritize materials and designs that not only comply with energy efficiency and safety standards but also enhance the overall aesthetic and character of the building. Consequently, the merely utilitarian design of outdated manufacturing buildings is even more penalizing.

In addition to the thermal inefficiency and architectural concerns, the frequent recurse to precast panels can also induce structural risks. The response of metal connections under seismic actions

largely proved to be inadequate resulting in partial collapses and failures. At the same time, when external walls are composed of inserted panels or masonry infills, the inclusion of ribbon windows can introduce structural challenges because of uneven distribution of loads, potentially inducing shear failure in the columns.

Given this scenario, a comprehensive range of retrofitting strategies has been proposed to enhance the performance of external walls, addressing multi-disciplinary issues. The strategies considered range from the integral replacement of existing wall components, to the adoption of various insulating and recladding techniques designed to improve thermal efficiency and overall building performance. In Table 5.13 the measures considered are collected and related to the technological solution currently adopted for external walls in the building under examination and the performances targeted.

Table 5.13 Retrofit measures for external walls in industrial facilities. *Source: elaboration of the author.*

Current state		**Retrofit strategy**		**Target performance**		
Technology	**Position**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Masonry / Built in place infills	Inserted	EW.1	Substitution with sandwich panels	X	X	X
Horizontal precast panels		EW.2	Substitution with Aquapanel panels	X	X	X
Horizontal precast panels or Vertical precast panels	External	EW.1	Substitution with sandwich panels	X	X	X
		EW.2	Substitution with Aquapanel panels	X	X	X
		EW.3	Installation of internal insulated counter-walls	X		
		EW.4	External recladding with sandwich panels	X		X
		EW.5	External recladding with ETICS	X		X
		EW.6	External recladding with Vêture system	X		X
		EW.7	Recladding with rainscreen façades			X
		EW.8	Recladding with metal meshes			X
		EW.9	Recladding with BIPV components	X		X
		EW.10	Addition of indirect green façades	X		X
		EW.11	Partial substitution with curtain walls	X		X

In the following, the different measures listed above will be discussed to highlight the main benefits or potential criticalities connected to each. It has to be remarked that whatever technological solution is chosen, the performance achieved must comply with the requirements set forth by national regulations for the various climatic zones. Where necessary, the thickness of the insulating layer to be added should be evaluated on a case-by-case basis, considering the characteristics of the existing wall.

- EW.1 Substitution with sandwich panels, EW.2 Substitution with Aquapanel panels

  These solutions foresee the complete substitution of the existing external walls and are the most impactful ones in terms of interruption to the working activities. Despite being applicable also in case of external cladding panels, these are particularly indicated for buildings currently featuring inserted infills or precast horizontal components. The latter in particular can induce shear failure mechanisms due to the inadequate design procedures adopted to face dynamic actions. The replacement of the existing rigid elements with lightweight cladding solutions can be highly beneficial in this case and should be recommended to ensure a substantial improvement in the structural performance of the building itself. Notably, for both metal sandwich panels or Aquapanel systems installation a careful analysis of the spans to be covered and the height of the walls is required. Adequate substructure have to be designed to accommodate the new cladding elements and the opening fixtures. Moreover, the mechanical properties of the innermost layer have to be properly designed in the EW.2 measure, taking into account possible impacts and damages induced by the ongoing manufacturing processes during the operational phase of the building.

  Specifically, the influence of precast horizontal panels on the structural behaviour of industrial buildings has been addressed in a publication entitled "*Territorial seismic vulnerability analysis of precast reinforced concrete buildings within Mugello industrial districts*", presented at the conference "Innovazione e sostenibilità nelle strutture in calcestruzzo" [21].

- EW.3 Installation of internal insulated counter-walls

  In case of external geometry of wall panels with complex shapes, retrofitting interventions can address the internal side of the walls to reduce the complexity of the installation procedures. This could be also the case of facilitates with significant machinery components installed on facades, such as ducts or pipes, that would require complex replacement operations. A practical solution can be represented by the addition of insulated counter walls

on the perimeter vertical closures. However, especially in environments where heavy machinery is used or where there is frequent movement of equipment and materials, .the risk of brittle failures should be considered. Counter walls should be hence constructed including layers capable of high impact resistance. Additionally, to result in both energy redevelopment and external aesthetic upgrade, this measure should be complemented by others capable of ameliorating the outside visual appeal of the facility (EW:7, EW.8, EW.9).

- External recladding with sandwich panels (EW.4), ETICS (EW.5), Veture system (EW.6), rainscreen facades (EW7), metal meshes (EW8)

  Retrofitting solutions that involve external recladding, allow to preserve in place the existing precast reinforced concrete panels. These provide significant mechanical resistance and their high thermal mass helps to improve the building's thermal behaviour during summer season and stabilize internal temperature fluctuations. However, the connections between these panels and the load-bearing structure must be carefully examined and replaced, reinforced, or substituted where necessary.

  ETICS solution, differently from the others, does not require the installation of a dedicated substructure but its applicability is strictly related to the geometry of the outermost layer of the existing panels: in case of complex sections in fact, the installation of the insulation layer may result compromised.

  Among the available recladding options, the Vêture system stands out for its superior aesthetic quality, making it a particularly suitable choice when visual appeal is requested. Nonetheless, this system requires a higher initial investment and poses challenges for damaged panels replacement. For these reason, the Vêture system can be recommended for buildings' portions hosting corporate headquarters or executive offices, where aesthetic attention is requested and durability is not compromised.

  Similar considerations can be applied for rainscreen facades, but in this case the thermal insulation is not necessarily included as this solution could be also applied as a simple finishing layer to improving the aesthetic quality. Similar solutions with metal meshes or decorative elements could be applied for the same purpose.

- EW.9 Recladding with BIPV components

External recladding with elements featuring photovoltaic modules can be a valuable solution to ameliorate at the same time the architectural quality and the energy performance of the building, ensuring energy production from renewables. The wide façade surfaces available, along with the regular layout of windows openings, make industrial buildings particularly suitable for this kinds of application. Different Building Integrate Photovoltaic solutions (BIPV) can be adopted, ranging from punctual installation of tilted panels to continuous recladding of facades. The supporting elements, as well as the increase in vertical loads on existing panels, must be analysed in detail.

- EW.10 Addition of indirect green façades

  The installation of vertical greenings on existing facades can be considered as a promising measure, capable of acting at both building and district scales. As previously introduced, indirect green cladding relying on metal cables or meshes as supports for vegetation growths should be preferred to limit the additional weights induced. Living walls solutions or modular configurations featuring pots installed at different heights should be avoided.

- EW.11 Partial substitution with curtain walls

  In case of deep renovation interventions including significant changes in the internal layout of the building, the removal of cladding panels in portions of the building and their replacement with curtain walls can be considered. This kind of measure significantly affects the global energy balance of the building, given its impact on both envelope thermal resistance, incoming solar radiation and natural lighting contribution. This kind of intervention can significantly enhance the architectural quality of the building but its higher investment costs and the considerable installation implications makes it suitable only in limited circumstances.

Interventions should be also foreseen to tackle deficiencies connected with the glazed portions of external walls and outdoor industrial doors. Windows and openings, particularly in older facilities, often feature single wired panes with frames lacking any thermal breaks. Additionally, both windows and doors, badly maintained over time, typically exhibit low airtightness, contributing to significant energy losses and reduced overall building efficiency. Notably, in case of the interventions on external walls foreseeing their complete replacement, the substitution of currently existing windows should be undoubtedly included. To prevent overheating issues in summer periods, the installation of shading devices could be evaluated. These can be external louvres or internal sheltering solutions, both in fixed or automatized configurations based on sensors input. The implementation of

automatization systems can also involve windows opening and can allow better indoor condition control and natural ventilation exploitation. All of the cited measures can be deployed individually or integrated. The retrofit interventions targeting these components are collected in Table 5.14.

Table 5.14 Retrofit measures for windows and industrial openings. *Source: elaboration of the author.*

Current state		**Retrofit strategy**		**Target performance**		
Element	**Criticalities**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Windows	Single glass pane Wired glass Frame without thermal break Compromised airtightness	W.1	Substitution of existing windows with new ones featuring stratified glazing and thermal break	X		
	Manual opening	W.2	Adoption of automatic opening systems	X		
	Lack of shading solutions	W.3	Installation of solar shading systems, both fixed or automatized	X		X
Industrial doors	Inadequate thermal insulation Compromised airtightness	W.4	Installation of new state-of-the-art sectional doors or industrial openings	X		X

5.2.2 Retrofit measures for roofing stratigraphy

In contrast to the considerations for external walls, the redevelopment of roofing stratigraphy requires a clear distinction between the various typological variants under evaluation, as each configuration presents unique characteristics that must be addressed. For this reason, the various measures will be presented with a clear distinction between the typological variants of interest. In this case both interventions addressing completion elements for the roofing stratigraphy and structural components and will be included.

Notably, for the latter, further analyses would be needed to act on connections between roofing, side beams, and columns in case of buildings featuring longitudinal frames or between roofing beams and columns for structures with transversal portals. Interventions can include in this case the strengthening of elements sections and the installation of dissipative connection devices. These aspects will not be detailed in the dissertation as they exclusively involve structural issues.

As for the energy performance, the national regulatory standards for the different climate zones and the corresponding thermal properties expected must be obtained regardless of the chosen solution. The selection of the most adequate retrofit strategy must be based on case-specific evaluations to guarantee the overall sustainability of the building redevelopment. The economic feasibility of the different solutions must be analysed considering the budget available for the initial investment and the reduction of operational costs achieved. The various measures presented are characterized by different impact on production activities and their suspension has to be considered according to the business scenarios of the company operating in the building. The environmental profile of each solution can be furthermore addressed as reference criteria by applying Life Cycle Assessment evaluations to exclude redevelopment strategies responsible of undesired impact on natural resources.

In the following sections, the typological variants identified in the territory will be analysed individually to address their specific characteristics. Some of the proposed measures will be highly case-specific, designed to address issues related to the particular roofing solutions of each typology, while others may be transversally applicable in multiple facilities. Additionally, a combination of different measures may also be considered, as detailed later.

The analysis of possible retrofit solutions is presented starting from buildings with precast double sloped roofing trusses (Sl_rc_slb variant), to later move on following the evolution of precast systems configurations. Table 5.15 collects the various measures proposed that will be detailed to discuss their benefits as well as the potential limitations and the required precautions to be accounted for in the design phase.

Table 5.15 Retrofit strategies for roofing redevelopment in buildings of the SL_rc_slb variant. *Source: elaboration of the author.*

Typol. variant	**Current state**		**Retrofit strategy**		**Target performance**		
	Structure	**Completion solution**	**Code**	**Measure**	**En.**	**Str.**	**Ar.**
SL_rc_slb	π slabs (+r. c. slab)	+ finishing Or +thermal insulation + finishing	RS.1	Precast beams removal and substitution with metal trusses		X	
			RS.2	π slabs removal and substitution with metal sandwich panels	X	X	
			R.1	Insertion/substitution of thermal insulation and external finishing	X		X
			R.2	Recladding with metal sandwich panels	X	X	X
			R.3	RS.2 + Extensive green roof installation	X	X	X
			R.4	Insulated false-ceiling installation	X		X
	Precast reinforced concrete purlins	+ asbestos panel + thermal insulation + asbestos corrugated panel Or + asbestos panel + asbestos corrugated panel	RS.1	Precast beams removal and substitution with metal trusses		X	
			R.5	Substitution of completion stratigraphy with metal sandwich panels	X	X	X
			R.3	R5. + Extensive green roof installation	X	X	X
			R.4	Insulated false-ceiling installation	X		X

- <u>RS.1 Precast beams removal and substitution with metal trusses, RS.2 π slabs removal and substitution with metal sandwich panels</u>

  These measures implies the complete substitution of the structural components forming the portal frames and roofing slab in case of π tiles. Given the intrusive nature of this operations,

there measures should be recommended in case of severe structural issues capable of hindering the integrity of the facility in case of seismic events. The proposed redevelopment strategies aim at reducing the seismic mass of the roofing stratigraphy. In case of the substitutions of the precast concrete beams currently in place with double sloped metal trusses, particular attention should be paid to the connections between the latter and the existing columns.

The RS.2 solution simultaneously enhances both structural and energy performance. However, the addition of new purlins may be necessary if the spans between consecutive portal frames are too large.

- R.1 Insertion/substitution of thermal insulation and external finishing

  In case of inadequate thermal insulation of the current roofing stratigraphy, both due to the lack of a specifically intended layer or bad preservation conditions, interventions are required. The addition or substitution of a layer with proper insulating properties is hence crucial to significantly enhance energy efficiency. The selection of the most adequate material should be based on economy or environmental criteria according to case-specific evaluations.

  For the finishing layer, Thermoplastic Polyolefin (TPO) membrane layers represent a promising solution as they offer durability, energy efficiency, environmental benefits, and cost-effectiveness. TPO membranes are lightweight, flexible, and easy to install through various methods, including mechanical attachment, adhesion, or ballasting, providing versatility for various roofing configurations. TPO membranes are at the same time highly resistant and durable, capable of withstanding harsh weather conditions, UV exposure, strong winds, and temperature fluctuations. They show good resistance also towards chemical agents ant his makes them suitable for being applied in industrial districts. Moreover, they are highly reflective and this reduces heat absorption improving the overall energy efficiency of the roof during the hottest periods to prevent summer overheating. In addition, TPO can be easily recycled reducing the overall environmental impact.

- R.2 Recladding with metal sandwich panels, R.5 Substitution of completion stratigraphy with metal sandwich panels

  The recladding of the external surface of the roofing slab with a newly installed layer of metal sandwich panels allows to address at the same time both architectural and energy issues. In this case a mediation substructure is necessary between the concrete load-bearing layer and the new panels, to which they will need to be fastened.

On the other hand, in case of buildings with precast reinforced concrete purlins and completion stratigraphy fostering multilayer packages, the latter can be easily replaced recurring to the metal sandwich panels solution. Given the generally shorter spacing between portal frames in these facilities, the existing purlins can also be removed if the new cladding panels are oriented parallel to the building's longitudinal axis and are attached to consecutive beams.

This solution allows for rapid installation procedures, effective thermal insulation and enhanced watertightness of the roofing. At the same time, the panels available on the market can also features ribs to facilitate the seamless integration of PV systems.

- R.3 Extensive green roof installation following the Substitution of completion stratigraphy with metal sandwich panels

  In the event of interventions that involve replacing the current slab with lightweight metal sandwich panels, the possibility of implementing an extensive green roofing system should also be considered. The reduction in weight achieved by substituting structural components with lighter alternatives can, in fact, facilitate the use of heavier finishing solutions such as green roof technologies. The introduction of a substantial growing media layer is effectively offset by the reduced weight of the new structure. Technological solutions available on the market now enable the combination of metal sandwich panel decks with vegetation, providing enhanced insulation and thermal inertia for the building. This approach not only improves aesthetic quality but also ensures positive effects at the district scale.
- R.4 Insulated false-ceiling installation

  Installing insulated false ceilings can be effective in enhancing thermal efficiency by reducing the volume of the heated space, thereby lowering heating energy demand. his approach can be particularly beneficial in large indoor spaces where the ceiling height is significant, such as workspaces in industrial facilities. However, when considering the installation of insulated false ceilings, it is important to take into account the building’s overall design and the intended use where they are supposed to influence .In environments where precise control of internal conditions is crucial or where the layout changes frequently, the flexibility and potential disruption associated with installing a false ceiling need to be carefully assessed. Moreover, the effect on lighting and aesthetics should be considered, as false ceilings can influence both the visual appeal and the distribution of artificial lighting in indoor environments. In workplaces with bridge cranes or other large overhead equipment, installing insulated false

ceilings may not be pursued due to the operational needs of these machinery, that require no obstructions and sufficient space for not interfering with their movement or maintenance.

When considering buildings with precast roofing beams and plain roof (P_rc_b typological variant), some of the previously discussed measures can be implemented alongside other solutions specifically designed to address their unique characteristics as reported in Table 5.16.

Table 5.16 Retrofit strategies for roofing redevelopment in buildings of the P_rc_b variant. *Source: elaboration of the author.*

Typol. variant	Current state		Retrofit strategy		Target performance		
	Structure	Completion solution	Code	Measure	En.	Str.	Ar.
P_rc_b	Y-section arched beams	Extrados: fibre cement vaulted panels Intrados: : fibre cement panels counter-ceiling with insulation layer	RS.1	Precast beams removal and substitution with metal trusses		X	
			R.2	RS.1 + Recladding with metal sandwich panels	X	X	X
			R.4	Insulated false-ceiling installation	X		X
			R.6	Substitution of extrados completion panels with sandwich panels with TPO finishing; internal counter-ceiling removal.	X	X	X
			R.7	R.6 + installation of fire-proof false-ceiling	X	X	X

- R.6 Substitution of extrados completion panels with sandwich panels with TPO finishing; internal counter-ceiling removal

  The solution is primarily meant to dismantle components affected by the presence of asbestos in both the internal ceiling panels and external closure covers, as well as to improve the thermal insulation and the watertightness of the roofing stratigraphy. Additionally, structural concerns are considered as this measure avoids increasing the load associated with roofing stratigraphy.

  For the roofing, steel sandwich panels can be installed , consisting a pre-installed synthetic TPO membrane at the extrados, corrugated sheets made of pre-painted galvanized steel with a thickness ranging from 0.4 to 0.8 mm, and an insulating layer of polyisocyanurate (PIR) or rockwool placed between the latter.

  The use of a TPO membrane with a separate weldable strip allows the panel to be employed in different geometries and inclinations. To properly fasten the completion panels, a specifically designed steel components is set to be fixed to the existing precast beams. The

latter, currently inducing severe linear thermal bridges, would be completely thermally insulated at the extrados in the retrofit configuration. Moreover adequate watertightness would be also guaranteed and concrete surfaces prevented form rainwater flowing over them. This measure is meant to preserve the precast beams, reducing the impact of the retrofit intervention., but allowing at the same time to eliminate the currently existing thermal deficiencies and prevent erosion phenomena. Thermal insulation and waterproofing would be also guaranteed in correspondence of the edge beams by installing specifically intended steel insulated profiles forming a new gutter for rainwater collection. Moreover, the geometry of the outer surface of the steel sandwich panels available in the market can include ribs that facilitate the installation of PV modules through dedicated components specifically designed. The presence of a newly introduced thermal insulation layer in external position, let to remove the internal counter-ceiling.

- R.7 Installation of fire-proof false-ceiling in addition to the previously described intervention
  When specific fireproof requirements are necessary, the installation of an internal counter ceiling with adequate fire resistance property can be foreseen. In this case the relative supporting elements can be fixed at the lower flange of precast beams and arranged in transversal direction with respect to the beams in order to prevent the inflection of the panels. Moreover, if the external insulation layer provided by the cladding panels is not sufficient, an extra-layer can be included over the counter ceiling itself.

- RS.1 Precast beams removal and substitution with metal trusses
  In case of buildings featuring precast roofing beams showing bad preservation state or not meeting the required structural standards, their removal and substitution with metal trusses can be proposed. This lead to a general reduction of the seismic mass associated with the roofing, given the lower weight of newly installed steel trusses. Moreover, currently installed roofing beams are spaced by interaxis ranging from 1.5 to 1.8 m while this intervention can allow to increase this distance reducing their number. Completion of roofing stratigraphy can be in fact realized recurring to metal sandwich panels relying on purlins that can cover wider spans (R.2).

When considering plain roof buildings with precast tiles (P_rc_t typological variant), the target building stock is generally more recent and shows better overall performances and preservation conditions. Moreover, given the peculiarities of the structural layout, interventions acting on load

bearing horizontal elements may result more complicated to be implemented. The measures referring to this building variant are expressed in Table 5.17.

Table 5.17 Retrofit strategies for roofing redevelopment in buildings of the P_rc_t variant. *Source: elaboration of the author.*

Typol. variant	**Current state**		**Retrofit strategy**		**Target performance**		
	Structure	**Completion solution**	**Code**	**Measure**	**En.**	**Str.**	**Ar.**
P_rc_t	Precast roofing tiles	Fibre-cement vaulted panels Or Sandwich completion panels	R.1	Insertion/substitution of thermal insulation and external finishing	X		
			R.4	Insulated false-ceiling installation	X		X
			R.5	Substitution of completion elements with metal sandwich panels	X	X	X
		Skylights	Reference to Table 5.19		X	X	X

- R.1 Insertion/substitution of thermal insulation and external finishing

  In buildings featuring precast concrete tiles as main roofing components, insulation layers can be included within the tile stratigraphy in more recent facilities or placed externally at the extrados. If not sufficient or deteriorated, thermal insulation can be substituted or integrated by installing an external layer. For the external waterproofing and finishing layer, TPO membranes can be used as previously specified.
- R.4 Insulated false-ceiling installation

  Buildings belonging to the typological variant under consideration are frequently characterized by significant portions of the roof covered by skylights or translucent portions. Installing counter-ceilings can be complicated in these conditions due to the complicate geometry to be adopted and to the difficulties connected with the integration of lighting portions. Once again, the suitability of this kind of solution has to be carefully evaluated according to the peculiarities of the case-specific building to be redeveloped.

Vaulted or sloped roofs with metal trusses, are typical of the most dated buildings among the industrial facilities investigated. Consequently, these structures show nowadays several criticalities from different points of view. However, actions to tackle roof stratigraphy deficiencies are particularly limited by boundaries and constrictions posed by the limited load bearing capacity of structural components and uncertainties on assumptions made during their design. The strategies referring to this building variant are expressed in Table 5.18.

Table 5.18 Retrofit strategies for roofing redevelopment in buildings of the V_m_ar and Sl_m_tr variant. *Source: elaboration of the author.*

Typol. variant	**Current state**		**Retrofit strategy**		**Target performance**		
	Structure	**Completion solution**	**Code**	**Measure**	**En.**	**Str.**	**Ar.**
V_m_ar Sl_m_tr	Metal double sloped or arched trusses	asbestos panel + thermal insulation + asbestos corrugated panel	RS.3	Existing trusses removal and substitution with newly designed ones		X	
			R.4	Insulated false-ceiling installation	X		X
			R.5	Substitution of completion stratigraphy with metal sandwich panels	X	X	X

- RS.3 Existing trusses removal and substitution with newly designed ones

  Given the age of these buildings, outdated design criteria and formulations may have been used during the design of the roofing trusses. Additionally, uncertainties regarding the actual mechanical properties and strength of the materials used can impact the assessment of both the static and dynamic capacities of the existing structures. When significant issues are identified, replacing the existing roofing trusses with new ones may be necessary. In cases where the trusses are supported by beams of the side longitudinal frames, replacing the roofing layers with elements capable of spanning greater distances (R.5) could reduce the number of trusses required ameliorating the structural behaviour. The substitution of roofing stratigraphy is in many cases induced not only by its low thermal resistance and airtightness, but also by the frequent presence of asbestos in this old facilities.
- R.4 Insulated false-ceiling installation

  The majority of the investigated buildings pertaining to this category do not have any counter-ceiling solution installed. In similar facilities, system ducts can be easily routed through the openings in the truss structures of the beams and installing counter ceiling decks can help to prevent them from the view enhancing the aesthetic appeal of the indoor environment.

All of the roofing configurations associated with each typological variant can include skylights components to provide natural lighting in the innermost area of the workings spaces. Depending on the different layout and technological solutions adopted for their implementation, different retrofit solutions can be considered. Anyhow, energy and visual comfort assessments should be carried out to evaluate the influence of glazed portions on the overall behaviour of the building. Based on the results obtained, a remodulation of their distribution, a reduction of their number or an increase in their share with respect to opaque areas of the roof can be considered as profitable. Similarly, in buildings with precast tiles and correctly oriented, the replacement of inserted skylights with emerging shed ones can ensure improved energy performance by preventing direct solar radiation. Skylights currently installed often exhibit low thermal resistance, poor light transmission, and compromised airtightness due to the insufficient performance of their frames. Table 5.19 offers a compendium of the retrofit initiatives targeting roof skylights in industrial buildings.

Table 5.19 Retrofit strategies for skylights redevelopment in industrial buildings. *Source: elaboration of the author.*

Typol. variant	**Current state**	**Retrofit strategy**		**Target performance**		
	Skylight configuration	**Code**	**Measure**	**En.**	**Str.**	**Ar.**
V_m_ar Sl_m_tr P_rc_slb P_rc_b P_rc_t	Inserted skylights	Sk.1	Redefinition of skylights layout	X	X	X
		Sk.2	Substitution of transparent portions with state-of-the-art polycarbonate panes	X	X	
		Sk.3	Replacement of frames components	X		
P_rc_b P_rc_t	Inserted skylights	Sk.4	Replacement of existing skylights with shed-ones	X	X	x
Sh_rc_t	Emerging skylights	Sk.5	Replacement of windowed portions with glass panes complying with current prescriptions			X
		Sk.6	Substitution/Thermal insulation of opaque components in shed structure	X	X	

5.2.3 Validation of results and quantification of energy saving potential

In the next paragraphs, the retrofit strategies previously introduced will be discussed making reference to real case study buildings exemplary of the most commonly retrievable conditions in the

industrial building stock addressed. In particular, the reference facilities selected present sloped and plain roofs with precast beams, as they proved the categories covering the highest number of structures, being at the same time also the most dated ones. Energy models of the facilities have been created for both current state and retrofit configurations to assess the energy saving potential of the redevelopment strategies.

Some general assumptions common to both the case study facilities were made. The companies hosted in the buildings generally operate on weekdays from 8:00 a.m. to 5:00 p.m., with customary closure periods from December 24th to January 6th during winter and 2/3 weeks in August for summer holidays. About 15 employees in average are involved in the working activities and based on the nature of their tasks, a metabolic rate of 167 W/person was set [22]. The heating systems are currently active from November to March, with sporadic activations outside this period being excluded from the simulations produced. A heating setpoint equal to 18 °C was set to reproduce the internal conditions usually encountered in the facilities inspected and the indications provided by the companies' ownerships. Natural ventilation rates were set at 0.25 ac/h, in accordance with UNI/TS 11300-1:2014 [23], which specifically addresses workspace requirements.

Natural infiltration is a critical factor in energy performance but at the same time it is extremely difficult to assess in existing industrial buildings, as widely discussed in the scientific literature [24]. The airtightness level was estimated at approximately 0.20 ac/h, based on UNI EN 12831 [25] and assuming a medium level of permeability as per Italian standards, accounting for the ventilation impact of opening large sectional doors during working hours. Given the reduced pressure and temperature differentials in unoccupied periods, a schedule was imposed in the models to lower infiltration rates at night.

The existing windows feature metal frames without thermal breaks and the following properties were assumed based on the findings retrieved during on site inspections and document collection: thermal transmittance of 3 W/m²K, solar factor of 0.6, and light transmittance of 0.5. The polycarbonate skylights, on the other hand, were assumed to have a thermal transmittance of 2.8 W/m²K, a solar factor of 0.6, and a light transmittance of 0.4.

5.2.3.1 Case study building: plain roof with precast beams category (P_rc_b)

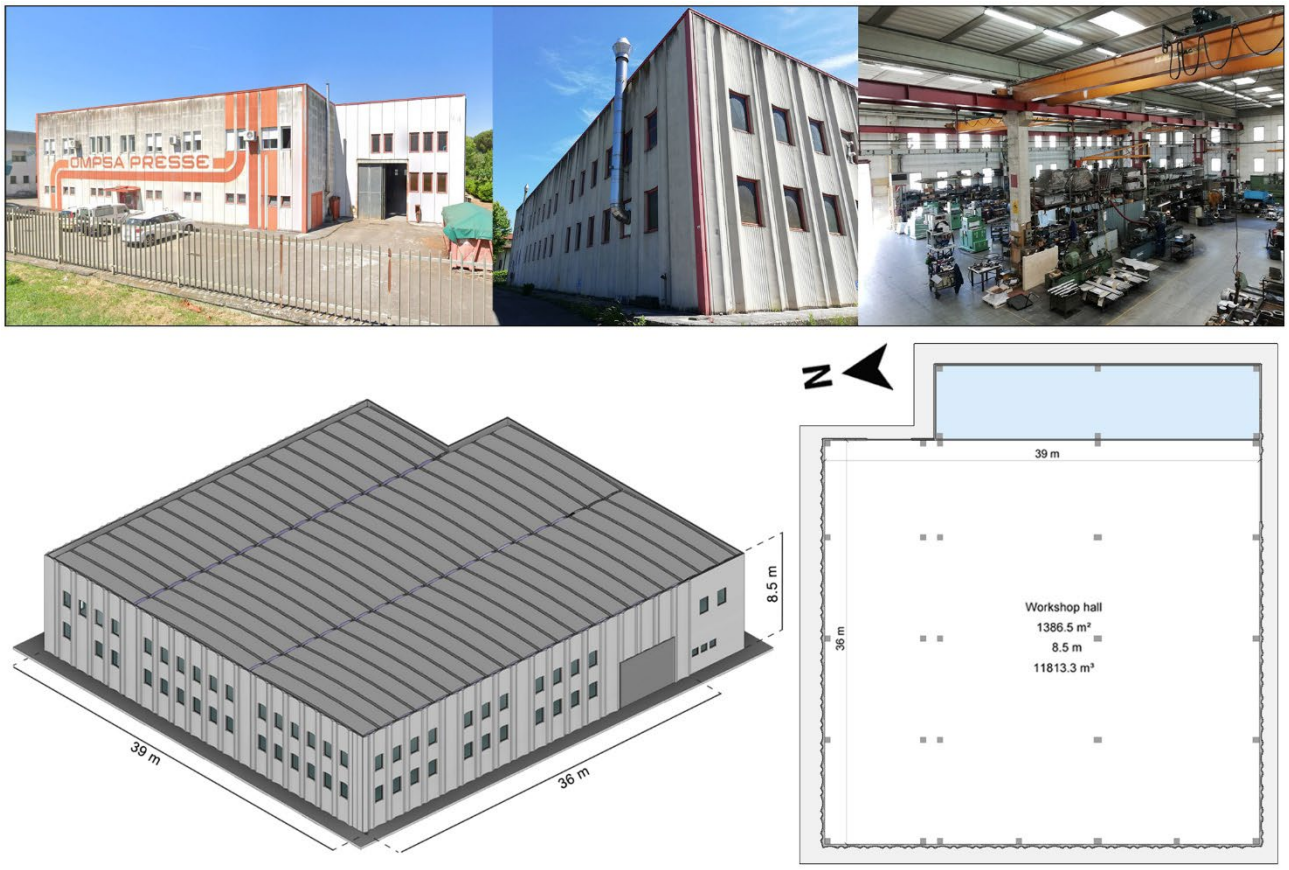


Figure 5.21 Case study building selected for Variant P_rc_b variant: photographical evidence collected on-site, 3D model, and plan layout. *Source: elaboration of the author.*

The case study is an industrial building located in an established industrial district in the Casentino Area of Tuscany (Central Italy), within the Municipality of Subbiano, province of Arezzo. The site falls within climate zone D, with 2041 heating degree-days (HDD), and is classified as having a temperate climate (zone C) according to the Köppen classification.

The building, constructed in 1982, has a total gross floor area of approximately 1,600 m² and consists of two distinct yet structurally independent sections. The front portion of the building is a two-story structure housing worker locker rooms, archive, and storage rooms on the ground floor, with the administration department and designers' office located on the upper floor. The workshop department occupies the majority of the building, covering around 90% of the total area. This workshop is a single-story, double-height space featuring two 14-meter-wide naves, with a smaller adjacent 8.5-meter-wide nave added in 1996. Overhead cranes are installed for lifting and moving heavy components and raw materials. The internal height is approximately 8.5 meters in the workshop, 3.9 meters in the ground-level ancillary rooms, and 3.1 meters in the upper-level offices, where a plasterboard drop ceiling is in place. A 3D representation of the building is hown in Figure 5.21,

along with photographical evidence and plan layouts, while the distribution of intended uses in the building is reported in Figure 5.22.

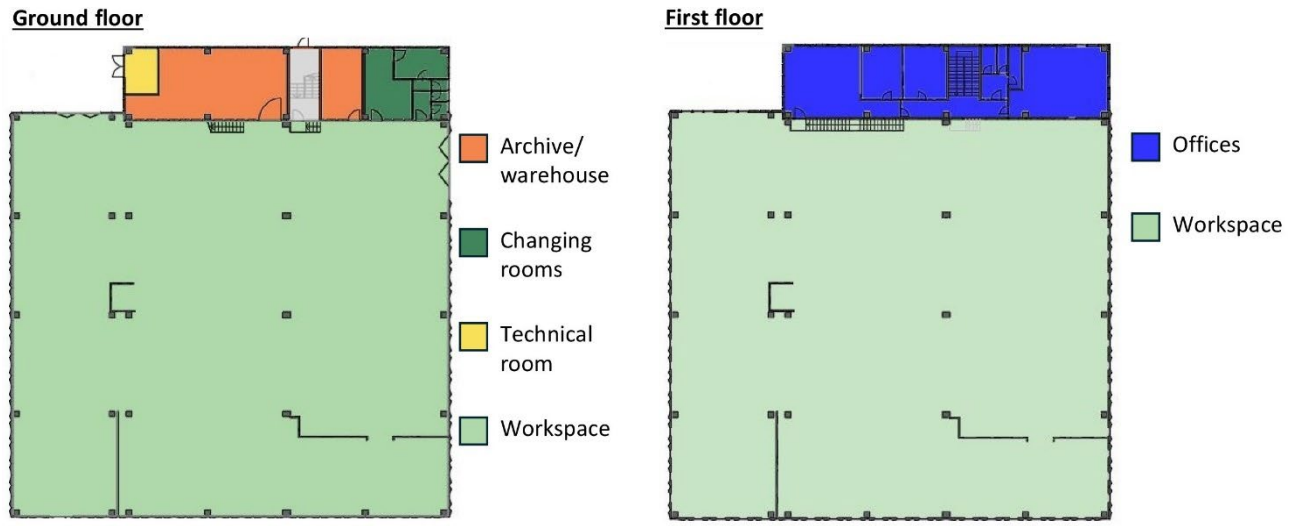


Figure 5.22 Internal layout and distribution of functions within the case study building. *Source: elaboration of the author.*

Both sections of the building are constructed using tenon head columns that present square or rectangular cross sections ranging between 0.50 m and 0.65 m on each side. The columns in the office area are tapered to facilitate connections with the beams on one or both sides. The prefabricated border beams with an H section are arranged around the perimeter and rest on the tops of the columns. Each beam is approximately 9 m long, with dimensions of 0.48 m width and 1 m in height. The roof beams with a Y section are 0.28 m wide and present a height varying from 0.42 to 0.75 m, are spaced apart by 2 meters, and are separated by closure blocks made of asbestos-cement. They span approximately 14 m. Translucent panels are incorporated as skylights. To create an internal drop ceiling, fibre-cement panels are laid on the lower flange of the beams, coupled with a 0.06 m rock wool insulating layer. The external walls consist of precast reinforced concrete panels in two configurations: a plain 0.13 m thick panel for the two-story section, and a concave-profiled panel with variable thickness from 0.13 m to 0.27 m, alternatively including two windows each, for the workshop area. In both configurations, an EPS layer was used to lighten the weight of panels themselves.

The main dimensional properties of the structural frames are illustrated in Table 5.20. Details about the external envelope components are collected in Table 5.21, Table 5.22, and Table 5.23 and graphically illustrated in Figure 5.23. The insulation layer was considered with a halved thickness to account for uncertainties about its real properties and preservation state.

Table 5.20 Geometrical characteristics of the structural layout of the original nucleus and the extension. *Source: elaboration of the author.*

Dimensions	Original nucleus	Extension
Total nave length	42.80 m	36 m
Span spacing)	9 m in workspace portion 6 m in office portion	9 m
Nave width	14 m	8.50 m
Number of naves	2	1
Number of spans	4 in workspace portion 1 in office portion	4
Total height	9.45 m	9.45 m
Height at roof beams intrados	8.50 m	8.50 m

Table 5.21 Stratigraphy and thermal properties of the curved precast vertical panels. An average thickness was assumed in this case. *Source: Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/ solar4030018.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m³]
Precast concrete	0.024	2.07	1000	2400
Insulation material [EPS]	0.06	0.04	1450	15
Precast concrete	0.020	2.07	1000	2400

Table 5.22 Stratigraphy and thermal properties of the plain section precast vertical panels. *Source: Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/ solar4030018.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m³]
Precast concrete	0.018	2.07	1000	2400
Insulation material [EPS]	0.045	0.04	1450	15
Precast concrete	0.018	2.07	1000	2400

Table 5.23 Layers and thermal properties of the roofing stratigraphy. *Source: Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/ solar4030018.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m³]
Asbestos-cement tiles	0.01	0.6	1000	1800
Glass wool	0.06	0.04	1030	12
Air gap	0.55	-	-	-
Asbestos-cement tiles	0.01	0.6	1000	1800

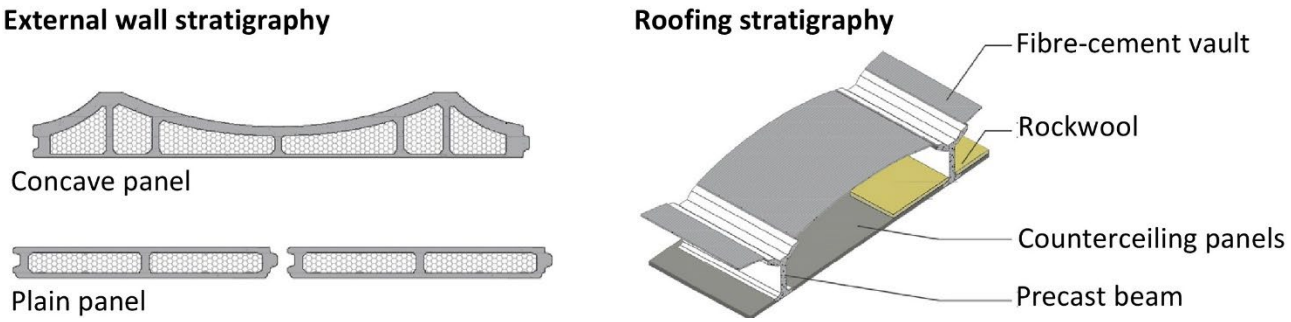


Figure 5.23 Graphical illustration of current envelope components: external walls and roofing elements. *Source: Re-elaboration of the authors from Banti N, Di Naso V, Ciacci C, Bazzocchi F (2022) Integrated Redevelopment of Industrial Buildings: a Case Study in Central Italy. In: Haydee B, Boffill Y, Lombillo I (eds) Rehabend 2022 Euro-American Congress CONSTRUCTION PATHOLOGY, REHABILITATION TECHNOLOGY AND HERITAGE MANAGEMENT. Circulo Rojo, Granada, pp 1740–1751.*

6 fan gas heaters are installed in the production area while a traditional gas boiler for archive, locker rooms heating and hot water production. Three external reversible heat pumps ensure air conditioning in the offices. The workshop hall lacks mechanical cooling, building automation, and monitoring systems. Fluorescent lamps are used for lighting throughout the building.

5.2.3.1.1 ENVELOPE RETROFIT: FAÇADE AND ROOF RECLADDING

The whole facility was modelled in DesignBuilder to evaluate the energy performance in both current and retrofit conditions. The various intended uses of the rooms and their using conditions were considered and the different thermal zones were set accordingly (Workshop hall, Office, Changing rooms; Archive and warehouse, Toilets) in the energy model. The results of the energy simulation over the heating period were validated comparing the simulated natural gas consumption for the month of January with the one derived from the actual bills provided by the company. According to this analysis, the latter proved to be about 9% higher than the simulated ones but this result was considered acceptable given the uncertainties affecting the energy modelling phase and the presence of extra gas demanding operations connecting with industrial processes not accounted for in the model. Given the considerable volume of the workshop hall and the lower efficiency of the heating system installed in this portion, approximately 85% of the total heating demand is referrable to it.

The share of heat losses was analysed making reference to Winter conditions to evaluate the energy behaviour of the building. As illustrated in Figure 5.24, external infiltration proved to be highly detrimental. Focusing on envelope components, roof emerged as highly dispersing, with a share higher then external walls. this can be justified by considering its wider surface and the convective ascensional currents inducing warm air stratification in the upper portion of the working areas. Acting on roof stratigraphy hence emerges as more promising than acting on external walls and openings.

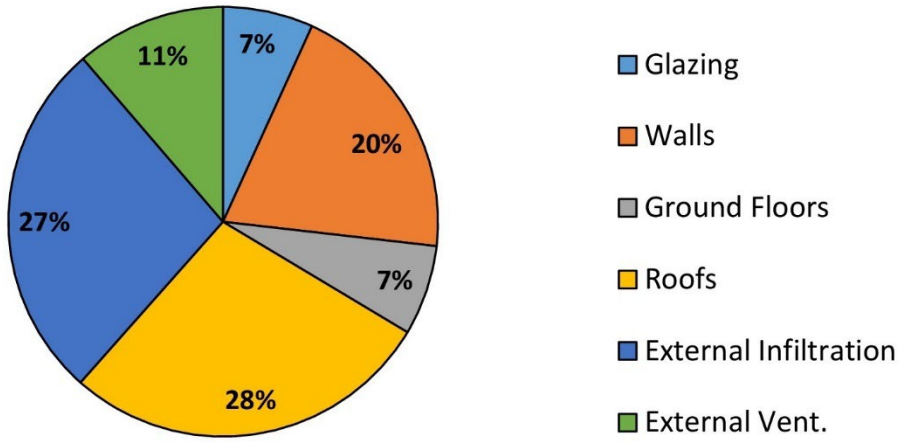


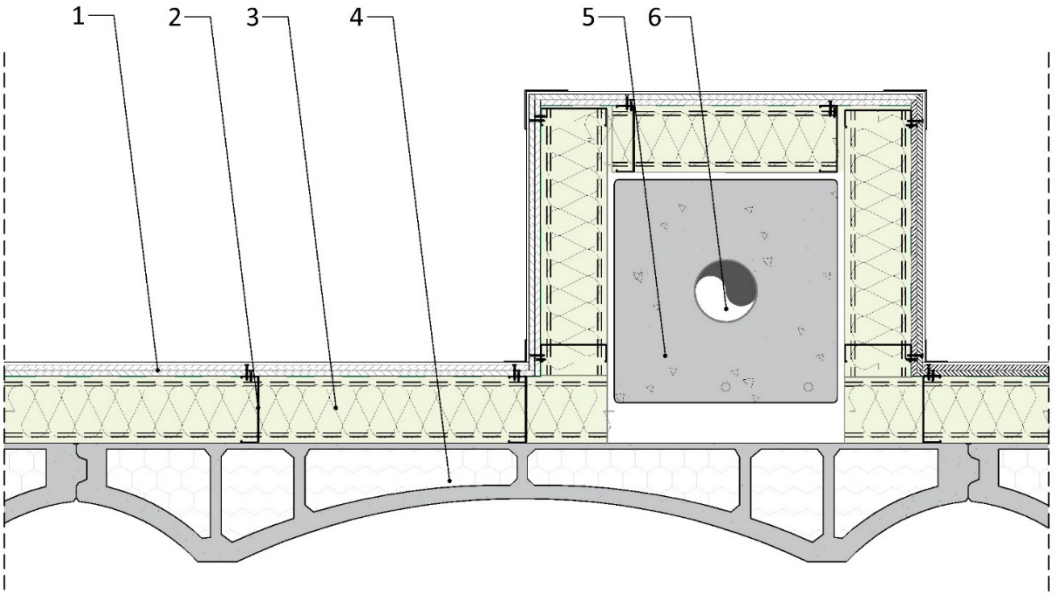
Figure 5.24 Share of heat losses through the envelope of the case study facility during January in current state. *Source: elaboration of the author.*

To account for the energy saving potential of measures targeting each envelope component, dedicated energy models were produced applying the corresponding changes in the construction section. The retrofit of current envelope components was considered, targeting both external walls and roof

stratigraphy. Specifically, for the redevelopment of the external walls to achieve the thermal performance standards required, the installation of an insulated counter wall (measure EW.3) and the substitution of current windows (W.1) and industrial doors (W.4) were considered. Table 5.24 shows the thermal properties of the renewed configuration, whose details are provided in Figure 5.25. The substitution of current windows was also foreseen (Solar Factor 0.51, U 1.20 W/m2K, Light Transmittance 0.74).

Table 5.24 Thermal properties of external walls stratigraphy in Building B. *Source: elaboration of the author.*

Current state			**Sandwich panels recladding**		
Material	**Thickness [m]**	**Conductivity [W/mK]**	**Material**	**Thickness [m]**	**Conductivity [W/mK]**
Precast concrete	*0.03*	*2.07*	*Precast concrete*	*0.03*	*2.07*
Insulation material [EPS]	*0.06*	*0.04*	*Insulation material [EPS]*	*0.06*	*0.04*
Precast concrete	*0.02*	*2.07*	*Precast concrete*	*0.02*	*2.07*
			Wood fiber insulation	*0.10*	*0.043*
			Gypsum-fiber plasterboard panels	*0.025*	*0.30*
Thermal transmittance	[W/m²K]	0.60	**Thermal transmittance**	[W/m²K]	0.24
Surface mass	[kg/m²]	107	**Surface mass**	[kg/m²]	148
Periodic thermal trans.	[W/m²K]	0.518	**Periodic thermal trans.**	[W/m²K]	0.045



1. Double gypsum-fiber board
2. Vertical C-shaped stud for drywall
3. Thermal insulation - Woodfiber
4. Exisitng precast concrete panels
5. Precast concrete column
6. Downpipe for rainwater

Figure 5.25 Horizontal section of the external walls in retrofit configuration. *Source: elaboration of the author.*

As for the roof, the removal of both intrados and extrados completion elements was foreseen to remove asbestos and ensure thermal, water, and air resistance. A dedicated metal substructure hanged at the extrados wings of the Y-section beams has to be adopted in this case to fasten an omega-shaped profile supporting the steel sandwich panels. Details are provided in Figure 5.26.

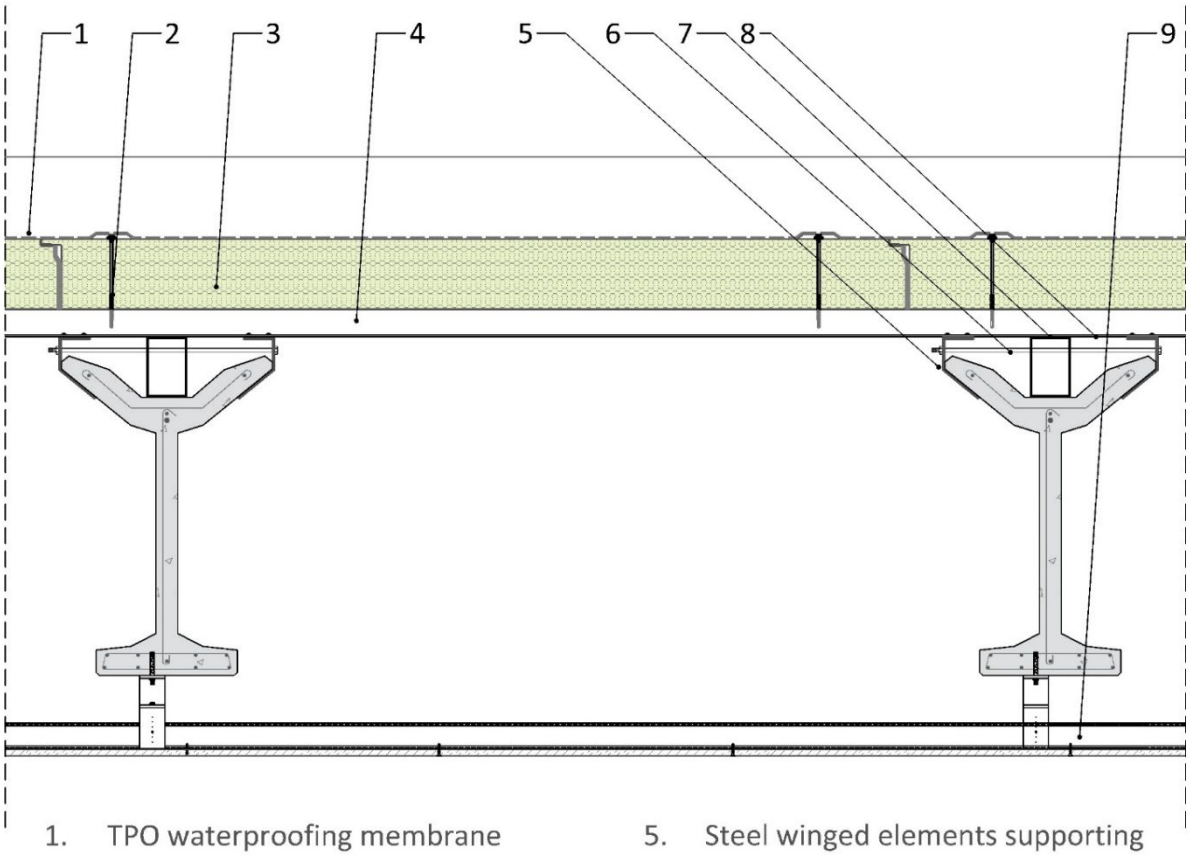


Figure 5.26 Transversal section of the roof stratigraphy. *Source: elaboration of the author.*

In Figure 5.27 a vertical section is provided to illustrate the details about the relation between roof and external wall and edge beam.

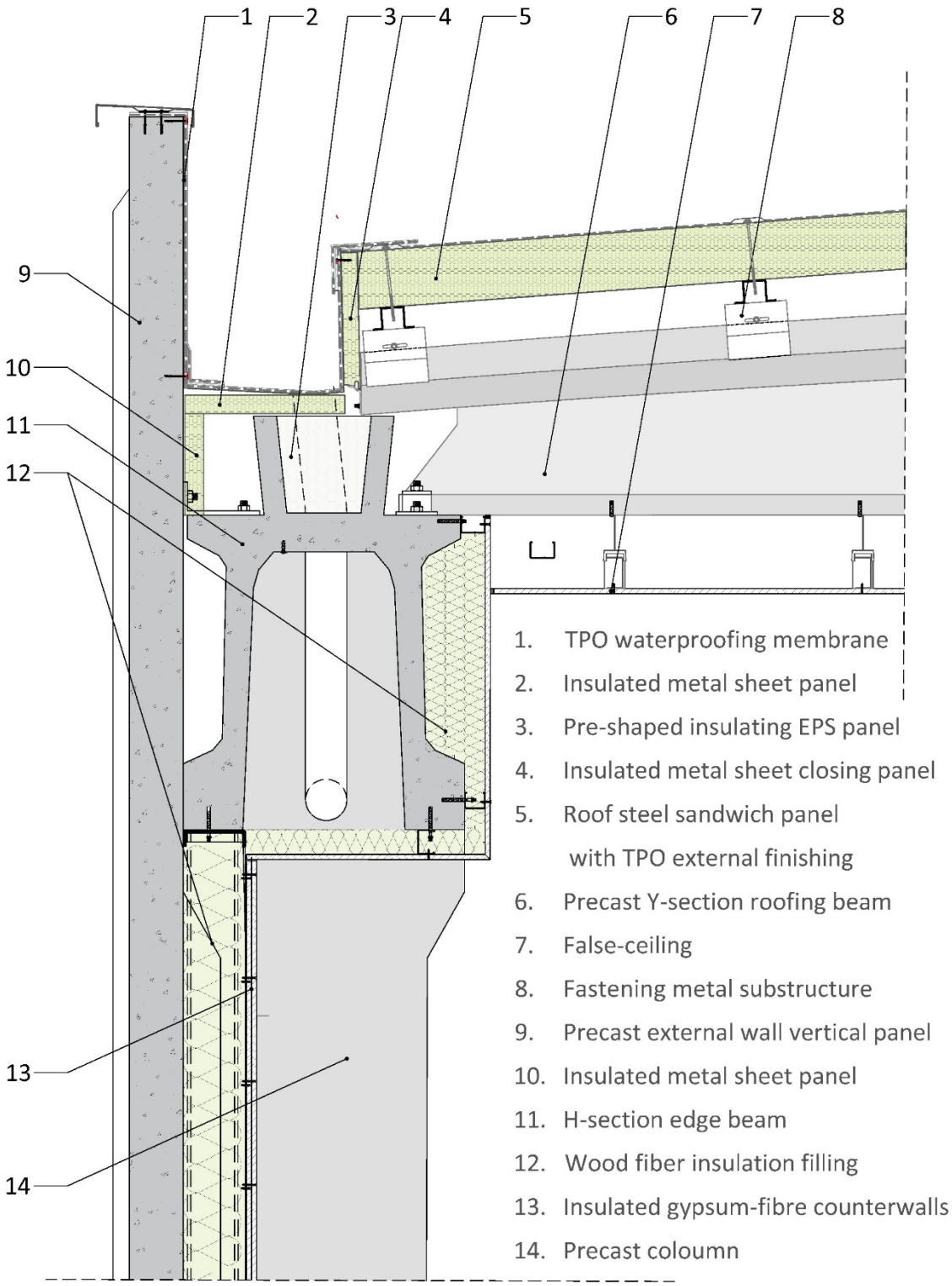


Figure 5.27 Vertical cross section in retrofit configuration. Details about roof and external walls recladding with steel sandwich panels. *Source: elaboration of the author.*

The results of the energy simulations carried out are illustrated in Figure 5.28, where the energy savings achieved acting on the different envelope components are reported on a monthly basis.

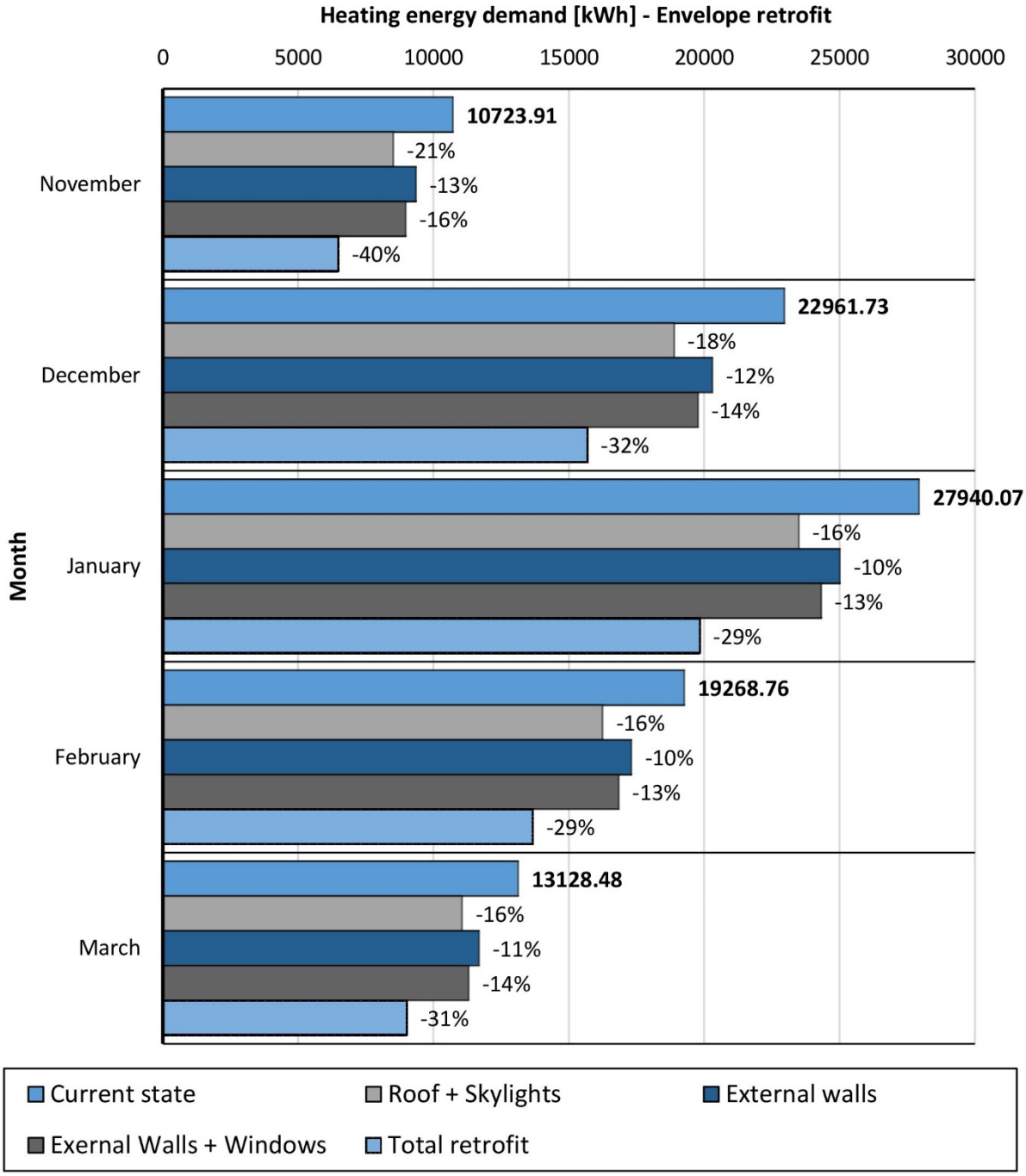


Figure 5.28 Heating energy demand in both current state and under retrofit scenarios. *Source: elaboration of the author.*

When considering the roofing retrofit, also the substitution of current skylights was foreseen as the substitution of the existing stratigraphy requires the complete removal of currently installed intrados and extrados fibre-cement panels with asbestos. As previously anticipated, roof retrofit is highly beneficial and allows to reduce the energy demand by 16% on average during the winter months, up

to 18% in January. Conversely, acting on the external walls is less effective: even accounting for windows substitution, the maximum energy saving achievable during January is about 13%. Combining retrofit interventions on both roof and external walls is recommendable: in this case the energy saving potential is much more consistent and roughly account for 30% from December to March, while reductions up to 40% are registered in November.

In the analysis caried out until now, the infiltration rate was left unchanged to focus on envelope performances. By the way, acting on these components results in improved airtightness at building level especially because of the replacement of existing skylights and windows with poor sealings and deteriorated frames or cracked glazing. For this reason, further simulations were produced accounting for ameliorated airtightness by reducing the infiltration rate. For both the retrofit scenarios involving the redevelopment of roof stratigraphy and external walls and windows, external infiltration was diminished by 15% while a 25% reduction was applied when considering the complete retrofit of the envelope elements. In Figure 5.29 the results obtained adopting these assumptions are reported. An extra 5% energy saving is achievable in case of single-element upgrades: roof retrofit and external walls redevelopment lead to an average global reduction in energy demand equal to 20% and 16% respectively. The effects of the enhanced airtightness can be particularly relevant when analysing the overall retrofit of the building: in this case the reduction of the air leakages induces a 40% reduction in energy demand, compared to the 30% decrease obtained without acting on the infiltration rate. The analysis carried out about the influence of the infiltration, let to highlight the need for accurate examination of this aspect as it is highly affects the building energy performance and poses at the same time uncertainties on the correctness of the simulations carried out. This is particularly relevant in case of industrial halls with considerable internal volumes.

In conclusion, the energy analysis performed let to assess a remarkable energy saving potential connected to retrofit actions addressing the external envelope components. Roof proved to be the preferable target for redevelopment initiatives given the higher heat losses rate associated. Including the effects of improved airtightness at building level, energy demand can be reduced by 20% by renewing the roof stratigraphy, by 16% enhancing the thermal performance of external walls and substituting existing windows, and by 40% coupling the previously mentioned measures.

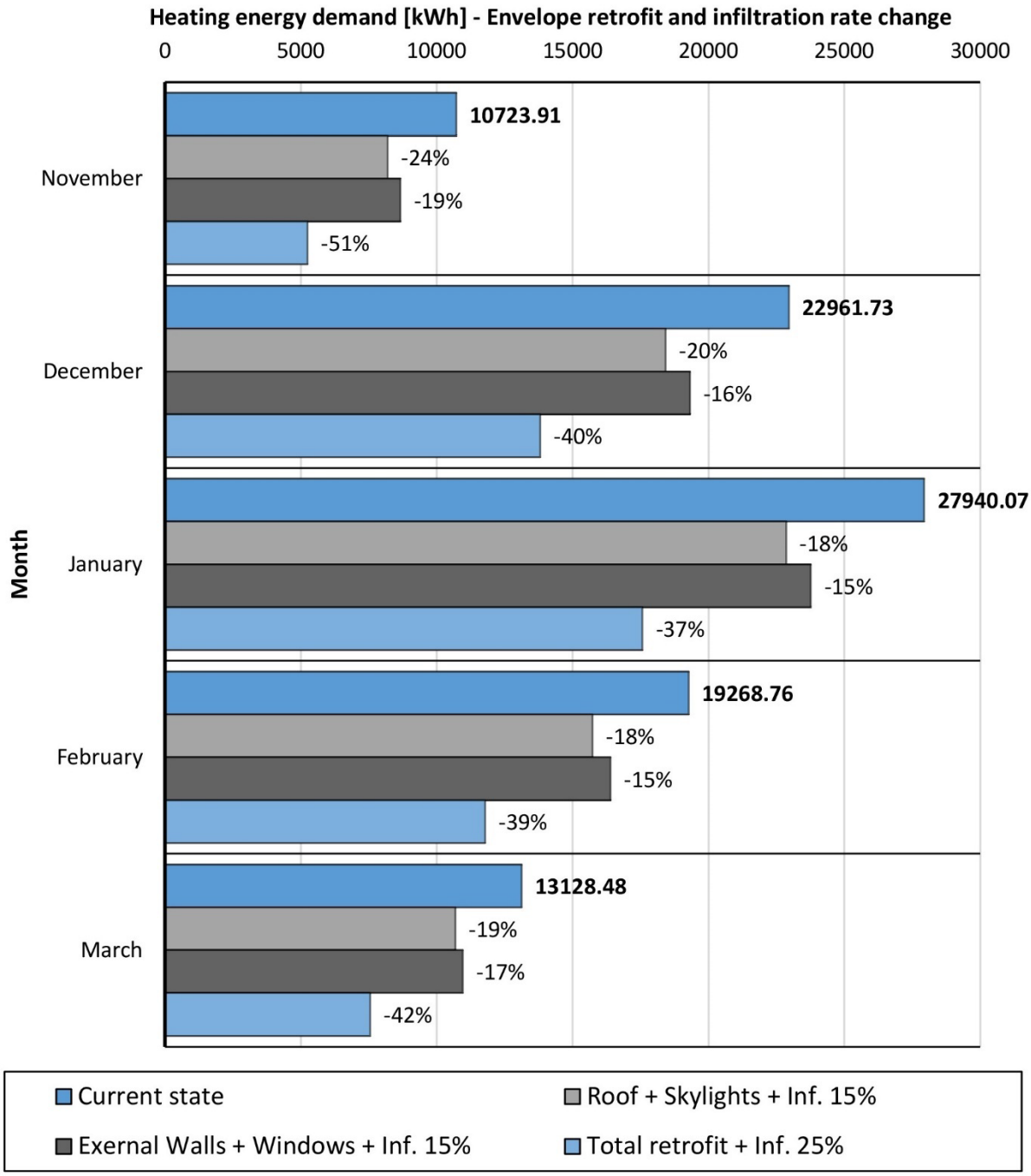


Figure 5.29 Heating energy demand in both current state and under retrofit scenarios and variable infiltration rates. *Source: elaboration of the author.*

5.2.3.2 Case study building: Sloped roof with precast beams category (Sl_rc_slb)

The facility selected is an industrial building situated in one of the industrial districts within the boundaries of the municipality of Barberino di Mugello, in the province of Florence. The industrial complex consists of two adjacent structures that belong to the same typological variant (Sl_rc_slb) but with different solutions for the structural connections between load-bearing elements, and envelope components, for both roofing system and external walls. The two portions were built in different periods, with their longitudinal axis perfectly oriented in E-W direction, and are structurally independent. The main differences between the two adjacent buildings are highlighted in Figure 5.30, where the two structures are refereed to as building A and B.

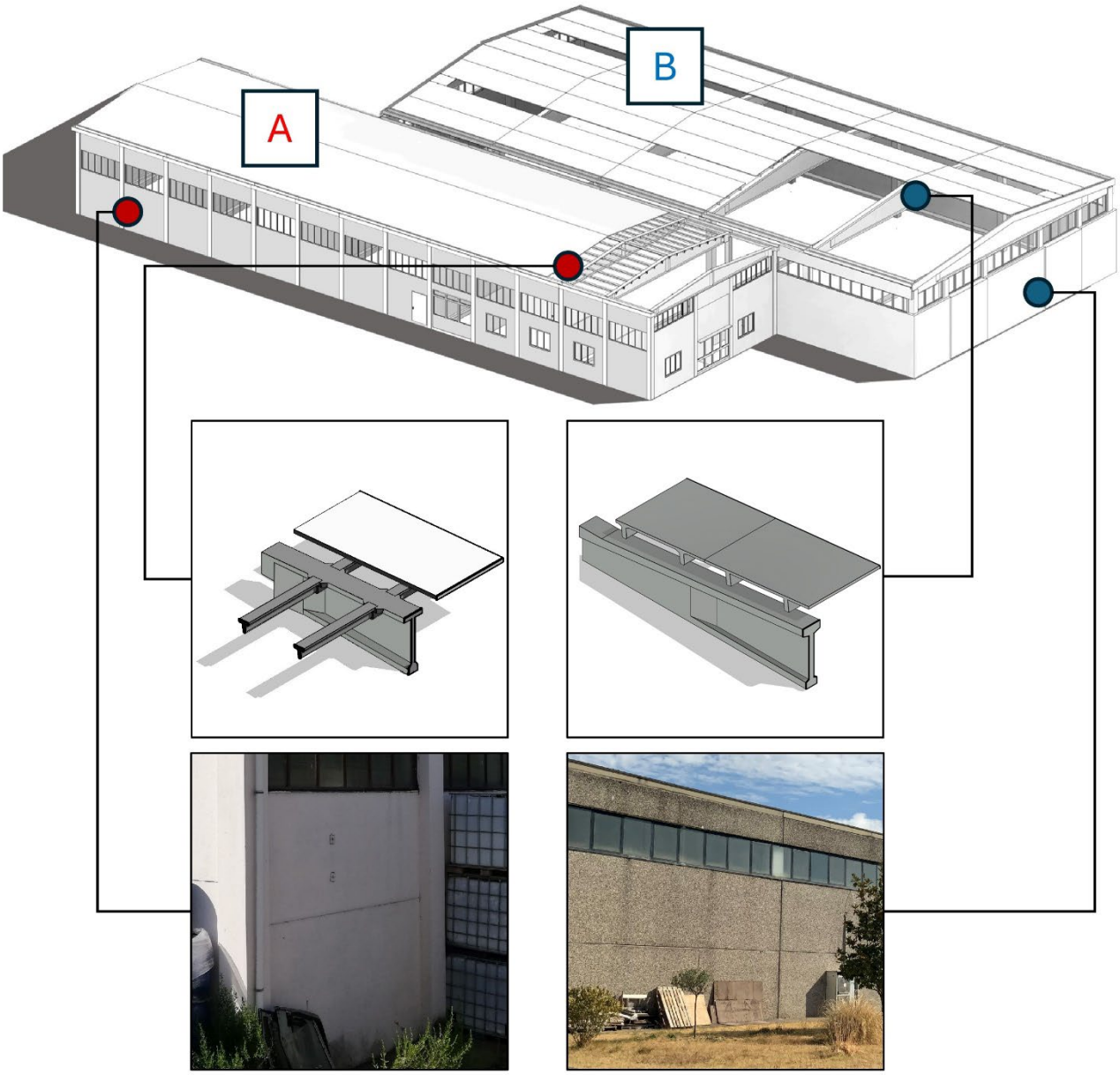


Figure 5.30 3D model of the facility with indications of the two structural units and details of roofing and external walls solutions. *Source: elaboration of the author.*

In Figure 5.31 the internal layout and distribution of the facility is provided. Currently the complex is occupied by two distinct companies operating in the chemical and mechanical sectors.

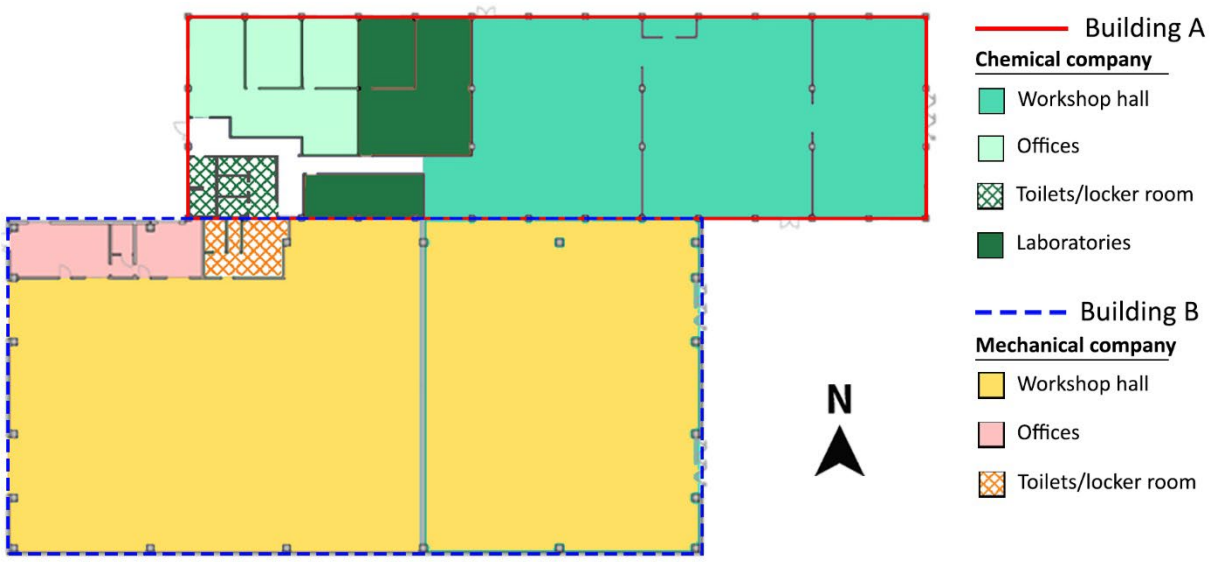


Figure 5.31 Plan layout and intended uses of the different areas of the buildings. *Source: elaboration of the author.*

Building A was built at the beginning of the '70s. The west facade features the main entrance while the opposite facade has a central industrial door flanked by two high windows. The main sides of the facility host upper ribbon windows. Currently, there are no roof openings. The fixtures, including windows, doors, and industrial doors, are original and do not meet current regulatory standards.

As for structural components, the columns are precast reinforced concrete, with a total of 32 external columns and 6 internal columns, all having a square cross-section of 0.40 m x 0.40 m. The roof beams are precast, reinforced, and prestressed concrete with a double-sloped design. They rest on the flat tops of the columns and are secured with a horizontal metal pin to prevent displacement. Each beam features an upper flange 0.28 m wide, a vertical web 0.05 m thick, and a lower flange 0.14 m wide and 0.075 m thick. The height of the beam ranges from 127.5 cm at mid-span to 29.5 cm at the supports. Positioned on the tops of the columns, the beams have an interaxis equal to the column spacing of 4 m. The beams are shaped on the exterior to provide support for the roof purlins. These are precast, reinforced, and prestressed concrete with a T-shaped cross-section, allowing them to fit into specific grooves formed on the exterior of the double-sloped beams. These purlins are mechanically secured to the beams with horizontal metal pins to prevent displacement. The net length of the purlins is 3.72 m, and they are spaced approximately 0.90 m apart. Figure 5.32 illustrates the roofing solution.

Figure 5.32 Roofing solution in building A. *Source: elaboration of the author.*

Also the gutters are made of precast reinforced concrete with a U-shaped cross-section and are supported on the tops of the columns. They collect rainwater from the roof, directing it to the downspouts located at the columns and, additionally, they help to stiffen the transverse frames.

The building features perimeter external walls almost uniformly distributed consisting of precast reinforced concrete panels installed horizontally within the grooves of column sections with a raw external finish with exposed concrete painted in white . These panels are made of two outer 3 cm thick concrete slabs connected by ribs, and internal layer of insulating material for both weight reduction and thermal insulation. The total thickness of each panel is 10 cm.

The heating system for the production area consists of a traditional gas-fired boiler and hot air distribution ducts, as illustrated in Figure 5.33 (COP 0.7). Offices, laboratories and changing rooms have independent heating and cooling systems including an external unit (heat pump) that serves one or more internal units.

Figure 5.33 Generation and distribution units in the workspace area of building A. *Source: elaboration of the author.*

Building B was built in more recent years, at the beginning of the '90s. The scheme of the openings is comparable to the one already described for building A, with continuous ribbon windows in the upper portion of external walls. The roof features two continuous rows of polycarbonate skylights spanning the entire length of the building. Columns features a for-head configuration and are characterized by a wider square cross-section (0.50 m x 0.50 m). The roof beams are precast, reinforced, and prestressed concrete with a double-sloped design, installed on the forked tops of the columns and secured with a horizontal metal pin. Each beam has a cross-section with an upper flange 0.40 m wide, a vertical web 0.11 m thick, and a lower flange 0.25 m wide and 0.13 m thick. Each beam spans an overall length of 23.10 m. The height of the beam ranges from 1.93 m at mid-span to 0.66 m at the ends. The roof π precast slabs are laid directly on the top surface of the double-sloped beams and are connected to the beams themselves through a system of reinforcement bars and a cast-in-place completion concrete pour. Each slab is 9.52 m long, 2.50 m wide, and 0.30 m high. Concrete gutters channels are in this case located at the extrados of roof beams. The roof finishing consists of an insulating layer placed directly on the slabs, covered by a waterproof membrane made of bituminous sheeting. The building features a perimeter cladding that consists of horizontal curtain-type precast reinforced concrete panels. In this case the total thickness is greater. The concrete layers, connected by ribs, are 0.06 m and 0.10 m thick while the internal insulating and lightweight layer is 0.04 m. The heating system for the production area (no cooling is provided) consists of an external heat pump and a system for delivering warm air into the space via two air heaters. Similarly, heat pumps are installed to provide air conditioning also in offices and restrooms.

The main dimensional characteristics of the two facilities are reported in Table 5.25 while the stratigraphy of building envelopes components are reported in Table 5.26, 5.27, and 5.28. In building A, roof has been recently substituted by removing the original asbestos containing fibre-cement

panels and installing a new metal sandwich panel deck at the extrados of the purlins (0.10 m thick, thermal transmittance 0.21 W/m2K).

Table 5.25 Geometrical characteristics of the structural layout of both buildings. *Source: elaboration of the author.*

Dimensions	Building A	Building B
Total nave length	52 m	48.10 m
Span spacing)	4 m	9.62 m
Nave width	14.20 m	22.60 m
Number of naves	1	1
Number of spans	13	5
Total height	7.58 m	8.48 m
Height at beams intrados	6.20 m	6.20 m

Table 5.26 Stratigraphy of external walls concrete panels in Building A. *Source: elaboration of the author.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m³]
Precast concrete	0.03	2.07	1000	2400
Insulation material [EPS]	0.02	0.04	1450	15
Precast concrete	0.03	2.07	1000	2400

Table 5.27 Stratigraphy of external walls concrete panels in Building B. *Source: elaboration of the author.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m³]
Precast concrete	0.03	2.07	1000	2400
Insulation material [EPS]	0.02	0.04	1450	15
Precast concrete	0.03	2.07	1000	2400

Table 5.28 Stratigraphy of roofing solution adopted in Building B. *Source: elaboration of the author.*

Material	Thickness [m]	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m³]
Precast concrete	0.05	2.07	1000	2400
Insulation material [Rockwool]	0.04	0.036	1030	40
Bituminous sheet	0.002	2.07	1000	2400

The facility was recreated in DesignBuilder to produce an energy model of both buildings to be later implemented in the evaluation of retrofit configuration and in the assessment of strategies' effectiveness. Energy demand over the winter period was calculated, converted in primary energy

adopting the corresponding factors (Natural Gas: 1.05, Electricity from Grid: 1.90), and compared with the one retrievable from the real energy bills provided by the companies. It was proved that the calculation model tends to slightly underestimate energy consumption but given the relevance of the assumptions made, the overall 6% discrepancy was considered widely acceptable. At the same time, the energy balance of the building in terms of dispersion trough building components was analysed and results reported in Figure 5.34.

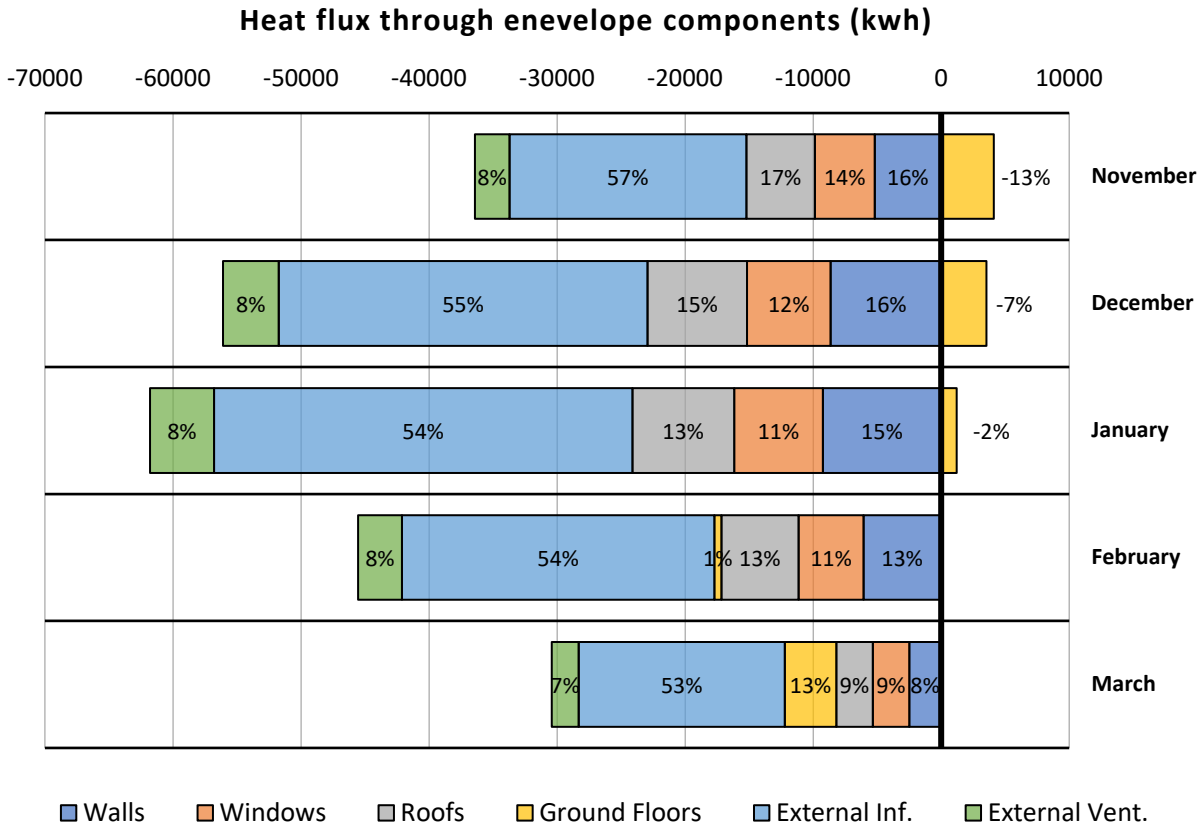


Figure 5.34 Heat flux per envelope component in the current state during the Winter months. Negative values indicate heat losses while positive ones represent thermal gains. *Source: elaboration of the author.*

The majority of heat losses are attributable to significant air infiltrations due to the poor airtightness of the building envelope components and frequent opening of industrial doors. Walls and windows collectively lose more heat than the roof, a result that contrasts with the expected behaviour for this type of building, where the roof is typically the component with the highest heat loss. In this case, however, this does not occur because part of the roof has already been renovated, with the installation of a new sandwich panel roofing layer in compliance with current regulatory limits.

5.2.3.2.1 ENVELOPE RETROFIT: FAÇADE AND ROOF RECLADDING

Different strategies for facades retrofit were applied to Building A and Building B to deal with the peculiarities of each facility in the existing conditions. In building A, the complete substitution of the precast concrete panels with a newly installed metal sandwich panels solution was tested (EW.1). In Building B, the recladding of existing concrete façade was considered, not removing the panels currently in place (EW.4). For the former, steel sandwich recladding components characterized by a 0.10 m thickness and 0.21 W/m^{2}K were adopted while the comparison of the properties of the walls in current and retrofit state is provided in Table 5.29. Once again, only half of the thickness of the insulation layer within current precast panels was assumed when calculating the thermal conductivity of the whole component. These aspects were analysed in the paper "*Toward integrated redevelopment of industrial buildings: a general intervention protocol and a case study*", in "In Transition: challenges and opportunities for the build heritage", Proceedings of the Conference 2023 of Ar.Tec (Scientific Society of Architectural Engineering) [26].

Table 5.29 Thermal properties of external walls stratigraphy in Building B. *Source: elaboration of the author.*

Current state			**Sandwich panels recladding**		
Material	**Thickness [m]**	**Conductivity [W/mK]**	**Material**	**Thickness [m]**	**Conductivity [W/mK]**
Precast concrete	*0.06*	*2.07*	*Precast concrete*	*0.06*	*2.07*
Insulation material [EPS]	*0.04*	*0.036*	*Insulation material [EPS]*	*0.04*	*0.036*
Precast concrete	*0.10*	*2.07*	*Precast concrete*	*0.10*	*2.07*
			Steel sandwich panel	*0.08*	*0.023*
Thermal transmittance	[W/m²K]	1.01	**Thermal transmittance**	[W/m²K]	0.19
Surface mass	[kg/m²]	385	**Surface mass**	[kg/m²]	397
Periodic thermal trans.	[W/m²K]	0.511	**Periodic thermal trans.**	[W/m²K]	0.012

In addition, the replacement of the existing windows is considered with new aluminium-framed windows featuring thermal break technology and an overall average thermal transmittance (frame + glass) below the minimum regulatory values. The geometry of the windows would not be modified. The main properties of the new glazing components are here listed: Light transmission (TL): 60%; Energy transmission (TE): 43%; Thermal transmittance (Ug): 1.2 W/m^{2}K; Solar factor (g): 0.51.

Figures 5.35 and 5.36 illustrate the retrofit interventions proposed for Building A and Building B, focusing on vertical cross-sections at the upper portions of the exterior walls and their interface with the roofing components.

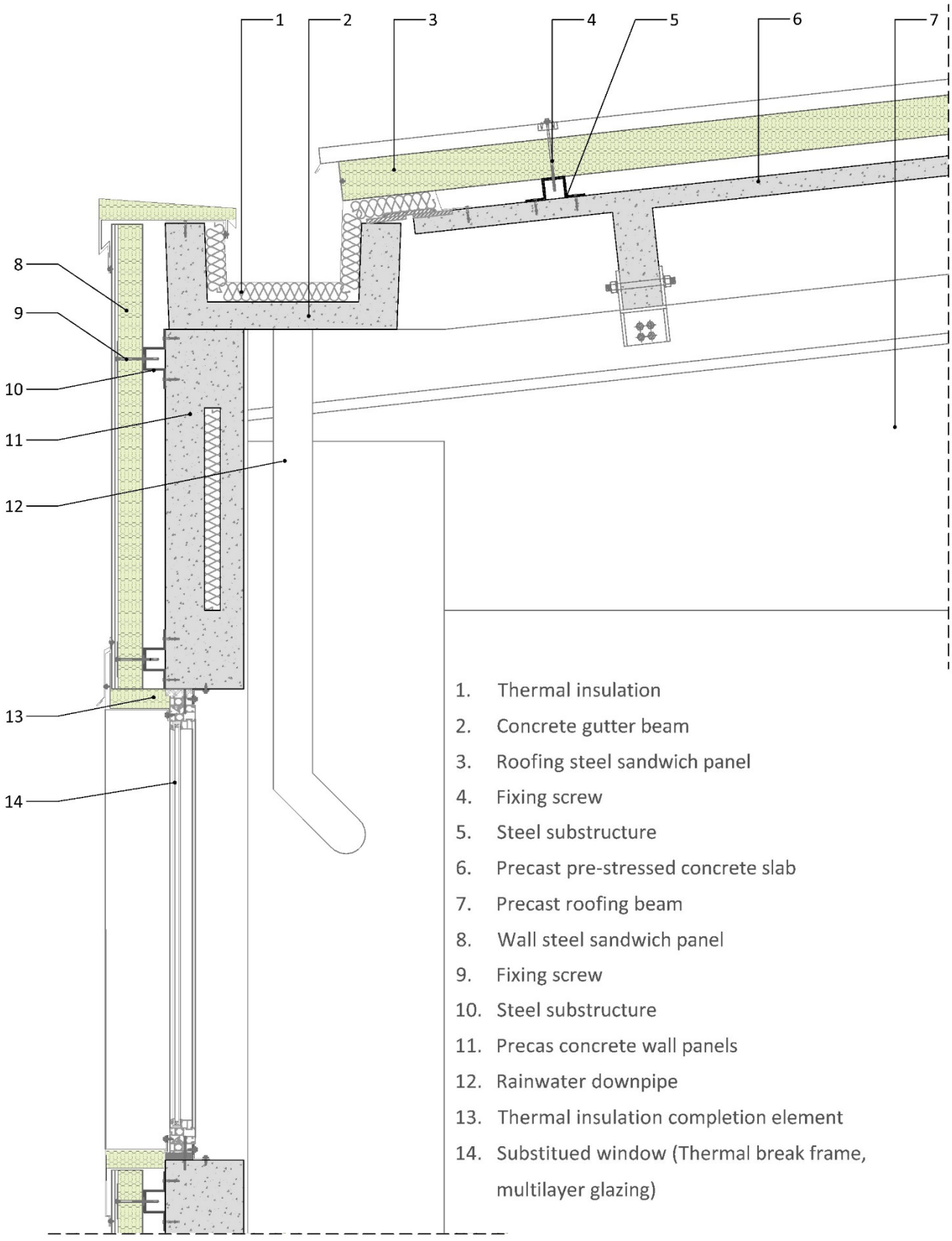


Figure 5.35 Vertical cross section of Building B - retrofit configuration. Details about roof and external walls recladding with steel sandwich panels. *Source: elaboration of the author.*

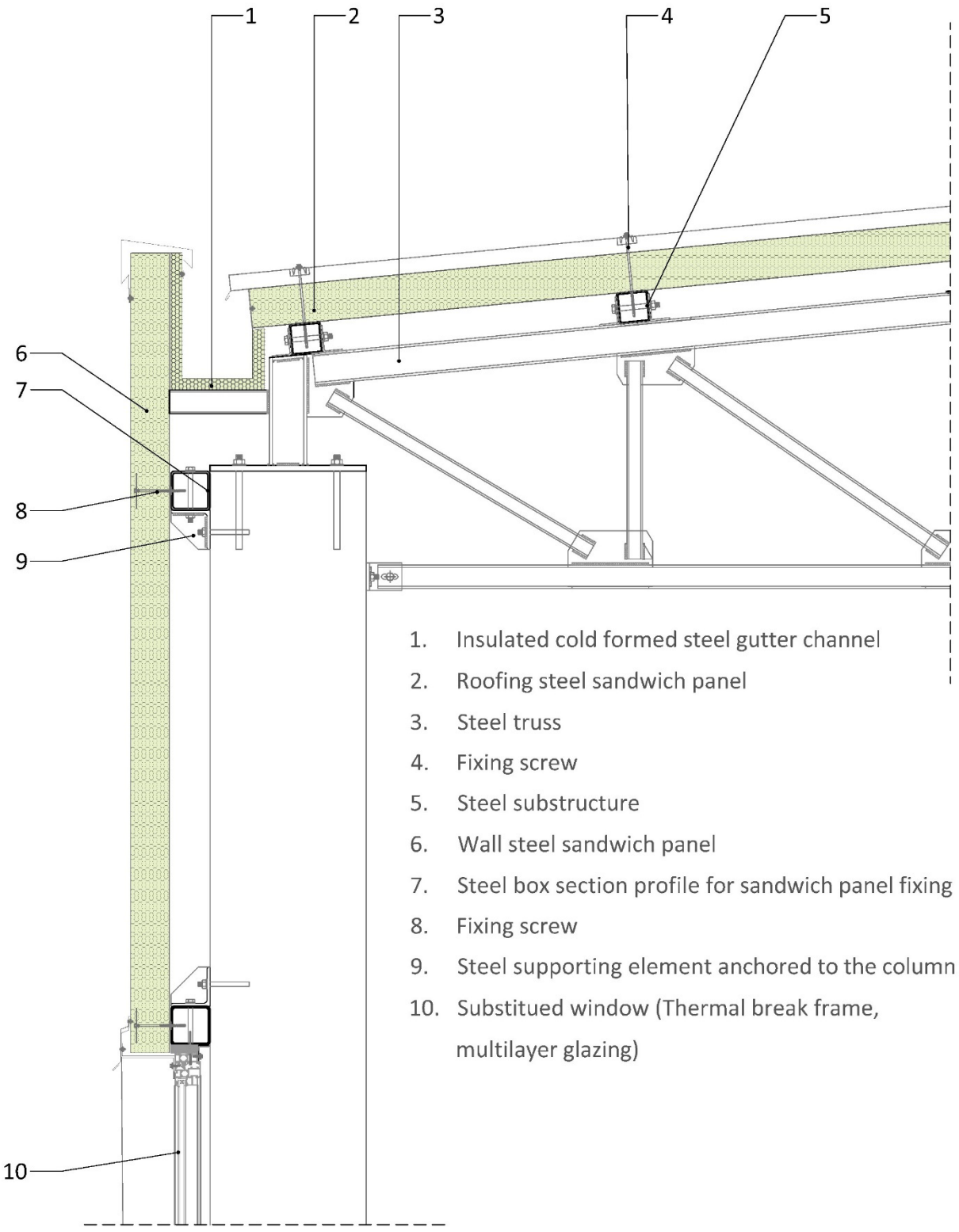


Figure 5.36 Vertical cross section of Building A - retrofit configuration. Details about roof beams substitution with steel trusses and replacement of external walls concrete panels with steel sandwich panels. *Source: elaboration of the author.*

Following the retrofit interventions on external walls, significant improvement in energy efficiency can be achieved. In addition, to account for the enhanced airtightness ensured by the complete redevelopment of cladding and windows components, the air infiltration rate during daytime was reduced by 30% in the energy model of the retrofit configuration.

The energy consumption data was compared to the current state, revealing an overall reduction in both electricity and gas consumption across all the months analysed. On average, the primary energy reduction is approximately 35%, which is a highly favourable result considering that the intervention is limited to windows and external vertical walls.

Given that walls and windows were previously identified as the main sources of heat loss among the building envelope components, this reduction is particularly significant. The improvement reflects the effectiveness of the upgraded thermal insulation and airtightness provided by the new windows and external wall treatments, confirming that targeted interventions on high-loss components can yield substantial energy savings with het losses reduced by 33% on average. A closer analysis of the diagram in Figure 5.37 reveals a marked reduction in heat loss from the walls compared to the current state: specifically, this percentage has been halved, now averaging around 7%.

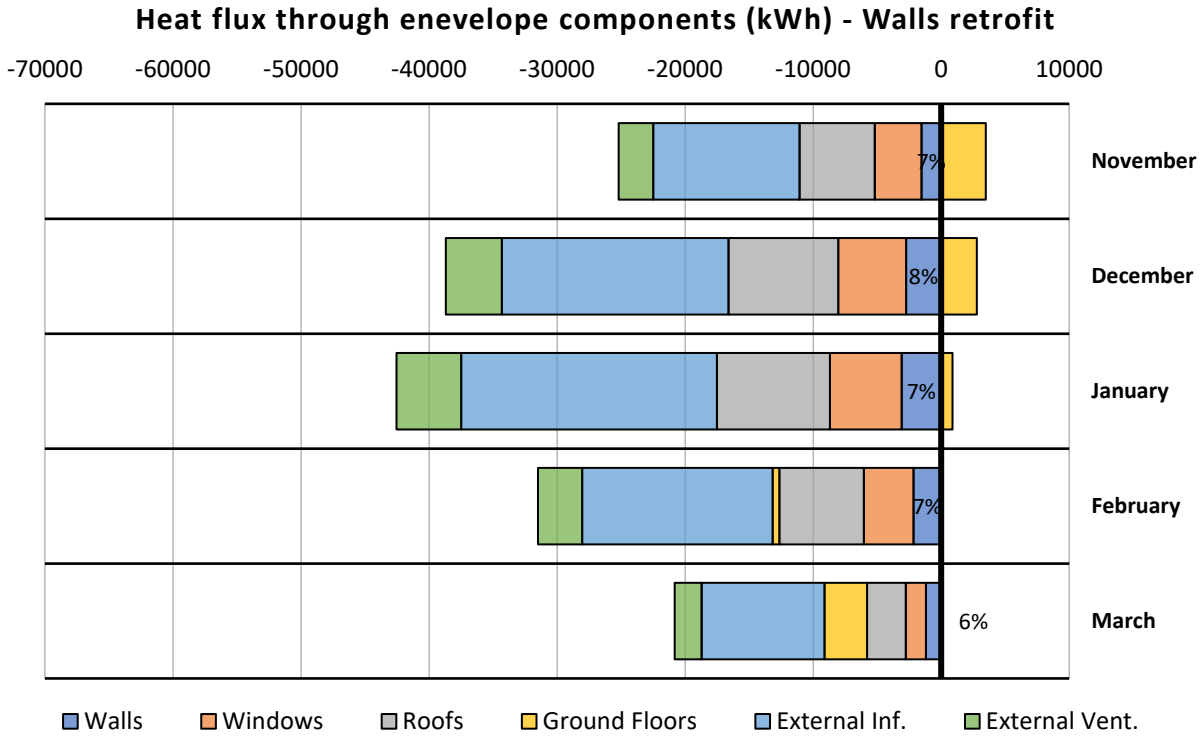


Figure 5.37 Heat flux per envelope component during the Winter months following external walls redevelopment. *Source: elaboration of the author.*

As for roofing components, different strategies were adopted in Building A and B to comply with the different structural systems of the two facilities.

The precast roofing components were supposed to be removed in Building A and completion elements substituted with metal purlins and sandwich panels (RS.1 + R.5), to exemplify the conditions connected to the most intrusive intervention level. Structural deficiencies were in this case of major concern given the dapped end configuration of the double slope beams and the poor connections with columns. Additionally, the existing concrete gutters were planned for removal, to be replaced with new channels made from metal sheets with insulating material in between, to eliminate thermal bridging.

In Building B, the removal of current insulation and finishing layer and the installation of a recladding sandwich panels layer made out of 0.10 m thick elements. The new roof covering would be secured to a framework made of omega-shaped, cold-formed steel profiles, anchored to the outer surface of the existing π roof slabs.

According to the same approach adopted for the external walls, a comparison between pre and post intervention conditions of the roofing layer in Building B is proposed in Table 5.30, while building A already features a redeveloped stratigraphy.

Table 5.30 Thermal properties of roof stratigraphy in Building B in current state and retrofit conditions. *Source: elaboration of the author.*

Current state			**Sandwich panels recladding**		
Material	**Thickness [m]**	**Conductivity [W/mK]**	**Material**	**Thickness [m]**	**Conductivity [W/mK]**
Precast concrete	*0.05*	*2.07*	*Precast concrete*	*0.05*	*2.07*
Insulation material [Rockwool]	*0.04*	*0.036*	*Steel sandwich panel*	*0.10*	*0.023*
Bituminous membrane	*0.002*	-			
Fiber cement corrugated panel	*0.065*	*0.50*			
Thermal transmittance	[W/m²K]	0.772	**Thermal transmittance**	[W/m²K]	0.21
Surface mass	[kg/m²]	135	**Surface mass**	[kg/m²]	133
Periodic thermal trans.	[W/m²K]	0.585	**Periodic thermal trans.**	[W/m²K]	0.15

The consequent energy simulations carried out revealed an overall average reduction in primary energy usage of approximately 34%. This is a highly favourable outcome, especially considering that the retrofit intervention only targeted the roof of one of the two parts of the facility. The percentage

reduction in energy consumption is comparable to that achieved with wall interventions, which, however, involved both buildings. Therefore, it can be concluded that the roof intervention is more effective than the wall intervention for this type of building. For completeness, the share of heat losses through building envelope components considering roof retrofit scenario is reported in Figure 5.38. In this case, heat losses proved to be diminished by about 25%.

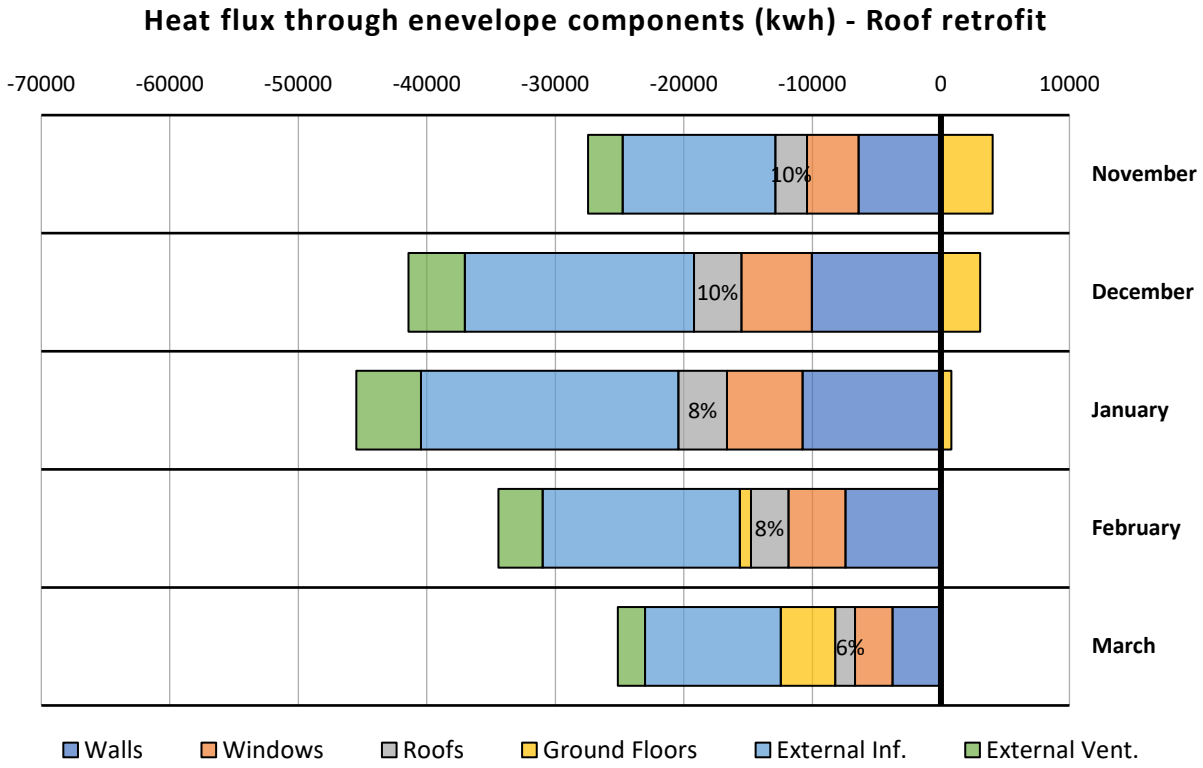


Figure 5.38 Heat flux per envelope component following roof retrofit intervention during the Winter months. Negative values indicate heat losses while positive ones represent thermal gains. *Source: elaboration of the author.*

The energy analysis of the building under review and the potential impact of the proposed retrofit measures were further evaluated by generating an energy classification for the entire complex. The EC700 software was utilized for this purpose, enabling the calculation of the building's energy performance in compliance with standard UNI/TS 11300 – 1:2014 [23]. In accordance with UNI EN 12831 [25], the software calculates heat losses due to transmission, ventilation, and heating system intermittencies. It also provides primary energy demand values, including those calculated under steady-state conditions for the heating system and domestic hot water production. The analysis methodology aimed to determine the building's global energy performance index, a key parameter for identifying its energy class. This classification is based on the guidelines for energy certification outlined in DM 26/06/2015, which defines the energy performance index (EP) as the ratio of thermal

demand to usable surface area. The relevant regulations also provide multiplication factors that define the boundaries of the different energy classes, allowing an assessment of how the building's performance compares to that of a reference building.

Different energy models were produced to reflect the current conditions and the retrofit state of buildings following both external walls and roof redevelopment. Results are synthesized in Figure 5.39, illustrating the energy performance of the facility across the three scenarios. Currently, the building has a global energy performance value of 73.73 kWh/m²/year and is classified as Class F This indicates poor energy efficiency and highlights the significant need for substantial improvements. After the retrofit of the external walls, the performance improves ranking the building in Class D (47.31 kWh/m²/year). Given the partial nature of roof retrofit, it results in a classification improvement to Class E (67.21 kWh/m²/year). The reduction in energy demand is in both cases driven by improved insulation and reduced air infiltrations. Anyhow, it clearly emerges that acting on sole building envelope is not sufficient to achieve the highest rates in terms of energy efficiency classification but acting on system and installations is needed.

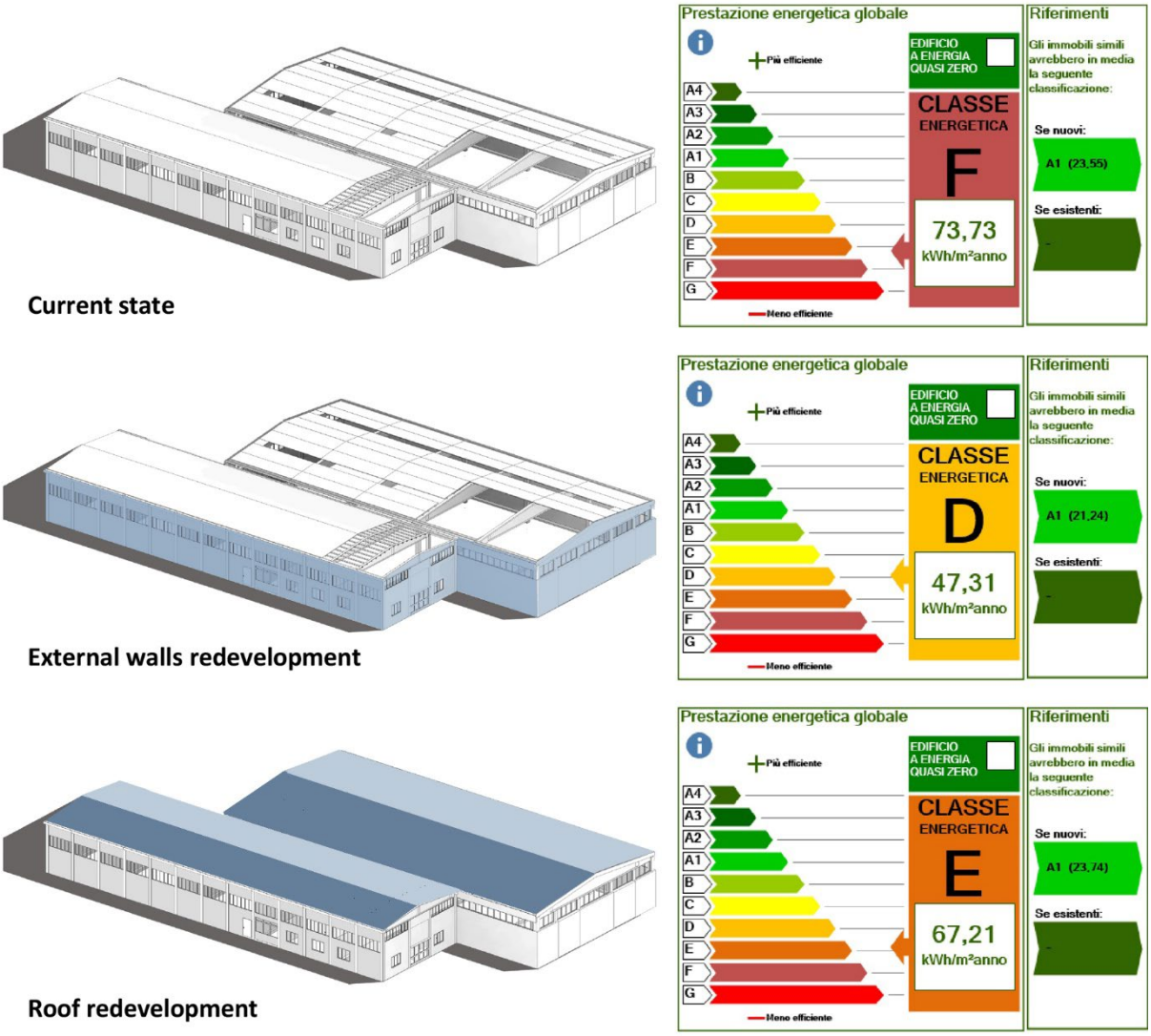


Figure 5.39 Energy classification of the facility under current and retrofit scenarios. *Source: elaboration of the author.*

5.2.3.2.2 GREEN ROOF INSTALLATION

The evaluation of the potential benefits of installing green roof as redevelopment strategy to target the deficiencies of current stratigraphy was carried out encompassing both environmental implications at district scale and the impact on the energy performance at building level. As previously mentioned, these aspects were developed in a dedicated scientific publication [18].

The same case study building of the same variant was considered, specifically considering the B portion, more representative of the building stock charactering the industrial district chosen for the study. Reference can be made to previous sections to recall the main distinguishing features of the facility and the properties of the envelope components. To reproduce a currently installed heating system, a traditional low-standard gas boiler with a coefficient of performance (COP) equal to 0.7 was adopted during the energy modelling phase. To evaluate the savings achievable for cooling demand during summer, a dedicated air-to-air heat pump (Energy Efficiency Ratio EER=3) was added in the model. In Figure 5.40 the DesignBuilder model of the buildings is illustrated: to quantify for the effects of the nearby structure, they were also introduced as simple mass elements.

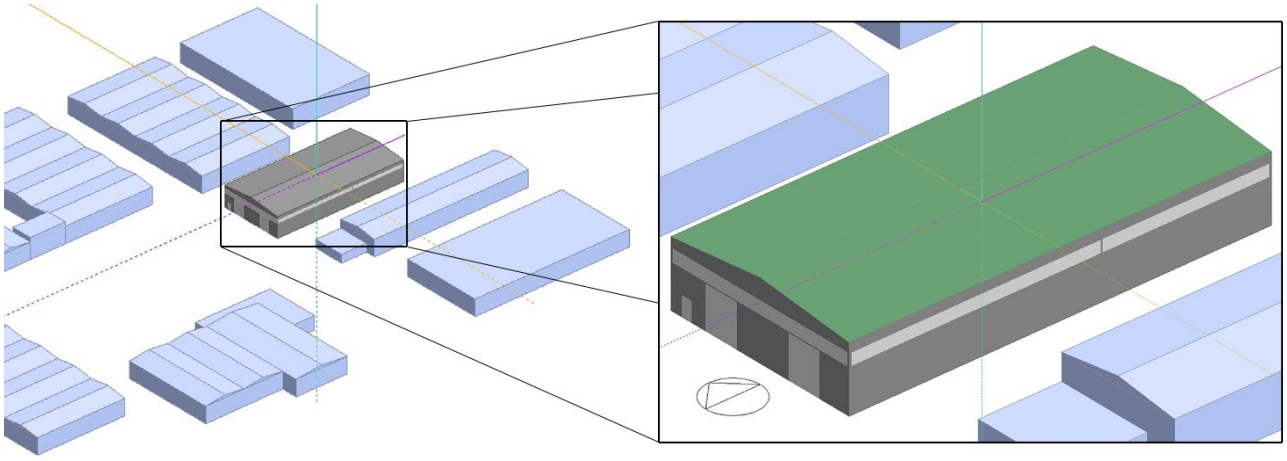


Figure 5.40 DesignBuilder model of the case study facility in the urban context. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

The retrofit scenario considered in this case only included roofing retrofit according to measure R.3, foreseeing the removal of π slabs, their substitution with metal sandwich panels and the adoption of extensive green roof stratigraphy as finishing solution. The new roof stratigraphy increases thermal insulation and periodic thermal transmittance, lowering at the same time the overall mass at the roof level. The comparison of the properties of the roof in current and retrofit state is provided in Table 5.31 while the new roofing stratigraphy is graphically reported in Figure 5.41.

Table 5.31 Thermal properties of roofing stratigraphy. *Source: elaboration of the author.*

Current state			Green roof retrofit		
Material	**Thickness [m]**	**Conductivity [W/mK]**	**Material**	**Thickness [m]**	**Conductivity [W/mK]**
Precast concrete	*0.024*	*2.07*	*Steel sandwich panel*	*0.12*	*0.023*
Insulation material [Rockwool]	*0.04*	*0.036*	*Filtering membrane*	-	-
			Draining layer	*0.005*	*0.50*
Bituminous sheet	*0.002*	*2.07*	*Soil*	*0.08*	*0.70*
Thermal transmittance	[W/m²K]	0.78	**Thermal transmittance**	[W/m²K]	0.19
Surface mass	[kg/m²]	124	**Surface mass**	[kg/m²]	95
Periodic thermal transm.	[W/m²K]	0.592	**Periodic thermal trans.**	[W/m²K]	0.064

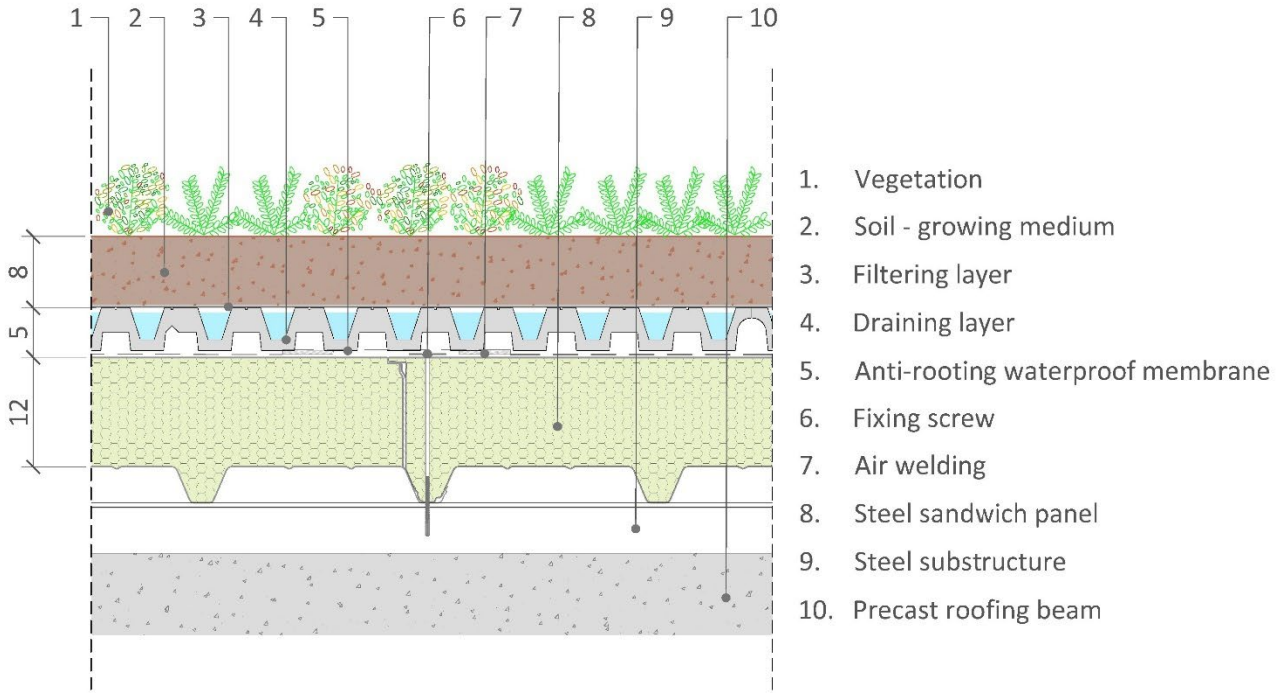


Figure 5.41 Extensive green roof stratigraphy in the retrofit configuration. *Source: elaboration of the author.*

Based on the simulation results, the extensive green roof significantly reduces heat loss through the external envelope by approximately 13%. As also highlighted in the literature, external infiltration plays a major role in heat losses for both configurations, with the roof being a close second in the current condition configuration. This finding suggests that priority should be given to improving roof stratigraphy in industrial building retrofitting projects. After the retrofit, roof-related heat losses decrease by about 75 but the heat flux is partially redistributed, with increases in heat losses through external walls and windows, which rise by 9% and 8%, respectively. The implementation of an extensive green roof significantly enhances the building's annual energy performance. The results reported below are illustrated in the graphics in Figure 5.42.

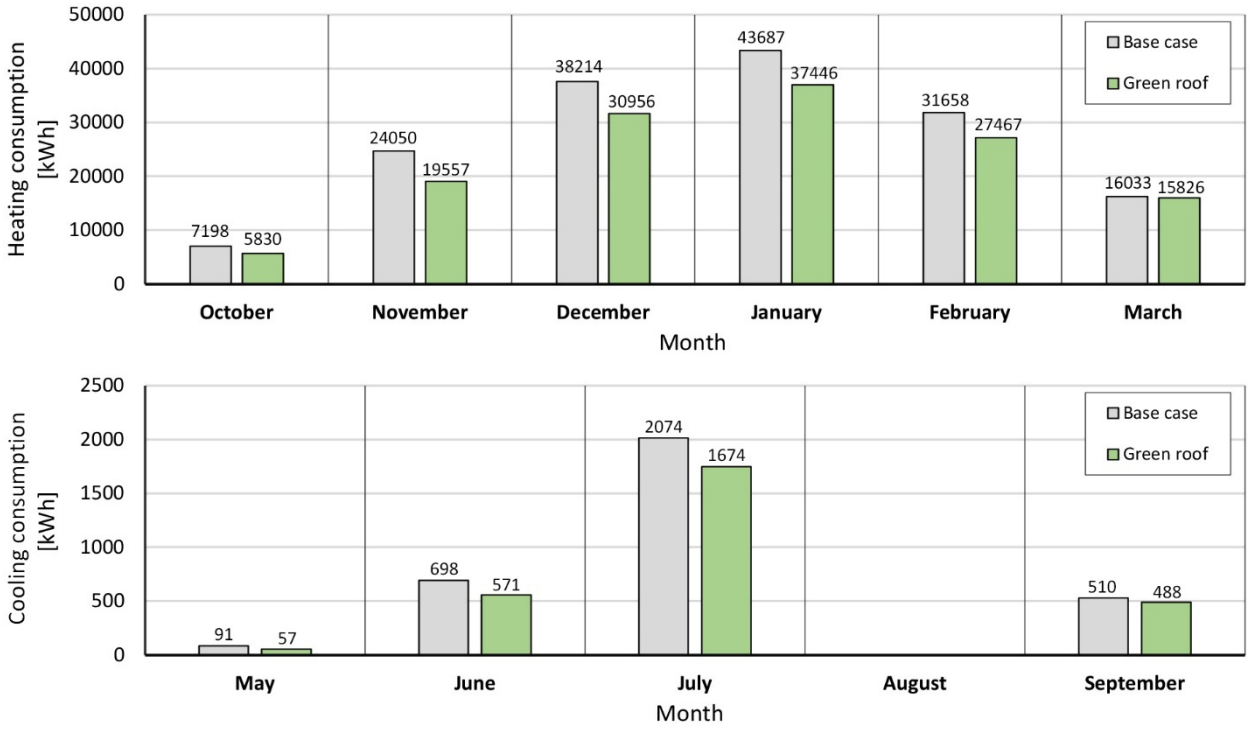


Figure 5.42 Heating and cooling energy demand in current state and retrofit conditions. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

During the winter season, heating consumption can be reduced by 15% (from 160,840 kWh to 136,369 kWh), with the highest energy savings observed in November and December showing a reduction of 19%. Conversely, the lowest savings are registered in March, when the external air temperature begins to warm. In the summer season, replacing the existing roof stratigraphy results in a cooling demand reduction of about 18%, quantified by considering the use of an air-to-air heat pump as previously specified. The most substantial benefit is achieved in May, with energy savings up to 37%. The reduction in building energy needs during the summer is closely linked to the outer and inner surface temperatures of the roof stratigraphy. For the outer surface, the maximum observed difference between traditional and green roof is 15°C while both ENVI-met and DesignBuilder simulations indicate a 9°C difference at the reference time selected for ENVI-met analysis (July 14th at 3 p.m.). Considering the hourly trend, unlike the daytime pattern, the surface temperature of the green roof is higher at night compared to the base case, due to the thermal mass provided by the substrate layer (0.08 cm). Both ENVI-met and DesignBuilder outputs are detailed in Figure 5.43.

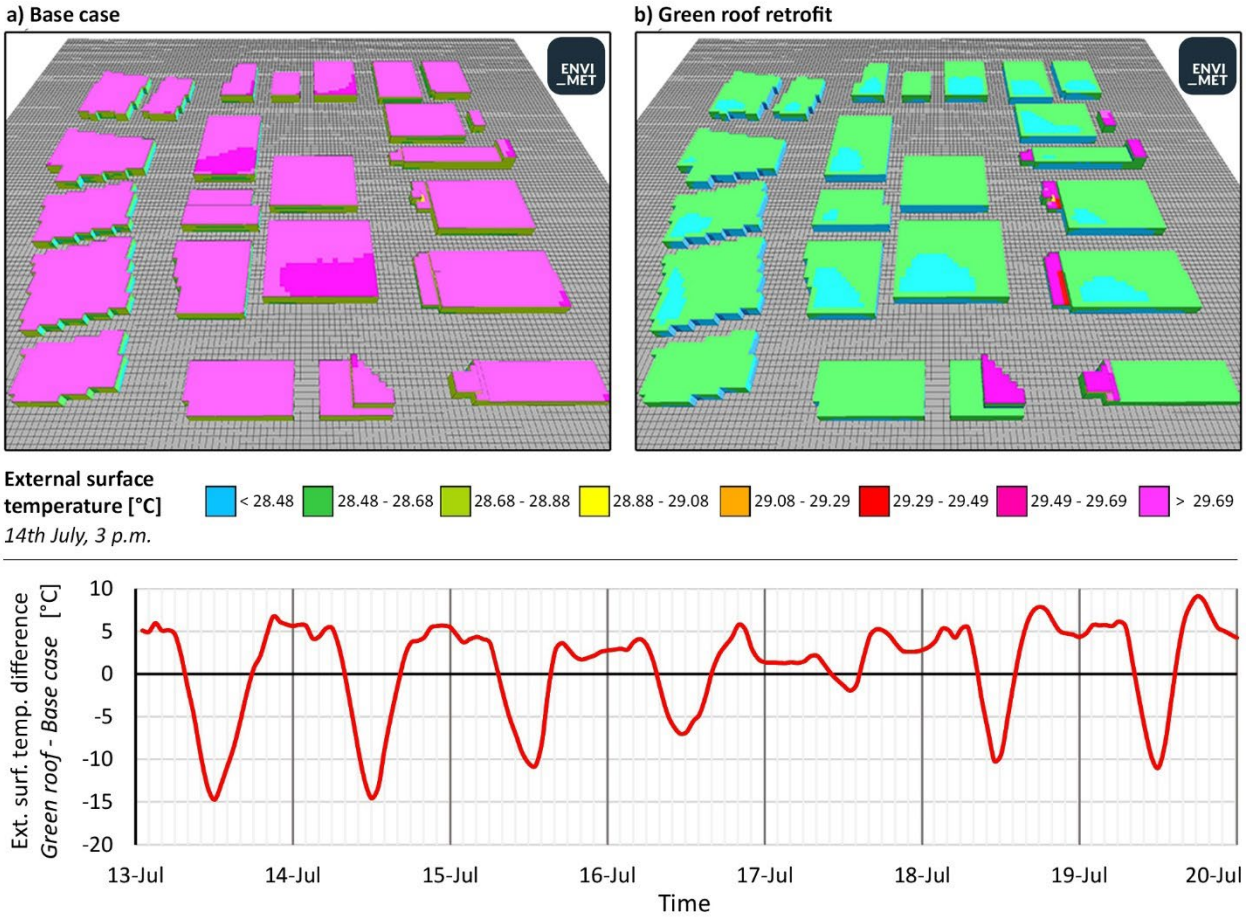


Figure 5.43 ENVI-met simulations results for external surfaces temperatures and DesignBuilder hourly trend in roof temperature difference in base case and green roof retrofit conditions. *Source: Re-elaboration from Ciacci C, Banti N, Di Naso V, Bazzocchi F (2023) Green strategies for improving urban microclimate and air quality: A case study of an Italian industrial district and facility. Building and Environment 110762. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110762.*

Based on these detailed outputs, indoor thermal comfort was also assessed, turning off the cooling system during this simulation to focus solely on the effects of the roof retrofit. The Predicted Percentage of Dissatisfied (PPD) was used as the reference index to evaluate workers' well-being. Following the adoption of the extensive green roof, the PPD decreases by approximately 10%, with an average reduction of about 4% during occupied hours over a reference week in July (13th–20th).

5.3 Internal conditions and system installations

Internal conditions in working places are crucial to ensure adequate comfort and wellbeing for employees, ensuring at the same time enhanced productivity [27]. For this reason, retrofit initiative for industrial buildings should be adequately consider not only the energy savings achievable but also the improvements and benefits achievable by effectively acting on crucial aspects such as adequate lighting conditions and prevention of possible overheating phenomena. As proved following the extensive recognition of the existing industrial building stock carried out, these aspects can pose significant challenges. Lighting systems are generally outdated from a technological point of view considering the lighting devices installed and the absence of automatization solutions. On the other hand, cooling systems are largely not installed and this can induce not appropriate working conditions during summer months in the manufacturing facilities. Both active and passive strategies can be deployed in these cases acting on both appropriate shading devices and system installations. Focusing exclusively on the enhancement of building envelope components may result inadequate, given the significant share of energy demand connected with the lighting, air conditioning, and ventilation systems. Renovating these installations requires a thorough, multidisciplinary evaluation to balance the often conflicting requirements of workspaces and industrial environments effectively.

In Table 5.32, Table 5.33, Table 5.34 the measures evaluated at this regard are listed while their application and evaluation will be discussed in the following paragraphs.

Table 5.32 Retrofit intervention and solutions for the lighting system. *Source: elaboration of the author.*

System	**Current state**	**Retrofit strategy**	
	Technology	**Code**	**Measure**
Lighting	Fluorescent lamps	L.1	LED lighting installation
		L.2	Automatic lighting conditions control through sensors

Table 5.33 Retrofit intervention and solutions for the heating system. *Source: elaboration of the author.*

System	Current state	Retrofit strategy		
	Technology	**Code**	**Heat generator**	**Air distribution and terminals**
Heating	Localized gas fan heaters Or Centralized boiler and hot air distribution systems	H.1	Gas condensing boiler	Heated walls
		H.2	Air-to-Water Heat Pump	
		H.3	Gas condensing boiler	Heated floor
		H.4	Air-to-Water Heat Pump	
		H.5	Gas boiler	Fan heaters
		H.6	Air-to-air heat pump	All air system

Table 5.34 Retrofit intervention and solutions for the energy production system. *Source: elaboration of the author.*

System	Current state	Retrofit strategy		
	Technology	**Code**	**PV panel**	**Position**
Energy product. from renewables	-	PV.1	Mono/polycrystalline rigid panels	Roof
		PV.2	Amorphous silicon panels	
		PV.3	Mono/polycrystalline rigid panels	External walls
		PV.4	Amorphous silicon panels	
		PV.5	Storage systems, Batteries	

5.3.1 Skylight configurations and lighting conditions

Artificial lighting is one of the most significative energy intensive operation in buildings. Focusing on the Italian scenario, it is projected to consume around 110 TWh by 2026, representing 40% of the country's total electrical energy demand [28]. In industrial buildings, artificial lighting can constitute a significant portion of the annual energy consumption due to the unique characteristics of these facilities, covering up to 30% of the total energy demand according to recognised scientific literature [29]. In this context, retrofitting existing artificial lighting systems or integrating/replacing skylights could significantly reduce energy consumption while enhancing visual comfort in workspaces. In this regard, promising insights are offered by existing studies. carried out in different geographic contexts and under varying boundary conditions suggest that combining skylights with artificial lighting and effective light control strategies can reduce energy demand by up to 80% under overcast conditions [30]. Starting from the typological classification produced, specific assessments were conducted to evaluate impact of three different skylight configurations, commonly used in Italian industrial buildings, on both the overall energy performance of the building and the thermal and visual comfort of workers. In addition, a LED lighting solution, coupled with two different control strategies, was also analysed to define retrofitting strategies addressing both the opaque and transparent elements of the building envelope as well as lighting system installations in existing manufacturing facilities.

The research described in this section is extensively detailed in the paper *"Influence of Skylights configurations on the energy performance and internal conditions in industrial buildings"*, currently under publication for the 2nd International Conference on Green Construction.

A hypothetical case study industrial building, representative of the typological solutions characterized by precast wing tiles, was considered to perform energy and lighting calculations in a DesignBuilder energy model. As previously detailed, this typological variant is typical of the more recent facilities and, consequently, better-performing envelope components if compared to the average performance of existing industrial buildings were foreseen. External walls were assumed to be realized using precast concrete sandwich panels characterized by a thermal transmittance (U) value equal to 0.427 W/m^2K. For roof stratigraphy, a thermal transmittance equal to 0.385 W/m^2K was considered assuming a layout with embedded thermal insulation and external membrane finishing. As for the windows, the following properties were included in the model: Solar Heat Gains Coefficient SHGC=0.5, Light Transmission TL=0.6 and thermal transmittance U=1.6 W/m^2K.

A fluorescent lamp-based artificial lighting system was deemed the most realistic scenario. A normalized power density of 1.16 W/m²-lux, with a radiant fraction of 0.42 and a visible fraction of 0.25, was used in the simulations.

The layout chosen for the facility is characterized by one single nave 20 m wide, covering about 725 m^2 for a total volume equal to 6054 m^3. Three different geometrical configurations of skylights were evaluated, to cover the different layouts available for these components and corresponding to different percentages of glazed portions. The distribution of skylights tested are illustrated in Figure 5.44. Configurations 1, 2, and 3 feature skylights on the rooftop, with varying levels of coverage relative to the total roof surface area: 24% for Configuration 1 and 9% for Configuration 2. For Configuration 3, which uses a shed roof design, performance is influenced by the orientation of the skylights, so two different layouts were analysed: one with a northern orientation (3N) and another with a southern orientation (3S). In addition, a base case configuration with no skylights (referred to as Configuration 0) and only side windows (window-to-wall ratio 4%) was also considered to evaluate the impact of skylights. The latter were considered as made of polycarbonate, characterized by a Solar Heat Gain Coefficient (SHGC) of 0.60, a Light Transmission (TL) of 0.40, and a thermal transmittance U-value of 1.65 W/m²K.

These layouts were analysed both individually and then in combination with LED lighting systems, paired with two different levels of lighting control: an on-off control and a dimming-type linear off control. The LED lighting devices were modelled according to the following characteristics: normalized power density equal to 0.58 W/m²-100 lux, and radiant and visible fractions equal to 0.01 and 0.10 respectively.

To assess the energy performance of these different configurations (1, 2, 3N, 3S), the heating demand during the winter period was calculated and compared with the base case scenario, which does not include any roof openings. Simulations were carried out considering climate zone D for energy calculations and assuming a heating system powered by a gas boiler with a Coefficient of Performance (COP) of 0.85, reflecting the outdated efficiency levels typical of many installed systems.

Simultaneously, visual comfort and natural lighting potential were evaluated using several key parameters: Average Daylight Factor (ADF), Uniformity Ratio (η), and illuminance (Em). The minimum daylight illuminance was set to 300 lux, in line with the requirements of UNI EN 12464-1,

which applies to generic activities in a typical industrial setting. Additionally, the uniformity ratio near the working area should be at least 0.5, with an acceptable discomfort glare index (UGR) of 25. According to CIBSE Guide A, an ADF in the range of 2-5% is recommended, as workplaces with an ADF below 2% generally require artificial lighting.

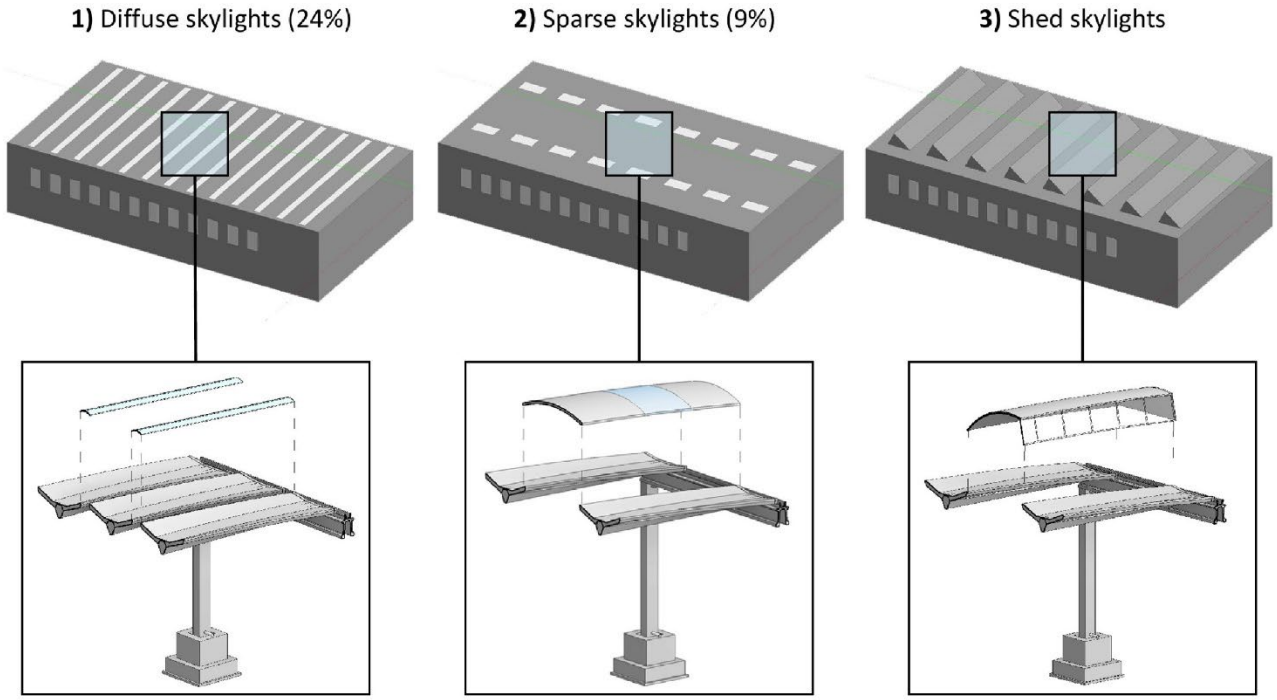


Figure 5.44 Building energy models and configurations of skylight distributions. *Source: Re-elaboration from Banti, Ciacci, "Influence of Skylights configurations on the energy performance and internal conditions in industrial buildings", currently under publication for the 2nd International Conference on Green Construction.*

Figure 5.45 shows the main outputs of lighting conditions study, reporting the distribution of illuminance and daylight factor in the working area for both the base case (Config. 0) and the skylight configurations evaluated.

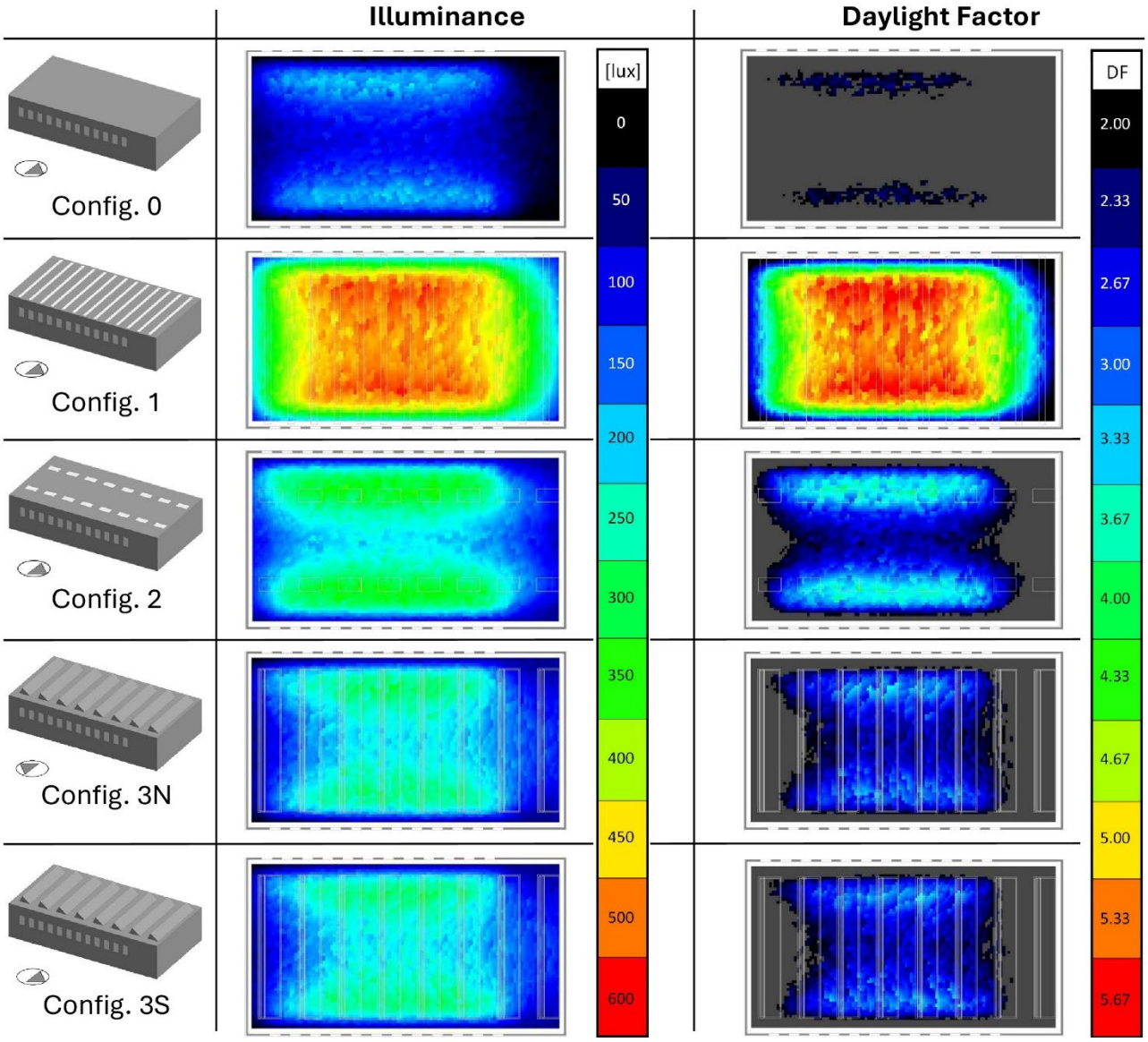


Figure 5.45 Results of lighting analyses, Illuminance and Daylight Factor levels. *Source: Re-elaboration from Banti, Ciacci, "Influence of Skylights configurations on the energy performance and internal conditions in industrial buildings", currently under publication for the 2nd International Conference on Green Construction.*

It clearly emerges that side windows alone are inadequate for providing sufficient natural light, resulting in an average daylight factor of just 1.2%. This finding is consistent with previous research, which indicates that achieving adequate lighting uniformity in industrial buildings typically requires a combination of side windows and skylights [31]. The simulation results reveal that Configuration 1, featuring diffuse roof openings with 24% skylight coverage, provides the most favourable lighting conditions. This setup meets the necessary illuminance levels, offering an Average Daylight Factor (ADF) of 4.6% and an average illuminance of around 350 lux. Deeper analyses would be required in case of specific visual tasks when the uniformity ratio can be relevant for workers. A recommended value of 0.5 is required in this case, higher than the 0.26 ensured by this configuration. Configurations 2 and 3 also perform well, achieving ADF values above 2% and maximum illuminance levels near

350 lux. Configuration 2 offers enhanced visual comfort, with a uniformity ratio equal to 0.20. Nonetheless, the lighting distribution maps indicate that these configurations exhibit lower daylight factor and illuminance values in the central zone of the workspace. For Configuration 2, this is largely due to the skylights' geometric placement closer to the building's perimeter. In Configuration 3, both for north and south exposed sheds, the lower values in the central area may be attributed to the contribution of windows on external walls in the side portions of the working area. A more detailed presentation of the outputs is proposed in Table 5.35.

Table 5.35 Results of lighting conditions simulations. *Source: elaboration of the author.*

		Config. 0	Config. 1	Config. 2	Config. 3N	Config. 3S
Floor Area within Limit	*[%]*	9.63	83.91	35.12	16.43	15.74
Average Daylight Factor	*[%]*	1.20	4.63	2.47	2.11	2.11
Minimum Daylight Factor	*[%]*	0.00	1.22	0.48	0.08	0.11
Maximum Daylight Factor	*[%]*	2.52	6.35	4.11	3.68	3.69
Uniformity ratio	*[Min/Avg]*	-	0.26	0.20	0.04	0.05
Min Illuminance	*[lux]*	0.01	115.15	45.66	7.31	10.34
Max Illuminance	*[lux]*	238.05	599.60	388.32	347.65	348.46
Average illuminance	*[lux]*	-	357.38	216.99	177.48	179.40

The heating demand was also evaluated and results are reported in Figure 5.46.

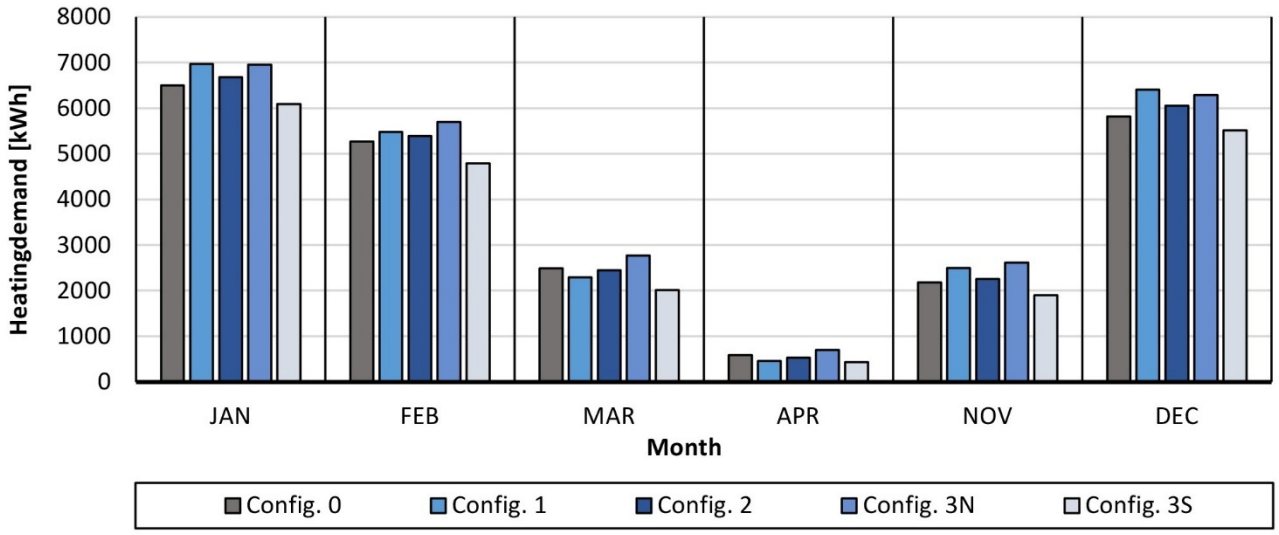


Figure 5.46 Results of heating demand simulations on a monthly basis in the different configurations. *Source: Re-elaboration from Banti, Ciacci, "Influence of Skylights configurations on the energy performance and internal conditions in industrial buildings", currently under publication for the 2nd International Conference on Green Construction.*

For all configurations, except the southern-oriented shed scenario (3S), the installation of roof skylights increases the building's heating demand during the colder months due to the lower thermal resistance of these components. In Configuration 1, this leads to a significant peak in November, with a 15% increase in heating demand. Configuration 2, while still affected, shows a smaller increase in energy consumption of around 4%. The shed's orientation plays a crucial role in energy demand. Northern-oriented sheds see an average 12% increase in heating needs during the heating season. In contrast, the southern-oriented shed offers a notable advantage in winter, reducing heating demand by an average of 13%, which translates to an energy saving of 2,055 kWh. This is because the glazed portion receives direct solar radiation for a larger part of the day, contributing positively to the building's energy balance. However, careful attention must be paid to potential summer overheating, which could cause thermal discomfort. The percentage of roof openings also impacts seasonal heating energy demand.

Figure 5.47 illustrates the lighting energy demand when LED lighting, combined with two different lighting control strategies, is used to replace the existing system. Replacing fluorescent lamps with high-efficiency LED lighting results in approximately 50% savings in electricity consumption. However, this reduction in internal heat gains from lighting increases heating demand by up to 10% in the scenario featuring dimming light control. When applying the on/off light control, significant electrical energy savings can be achieved, particularly during the summer months when artificial lighting can be turned off for much of the working day. However, during the winter season, these savings decrease by up to 20%, with the southern-oriented shed configuration again emerging as the most advantageous. The results for the dimming control system are similar but offer greater electrical energy savings due to more precise light modulation. Overall, significant performance improvements in manufacturing buildings can be realized by leveraging natural lighting and upgrading to more efficient lighting systems. This approach also necessitates modifications to the rooftop structure to accommodate skylights. Among the configurations studied, the southern-oriented shed proved to be the most favourable, as it provides the minimum required daylight illuminance while significantly reducing heating energy demand during winter. Nevertheless, it is crucial to carefully assess potential glare-induced discomfort and consider mitigation strategies and shading devices to prevent overheating in the summer months.

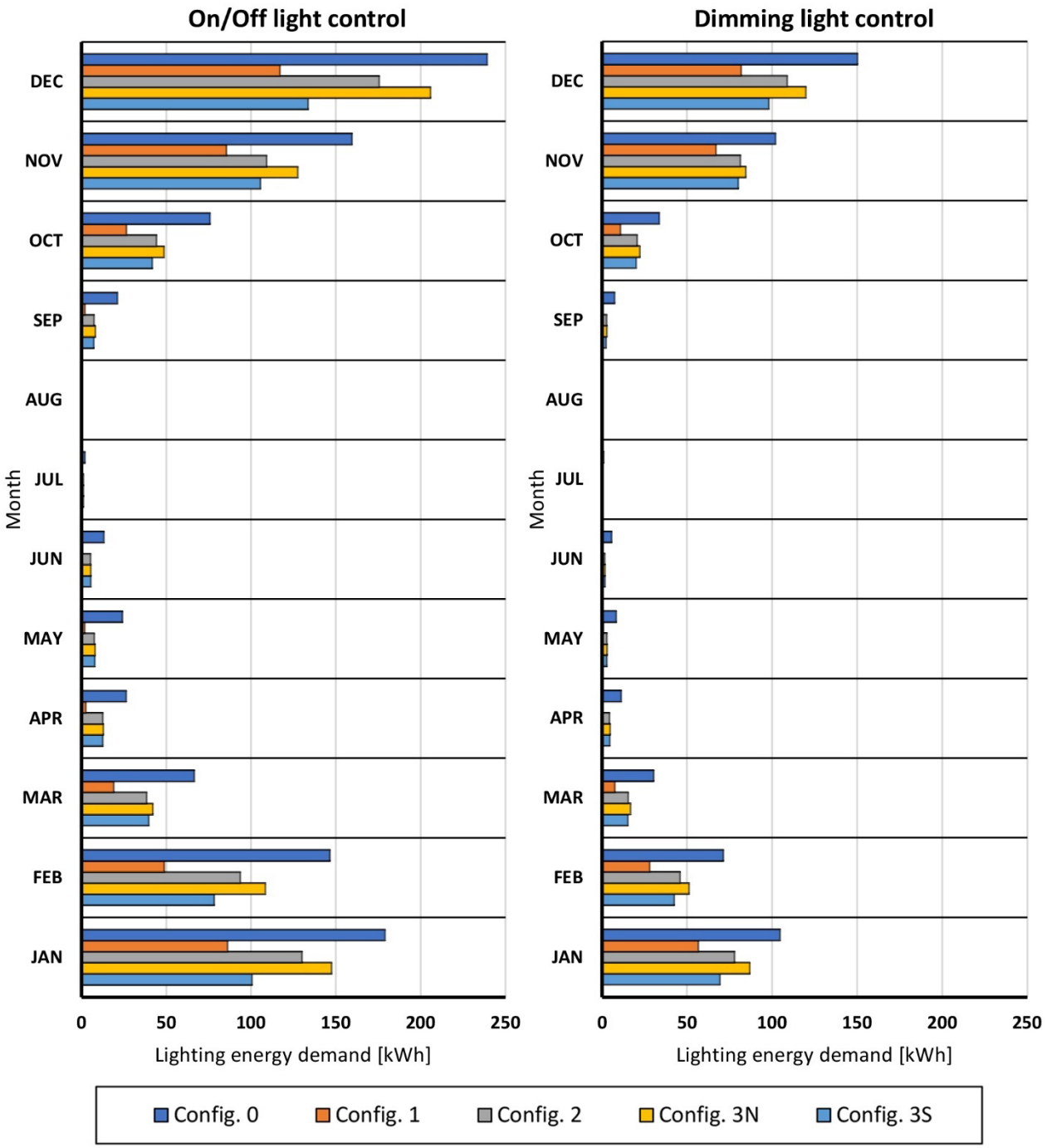


Figure 5.47 Lighting energy demand considering the two different scenarios for lighting control technologies. *Source: Re-elaboration from Banti, Ciacci, "Influence of Skylights configurations on the energy performance and internal conditions in industrial buildings", currently under publication for the 2nd International Conference on Green Construction.*

5.3.2 Summer overheating evaluation

Ventilation conditions in industrial and commercial buildings are crucial because they directly impact energy consumption, operational expenses, and the perception of thermal comfort inside the facility [32]. Currently, cooling needs during summer season are largely disregarded and no specifically intended system is generally installed in working areas of industrial facilities. However, their characteristics and the currently ongoing climate change scenario can induce significant issues connected with discomfort conditions. The already introduced raise in external temperature negatively affects the thermal comfort of occupants and increases the cooling energy requirements of buildings during the summer and transitional seasons. As outlined by the extensive state of the art review produced, there is a research gap in systematic studies about passive measures to be applied to existing industrial buildings in an integrated manner to mitigate the risk of overheating. Following this consideration, specific studies were carried out to evaluate different strategies, along with other potential measures, to be implemented in manufacturing facilities aiming to improve internal comfort conditions, reduce health risks for workers during occupancy hours, and lower operational costs.

The research described in this section is extensively detailed in the paper *"Strategies to Face Overheating in Industrial Buildings Located in Mediterranean Climate Area"*, in the Proceedings of the 11th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering) [33].

From a methodological point of view, the same case study hypothetic facility introduced in the previous section was considered making reference to the configuration with integrated and diffuse polycarbonate skylights. This roofing solution is especially prone to overheating due to its large transparent surface exposed to direct sunlight. For both geometry, dimensions, envelope characteristics and system properties, refence can be made to the values provided before.

To address overheating issues, this study considered several intervention measures, targeting both the external envelope and the use of natural ventilation:

- External Envelope:
  - Solar Shading Systems: Two types of external solar shading systems were evaluated for the windows. The first system, "Louvres," consists of fixed metal horizontal louvres with 0.20 m long blades, spaced vertically by 0.3 m, and tilted at a 15° angle. The second system, "Shaders," is an automatic shading system with metal blinds that adjust based on the internal air temperature. These blinds have 0.025 m wide blades, spaced vertically by

0.02 m, with a 45° tilt angle and a setpoint activation temperature of 25°C. The shading system was applied only to glazed portions of the external walls, as the current skylight design does not allow for shading installation.

  - Cool Roof Installation: The study explored replacing the existing elastomeric bitumen membrane with a thermoplastic PolyOlefin (TPO) membrane with high solar reflectance or applying a light, protective, weather-resistant acrylic paint. Regardless of the chosen technology, the cool roof was modelled in DesignBuilder by setting the external surface's solar absorptance to 0.13.
  - Skylight Reduction: The surface area of the skylights is supposed to be reduced by 50%, and the combination with the cool roof application also was tested to maximize benefits.

- Natural Ventilation:
  - Enhanced Natural Ventilation: Natural ventilation was optimized for passive cooling while maintaining the minimum required air change rate during occupancy (0.26 v/h), which corresponds to about 25% windows opening. To facilitate free cooling, the airflow rate is doubled between 8:30 and 11:00 a.m., during which external temperatures are lower than internal ones.
  - Night Cooling: Passive cooling was tested at night (12:00 p.m. – 8:30 a.m.) with two different airflow conditions: maintaining the minimum air change rate of 0.26 v/h or reducing it to 0.13 v/h. Night cooling requires an automatic system for opening apertures, including sensors and mechanized frames.
- Lighting Replacement:
  - LED Lighting: The existing lighting system was supposed to be replaced with a more efficient one with lower heat internal emissions. The proposed LED lighting system has a normalized power density of 0.58 W/m²-100 lux, a radiant fraction of 0.01, and a visible fraction of 0.10.

The effectiveness of these passive and active strategies was evaluated by referring to internal air temperature, cooling energy needs (assuming a cooling system with an Energy Efficiency Ratio (EER) of 3), and overall energy performance in terms of gains and losses through the external envelope during a summer design working week (June 20th-24th). The results of the research are presented below, while in Figure 5.48 the outdoor dry-bulb temperature is reported to compare it with the indoor values registered during simulation.

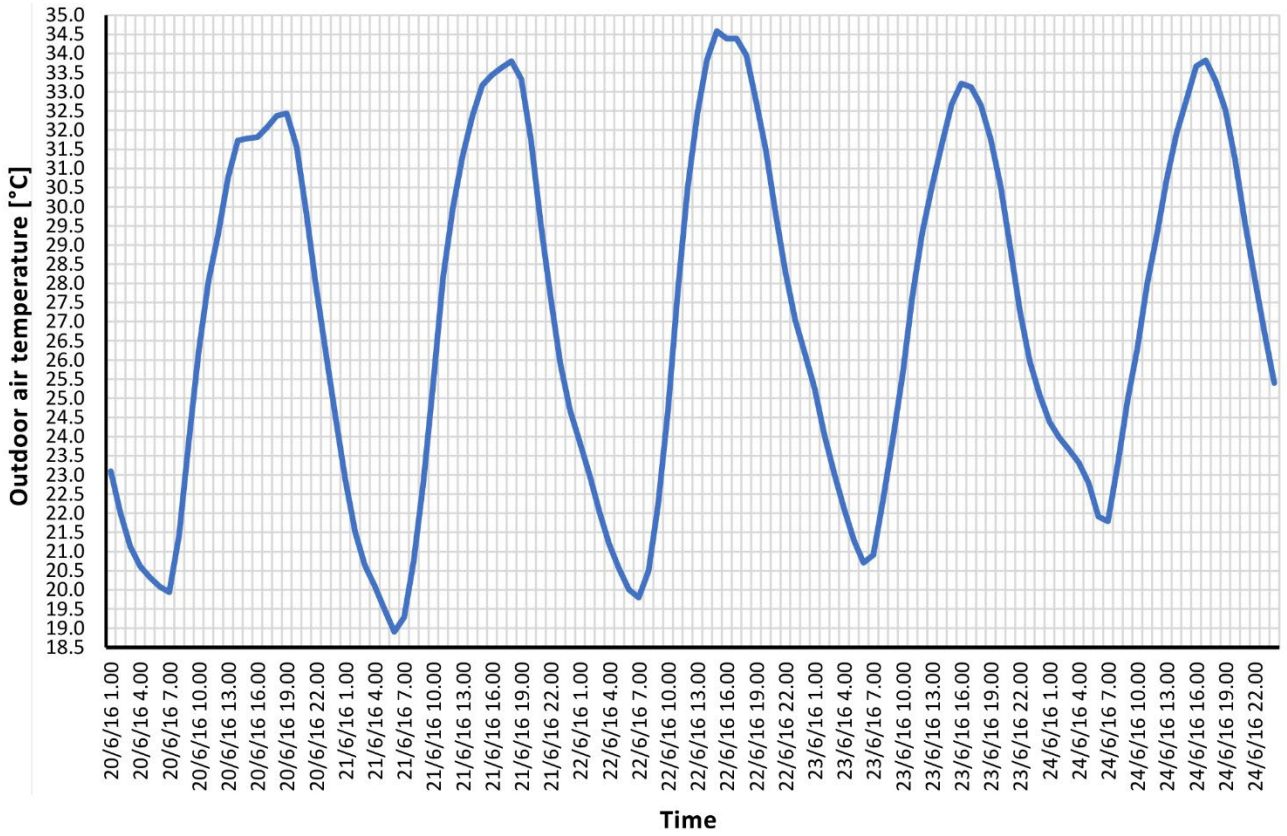


Figure 5.48 Outdoor dry bulb temperature over the analysis period for the location considered. *Source: elaboration of the author.*

Figure 5.49 reports the internal air temperature within the workspace under existing conditions and after applying the retrofit measures addressing the external envelope.

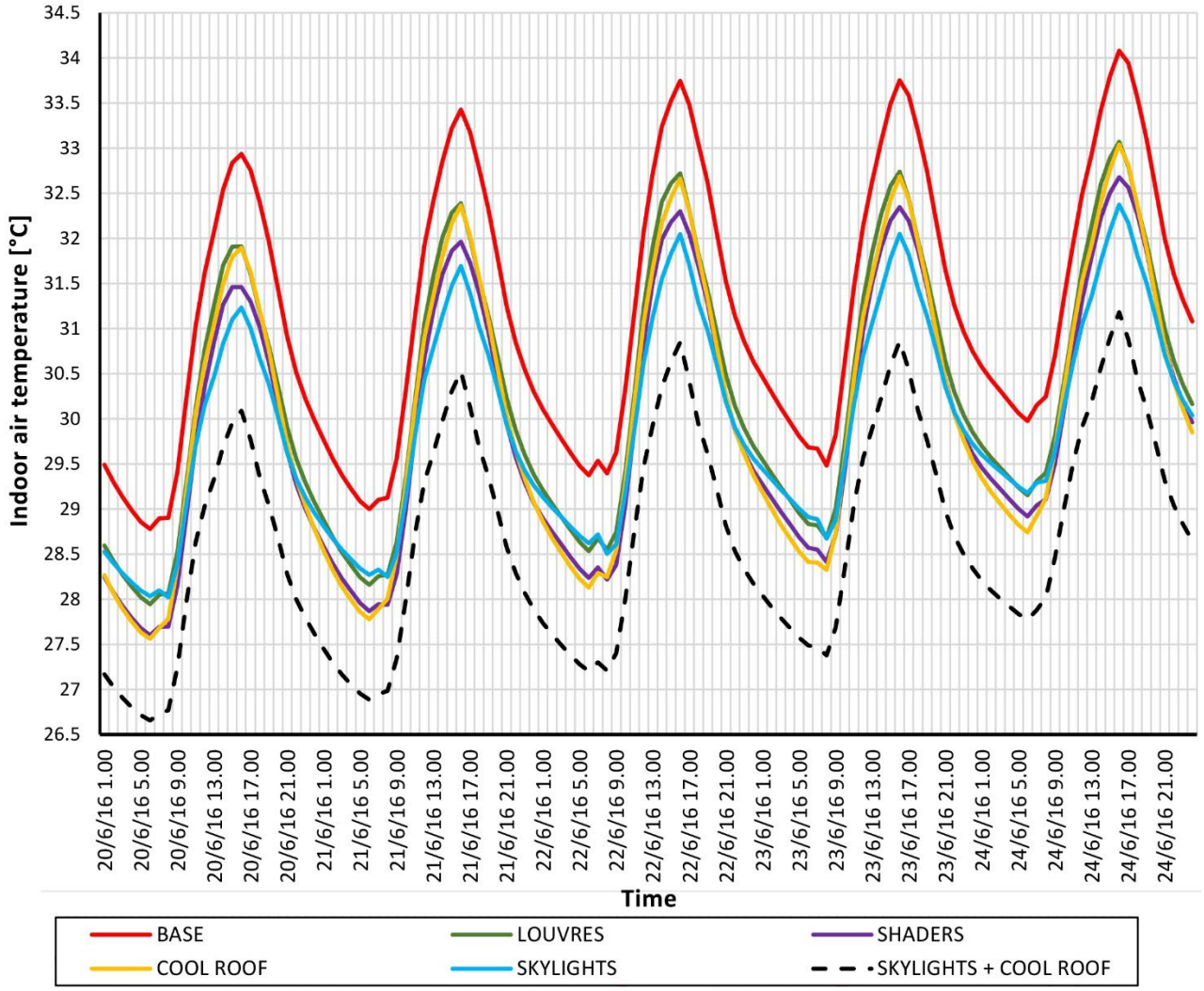


Figure 5.49 Indoor air temperature in the base case and under the different retrofit scenarios considered for external envelope upgrading. *Source: elaboration of the author.*

Overheating conditions can be highlighted in the base case that exhibits the highest internal air temperature. This is closely linked to the presence of skylights and to the thermal properties of the external envelope, such as solar absorptance, which influences the amount of solar gains entering the building during the summer design week. Among the passive strategies evaluated, the combination of reducing skylight surface area and installing a cool roof emerged as the most effective solution. This combined approach led to a temperature reduction of about 3°C compared to the base case, significantly improving thermal comfort for workers. While other passive strategies performed similarly, cool roofs and shaders showed slightly better results, with an average temperature decrease of 1°C. For the latter, it is important to consider the design of solar shading systems such as the louvres, to ensure their effectiveness in summer without hindering solar gains in winter. The integration with enhanced automatic control provided by sensors makes shaders a preferable option, as they balance shading with natural lighting without overly compromising both the performances.

Figure 5.50 illustrates the impact of ventilation cooling strategies on internal air temperature.

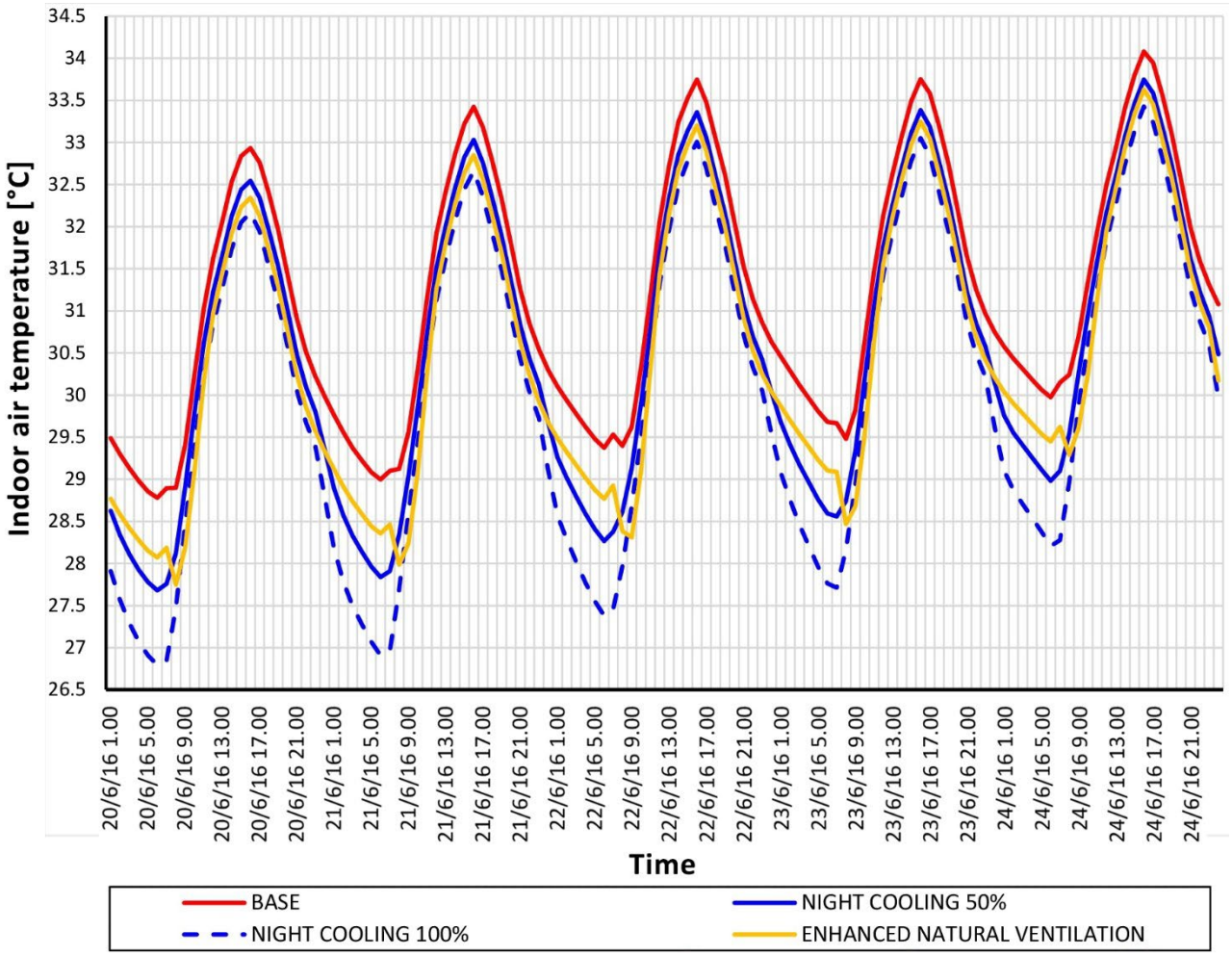


Figure 5.50 Indoor air temperature in the base case and following the implementation of the different ventilation strategies included in the research. *Source: elaboration of the author.*

It's essential to separately analyse the effects at nighttime and at daytime. The outputs of simulations shows that during nighttime, the full opening night cooling is the most effective approach, reducing internal air temperature by approximately 2.5°C by 5:00 p.m. This reduction enhances thermal comfort in the morning and, if a cooling system is used, decreases the time and the energy required to obtain and maintain over time the target indoor temperature. The other two ventilation strategies investigated let to obtain similar outcomes, with internal temperatures about 28°C between 5:00 a.m. and 9:00 a.m. When the enhanced ventilation scenario proposed is considered, the internal temperature drops as soon as the windows are opened as retrievable in the graphical representation of the results. During working hours, the differences between the passive strategies are less appreciable even if the 100% night cooling method offers the greatest reduction, approximately equal to 1°C. Further considerations have to be formulated when considering natural ventilation conditions in industrial buildings. The effectiveness of natural ventilation in providing adequate air changes and

passive cooling is closely tied to the presence of internal heat sources, since many studies have pointed out that natural ventilation is often insufficient in environments with significant internal heat generation [34]. Additionally, it's important to consider door openings in industrial buildings, frequently overlooked in research. Furthermore, in real working conditions, windows are often kept closed or only opened infrequently, despite the need for proper air exchange. The large volume of industrial spaces often induce a misleading perception of air quality in working spaces, leading to windows remaining closed and not guaranteeing adequate standards.

The analysis of internal air temperature in case of fluorescent lamps and LED lighting adoption is reported in Figure 5.51. This measure influences the value of the indoor air temperature at a limited extent with respect to the other strategies introduced before. A reduction of 0.5°C is obtained following a decrease in internal gains equal to 0.7 W/m^2-lux but a consistent reduction in energy demand (about 50%) for lighting is ensured in this case.

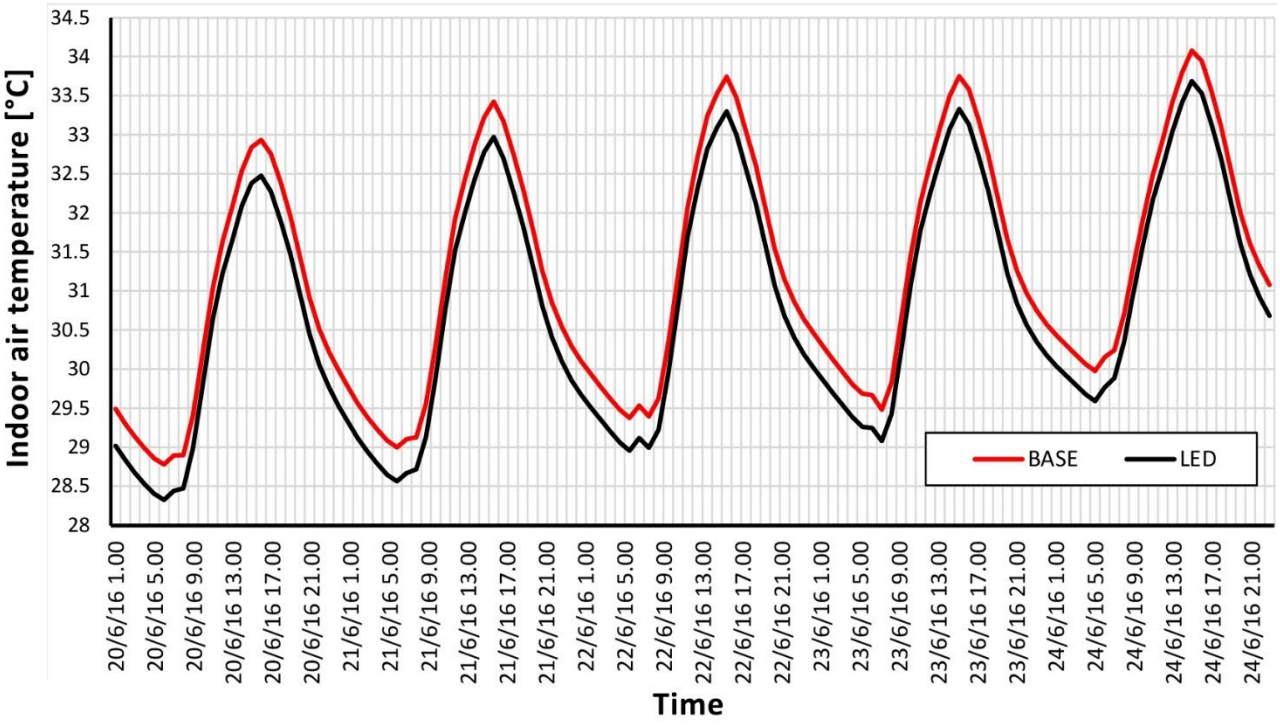


Figure 5.51 Indoor air temperature following the implementation of a LED lighting system in substitution of fluorescent lamps. *Source: elaboration of the author.*

Focusing on the average indoor air temperature for each of the proposed interventions during the occupied periods of the summer design week (from 8:00 a.m. to 5:00 p.m) let to derive more generalized conclusions. In the base case scenario, the indoor temperature averages 31.8°C. while all the measures under consideration achieve a modest reduction in this temperature during working hours. Among the strategies, the combination of reducing skylight area and installing a cool roof

stands out as the most effective, ensuring a temperature decrease of about 2.5°C. This significant result underscores the importance of acting on both solar gain and roof insulation to mitigate overheating. On the other hand, it is important to recognize that natural ventilation plays a more limited role in lowering the average temperature during the day. Since its primary benefits can be observed during the nighttime and early morning hours. Anyway, this distinction highlights the complementary nature of these strategies and the potential benefits of their integration. Envelope modifications like cool roofs and skylight adjustments provide substantial cooling effects during daytime, while natural ventilation helps maintain lower temperatures at the start of the workday and enhanced temperature ranges for the colling systems.

The comparison of the various strategies addressing overheating during the summer design week also included the analysis of the energy needs for a hypothetical cooling system. Figure 5.52 shows the related energy demand for all the strategies.

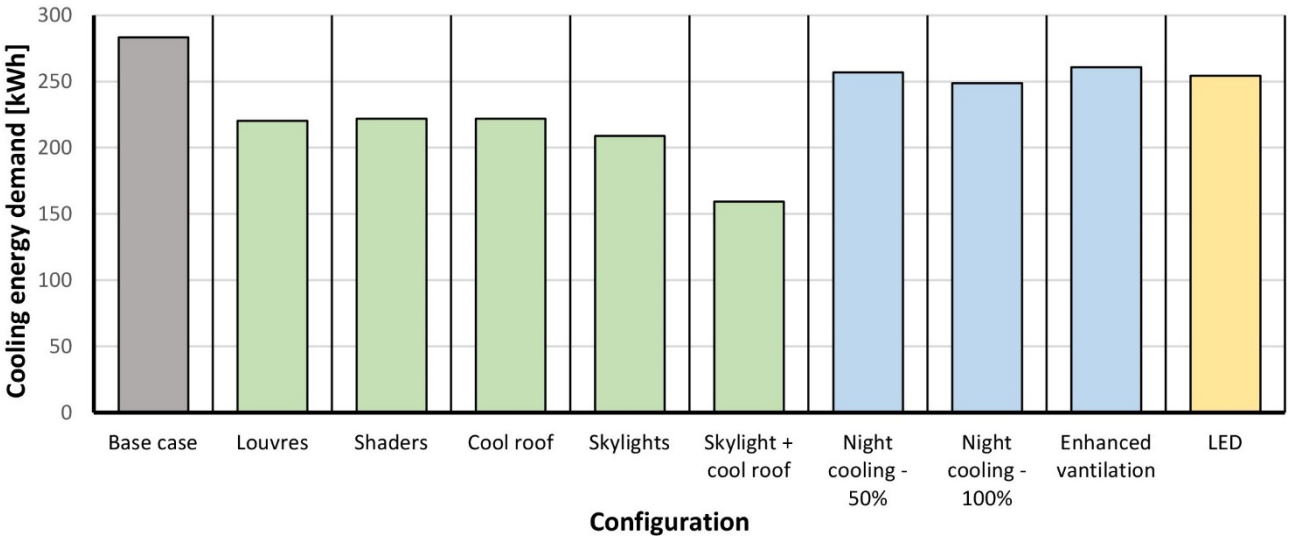


Figure 5.52 Energy demand for cooling purposes over the reference week under the different scenarios evaluated. *Source: elaboration of the author.*

Measures addressing the external envelope are generally more promising in reducing cooling energy demand than passive cooling strategies alone. The performance of louvres, shaders, and the cool roof strategy is relatively similar, while reducing the skylight surface area has a much more significant impact on energy demand. By increasing the opaque roof surface, solar gains through the roof are reduced, thereby improving the building's energy performance during the summer. The combined strategy of reducing skylight area and applying a cool roof is the most effective also from an energy saving standpoint, as it leads to the most substantial decrease in energy consumption by approximately 45%. This is largely due to the fact that the reflective coating can be applied to a larger

portion of the roof, previously covered with skylights, thus maximizing its effectiveness and to the lower percentage of glazed area letting in a reduced quantitative of solar radiation.

In conclusion, the main findings reported below were assessed following the research carried out:

- The combination of a cool roof and reduction of skylight area, proved to be the overall most effective strategy in reducing summer overheating. This solution reduces the peak internal air temperature by 3°C and the average indoor temperature during occupancy hours by 2.5°C.
- Cool roofs and solar shading systems (like louvres and automatic shaders) also contribute to a significant reduction in overheating, reducing the internal temperature by about 1°C on average in the occupied time.
- Natural ventilation, particularly night cooling, was found to be effective in lowering indoor temperatures during early working hours by up to 2.5°C, improving thermal comfort and reducing cooling energy consumption in case of dedicated systems are installed.
- LED lighting installation to replace less efficient traditional systems, has a minor effect on reducing internal heat gains but significantly contributes to overall energy efficiency.
- Overall, strategies targeting the building envelope are the most effective in mitigating overheating risks, with more promising outcomes with respect to the ones relying on natural ventilation.

5.3.3 BIPV shading system

As previously introduced, the analysis of shading solutions should be carefully examined to balance the needs of reducing internal overheating without compromising the exploitation of natural lighting to ensure adequate luminance levels.

In this context, simulation and modelling techniques have become increasingly effective and, when integrated with a parametric design approach early in the design process, they enable designers to make more informed decisions. At the same time, generative design procedures emerged as useful tools during the initial stages of decision-making processes in buildings industry [35]. These tools also enable the incorporation of optimization analyses and design optioneering procedures [36] [37], which are highly valuable for comparing different design alternatives and ultimately choosing the most suitable one according to project requirements.

In the literature [38], several applications of similar approaches can be retraced with reference to solar studies and related indoor comfort issues, with building facades being the most frequently explored components for parametric modelling applications. Facades have become particularly attractive for these studies, especially with the increasing adoption of technological solutions like Building Integrated Photovoltaics (BIPV). The latter allow to ameliorate at the same time the visual appeal of facilities and increase the contribution of energy from renewables to the energy balance of buildings. Similarly, research about lighting can be conducted using comparable methodologies, as highlighted in review papers [39]. Regarding building technologies, existing studies often focus on specific components of the building envelope (e.g., skylights) that directly affect thermal and visual comfort, but typically relying on traditional investigation methods. However, industrial buildings are usually overlooked for such technological solutions and research approaches.

Given the considerable solar exploitation potential of facades of industrial facilities, the research was deepened to evaluate retrofit solutions for the facades of existing industrial buildings by applying generative design and optimization tools in the design of a BIPV system and the development of shading solutions for glazed areas. The study, carried out relying on advanced procedures and tools to overcome the limitations found in the literature when defining optimized configurations, included evaluation criteria related to energy efficiency, economic viability, and comfort aspects.

Alternative measures were evaluated using multi-objective optimization and daylight simulations, focusing on the installation of BIPV facade recladding and the adoption of external louvers on south-oriented openings to mitigate indoor overheating.

The research described in the following is extensively detailed in the paper "*Enhancing Industrial Buildings Performance Through In-formed Decision-Making: Generative Design for BIPV and Shading Systems Optimization*" published in Solar [40].

A case study building, representative of the typology with plain roof and precast beams, characterized by a commonly retraceable distribution of openings on facades, was initially selected and the following methodological steps were consequently applied, as summed up in Figure 5.53.

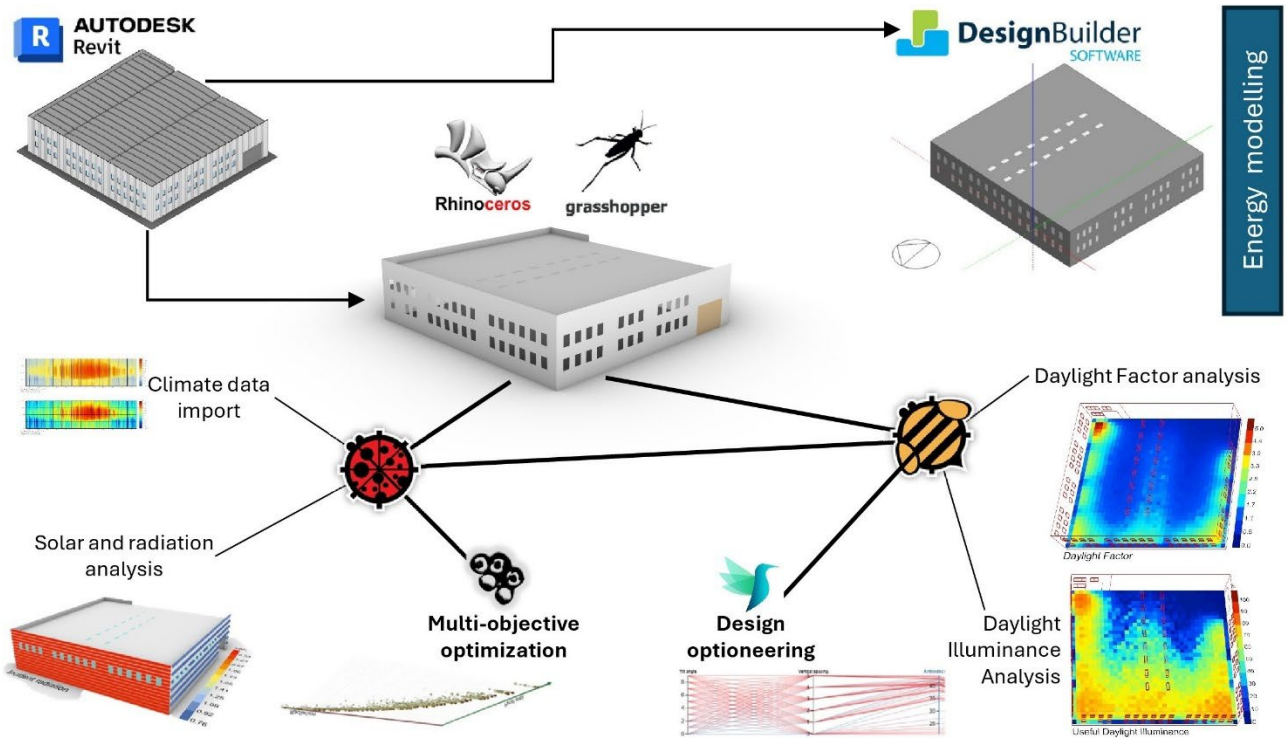


Figure 5.53 Graphical synthesis of the methodologic workflow and overview of the simulation tools applied. *Source: Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/solar4030018.*

- Initially, the building was accurately modelled in a BIM environment using Revit [41], and this digital representation served as the foundation for all subsequent applications and assessments conducted in the research.

- Visual programming language algorithms were developed exploiting the interoperability between Revit and Rhinoceros Grasshopper. These scripts were designed to seamlessly integrate input data and results from various script components, facilitating the use of multidisciplinary simulation tools. The key points can be summarized as follows:

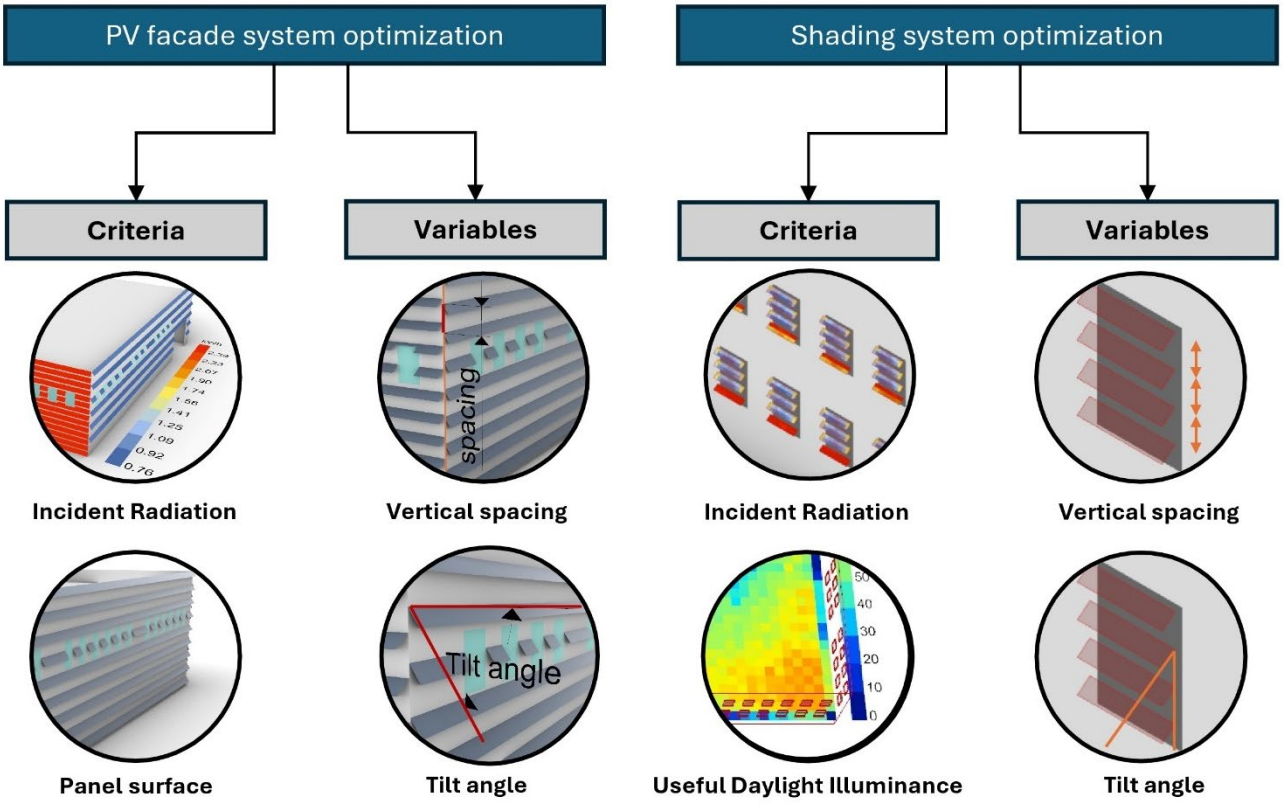
    - The Ladybug plugin and its components were employed to import and analyse climatic data, producing solar and radiation analyses. A multi-objective optimization study was performed using the Octopus plugin to evaluate the layout of BIPVs applied to the different building facades. Evaluation criteria included energy production and initial investment costs. Energy production was quantified by total incident radiation, while investment costs were assessed based on the total area of installed panels. The incident radiation data, critical for assessing the productivity of the solar PV system, was calculated using the Ladybug plugin's simulation engine and integrated into the Octopus optimization.

    - The Honeybee plugin was utilized to assess visual comfort conditions, performing daylight simulations based on daylight factor (DF), daylight autonomy (DA), and useful daylight illuminance (UDI). Various configurations of building apertures were evaluated to reflect common layouts in manufacturing facilities, including windows arranged in single or double rows on each facade, the presence of roof skylights, and combinations of these scenarios.

    - The outputs from daylight illuminance and incident radiation studies were used to define optimized solar shading system configurations. Various alternative solutions were evaluated using a design optioneering approach, facilitated by the Colibrì plugin [34] for Grasshopper. These options were evaluated during the summer solstice in the occupancy period. The results were analysed using Design Explorer by Thornton Tomasetti [35], which facilitates the comparison and filtering of the solutions based on desired outputs or design constraints. For this study, the primary design factors were the amount of solar incident radiation and the average internal UDI values, aiming to find a configuration that minimizes excessive solar radiation while maintaining adequate natural lighting.

- The results for both the BIPV layout and louvre configurations were further refined through energy simulations in DesignBuilder. The geometry of the single zone was exported from the Revit model to in the energy model in the DesignBuilder environment, where simulations were performed to derive the energy production achievable through the optimized BIPV implementation.

The criteria and variables adopted in each optimization procedure, as well as the values considered for each parameter, are illustrated in Figure 5.54.



Element	Dimensions	
PV panel	1.09 m	0.58 m
Louvres blades	1.10 m	0.20 m
Parameter	**Range**	**Increment**
PV - Vertical spacing	0.5 m - 1.5 m	0.20 m
PV - Tilt angle	0° - 90°	10°
Louvres - Vertical spacing	0.20 m - 1 m	0.20 m
Louvres - Tilt angle	0° - 90°	10°

Figure 5.54 Evaluation criteria, variables and values for parameters applied during the optimization and design optioneering procedures. *Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/ solar4030018.*

The main characteristics of the case study building selected for the study can be found earlier in this dissertation.

The PV panels considered for energy production simulations features monocrystalline silicon cells with a maximum power equal to 110 W and are characterized by an efficiency around 17%.

Solar and radiation studies encompassed both the summer and winter solstices (June 21st and December 21st) and were performed between 7:00 a.m. and 6:00 p.m. to correspond with the operational hours of the building. This was meant to maximize the photovoltaic system's yield during the active hours of machinery and equipment, to ensure efficient and concurrent energy production and usage. Energy simulations to assess the impact of louvres on reducing indoor temperature, were carried out for 21st June.

The results shown in Figure 5.55 pertain to the optimization of PV panels layout, displayed according to the Pareto front visualization. The Y-axis represents the area of PV modules, while the incident radiation is reported on the X-axis, with its inverse value used since the optimization algorithm operates based on minimization criteria. The Pareto front, highlighted in red, collects the "non-dominated" solutions that offer the best possible trade-offs between conflicting objectives.

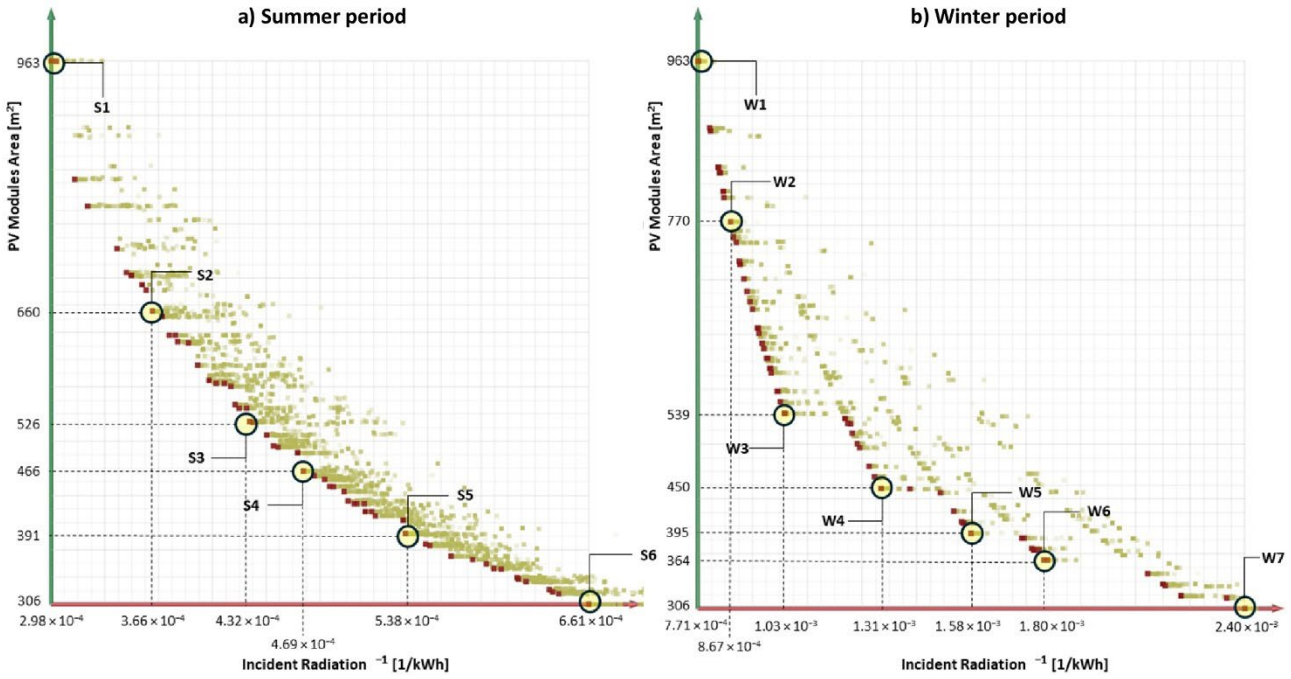


Figure 5.55 Results of optimization studies about PV panels layout for both summer and winter periods. *Source: Source: Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated*

Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/solar4030018.

Table 5.36 details the values of tilt and spacing for each layout pointed out along with the corresponding PV area and radiation.

Table 5.36 Results of PV layout optimization for summer conditions. *Source: elaboration of the author.*

Layout	E Facade		W Facade		S Facade		PV Area	Incident Radiation
	Tilt	Spacing	Tilt	Spacing	Tilt	Spacing		
S1	−75°	0.5 m	−75°	0.5 m	−50°	0.5 m	963 m^2	3356 kWh
S2	−45°	0.9 m	−75°	0.5 m	−25°	1.1 m	660 m^2	2729 kWh
S3	−45°	0.9 m	−45°	0.9 m	−25°	1.1 m	526 m^2	2313 kWh
S4	−55°	1.1 m	−55°	1.1 m	−25°	1.1 m	466 m^2	2133 kWh
S5	−45°	1.3 m	−45°	1.3 m	−25°	1.1 m	391 m^2	1859 kWh
S6	−35°	1.5 m	−35°	1.5 m	−35°	1.5 m	306 m^2	1512 kWh

Solutions S1 (East, West: tilt -70°, spacing 0.5 m, South: tilt -50°, spacing 0.5 m) and S6 (East, West, South: tilt -35°, spacing 1.5 m) are the opposite conditions, maximizing the PV panel surface area and minimizing it. Configuration S1 provides the largest PV surface area, totalling 963 m², with an incident solar radiation of 3356 kWh. This arrangement ensures a higher level of incoming radiation compared to a configuration where the facades are fully covered with vertical PV panels, which would reduce solar incident radiation by about 14% (2904 kWh). However, installing vertical panels is easier because the supporting sub-structure is simpler. Configurations S3, S4, and S5 show only a difference of about 200 kWh in total incident radiation. Notably, however solution S4 emerges as particularly favourable. In this configuration, the South-facing facade features a higher concentration of modules tilted at steeper angles, improving solar capture compared to the generally less productive West and East facades. Configuration S4 (East, West: tilt -55°, spacing 1.1 m, South: tilt -25°, spacing 1.1 m) is preferable over the other intermediate layouts, as it offers a 17% rise in solar radiation capture potential with a limited increase in PV surface area (16%).

The procedure was repeated for the winter design day (21st December), with results summarized in Table 5.37. In winter, the tilt angles of the panels tend to be more vertical to deal with the lower solar altitude. Solution W1 (East, West, South: tilt -70°, spacing 0.5 m), maximizing the number of panels installed corresponding to 963 m² of PV modules, captures 1298 kWh of solar radiation, only a 6% reduction compared to an hypothetical full PV cladding of the walls. The southern facade alone

captures in this case 65% of the total solar radiation, making it a cost-effective option if the budget is limited. Conversely, solution W7 (East, West and South: tilt -70°, spacing 1.5 m) minimizes the PV area, reducing the captured solar radiation by 32%. Intermediate configurations offer a balance between the extremes, with configuration W4 (East, West: tilt -70°, spacing 1.5 m; South: tilt -70°, spacing 0.7 m) that captures 761 kWh of solar radiation using 450 m² of PV panels and recommendable due to its effective use of the southern facade.

Table 5.37 Results of PV layout optimization for winter conditions. *Source: elaboration of the author.*

Layout	E Facade		W Facade		S Facade		PV Area	Incident Radiation
	Tilt	Spacing	Tilt	Spacing	Tilt	Spacing		
W1	−70°	0.5 m	−75°	0.5 m	−75°	0.5 m	963 m²	1298 kWh
W2	−70°	1.3 m	−75°	0.5 m	−75°	0.5 m	770 m²	1153 kWh
W3	−70°	1.5 m	−70°	1.5 m	−70°	0.5 m	539 m²	970 kWh
W4	−70°	1.5 m	−70°	1.5 m	−75°	0.7 m	450 m²	761 kWh
W5	−70°	1.5 m	−70°	1.5 m	−75°	0.9 m	395 m²	632 kWh
W6	−70°	1.5 m	−70°	1.5 m	−70°	1.1 m	364 m²	555 kWh
W7	−70°	1.5 m	−70°	1.5 m	−70°	1.5 m	306 m2	417 kWh

To assess the energy production potential of the façade-integrated PV modules configured according to the W4 configuration, a dedicated DesignBuilder model was created, incorporating the solar collectors' geometry and technical specifications. Figure 5.56 illustrates the energy production alongside lighting and heating demands for the winter period (1st November – 31st March), with data provided for monthly, daily, and hourly distributions, covering the entire period, the month of December, and a specific design week around 21st December. The graphs show that the energy produced by the façade-mounted PV panels is generally insufficient to meet the building's energy needs throughout the winter, except in March when production peaks at over 4500 kWh. Daily data reveal that on weekends, when the building is not in use, surplus energy is generated, which could be stored or sold back to the grid. Hourly data highlight a mismatch between energy production and demand; during peak demand at the start of the workday, the PV modules don't generate enough energy. The peak energy production occurs later in the day, leading to a misalignment with demand. To maximize energy generation, it’s recommended to pair the façade PV modules with additional panels on the roof, utilizing the larger surface area available.

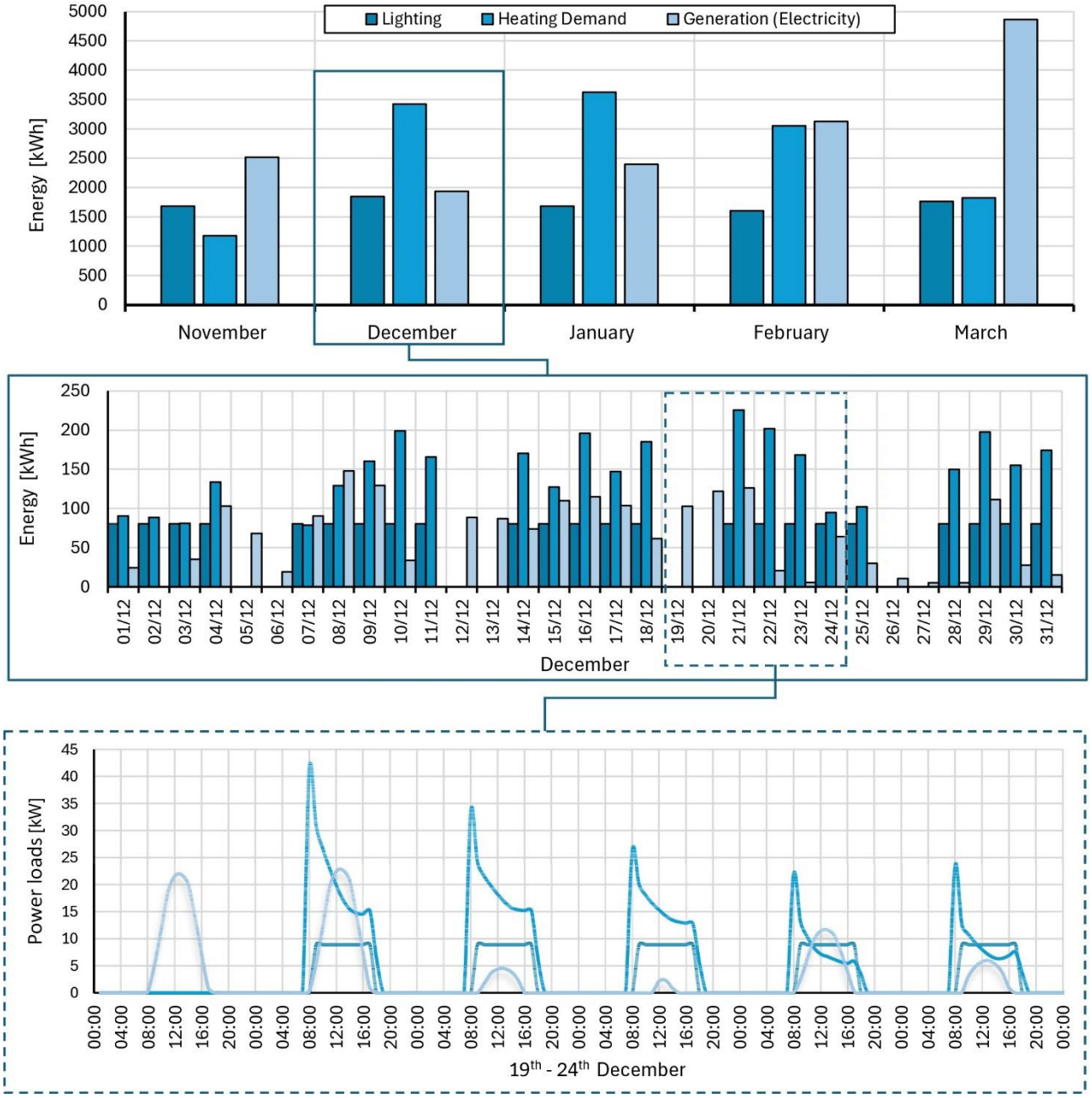


Figure 5.56 Energy demand and production profile in the advisable configuration for winter: seasonal, monthly and daily trends. *Source: Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/ solar4030018.*

Internal lighting conditions were hence analysed in detail and Figure 5.57 shows the spatial distribution of DF, DA, and UDI values within the working environment, considering distributions of the openings that that align with common configurations in existing built heritage. A single row of windows is inadequate for facilities with a large internal volume, as evidenced by the DF values ranging between 0.08% and 1.6%. Additionally, UDI thresholds are not met for over 50% of the year in most of the working area (1309 out of 1330 points, based on a 1-meter grid). The lighting maps indicate that UDI decreases with increasing distance from the windows], and the tested WWR

(window-to-wall ratio) is insufficient for the building's size. All parameters (DF, DA, UDI) decrease when the percentage of openings in the external envelope is reduced. The average DF improves with a configuration of two rows of windows, reaching 1.12%. The most effective setup for visual comfort includes two rows of windows on each facade and skylights on the roof, which significantly enhances UDI levels, particularly in the building's central area, with values between 40% and 70%. This setup reduces the number of points below the UDI threshold for 50% of the year to 627. However, only areas near the windows achieve a DF value higher than 2.2%.

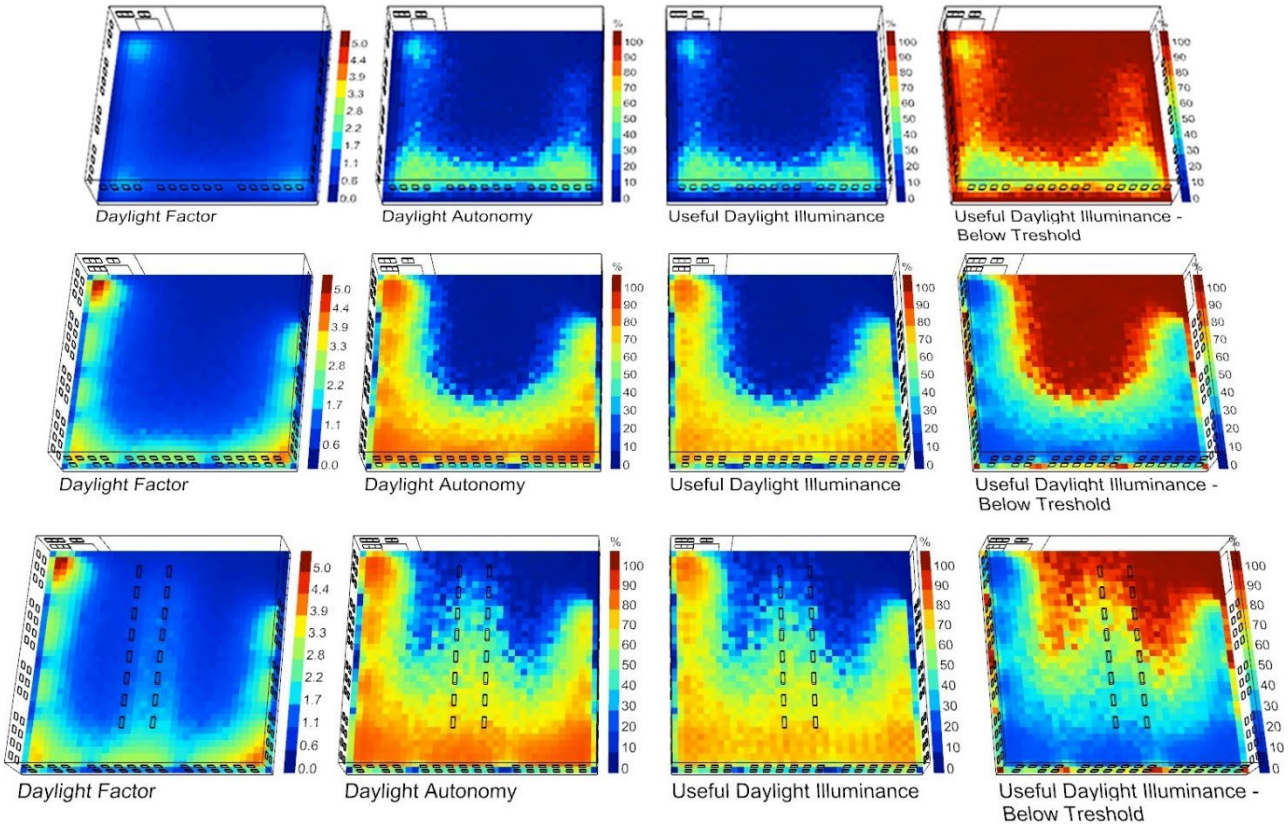


Figure 5.57 Results of visual comfort and lighting assessments. Starting from the top: single row of openings, double row of openings, double row of openings and skylights. *Source: Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/ solar4030018.*

The investigation of lighting conditions was deepened to evaluate a solar shading system for south-facing windows. This was based on the layout of the case study facility, featuring a double row of windows and roof skylights. To identify the optimal configuration, a design optioneering technique was used. Due to the limited number of possible alternatives, the outputs were manageable for analysis carried out autonomously as shown in Figure 5.58.

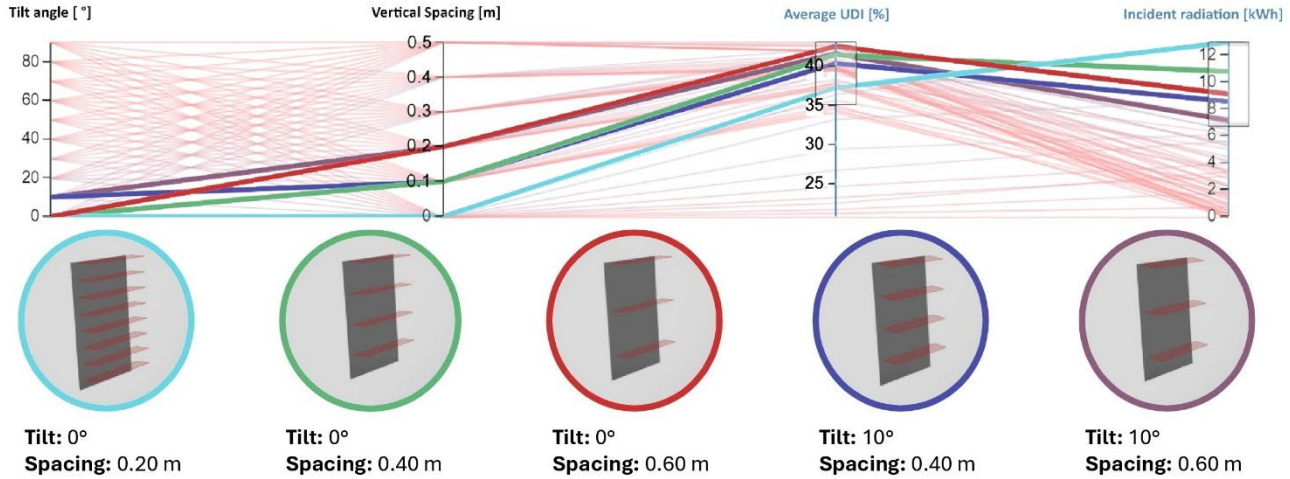


Figure 5.58 Design optioneering based selection of louvres configuration. Selection of the solution of interest by imposing the target performance for UDI and incident radiation. *Source: Re-elaboration from Banti N, Ciacci C, Bazzocchi F, Naso V Di (2024) Enhancing Industrial Buildings ' Performance through Informed Decision Making : A Generative Design for Building-Integrated Photovoltaic and Shading System Optimization. Solar 4:401–421. https://doi.org/https://doi.org/10.3390/ solar4030018.*

The graph indicates that to block incident radiation while maintaining natural daylight, configurations with horizontal (or nearly horizontal) blades spaced at various intervals are preferable. Since the simulations were based on summer solstice conditions, horizontal overhangs are ideal for maximizing solar shading in summer without hindering natural lighting during other seasons, when sunlight is beneficial. The effectiveness of solar shading improves when vertical spacing between horizontal slats is reduced to 0.20 m, while increasing the distance between shading blades enhances UDI levels to between 35% and 40%. Conversely, layouts with steeper tilt angles (over 45°) can negatively affect visual comfort, as the average UDI drops below 25%, and solar shading in summer is partially compromised.

To assess the effectiveness of reducing summer overheating, specific simulations were conducted in DesignBuilder. These simulations compared the base case building without solar shading to two previously introduced configurations, by analysing indoor air temperatures. The layouts investigated are the one with tilt angle equal to 0° and a vertical spacing of 0.20 m and the one with tilt angle equal to 10° and a vertical spacing of 0.40 m. The results revealed that both shading solutions are similarly effective in lowering indoor temperatures, with a slight advantage for the first configuration mentioned, in line with the earlier optioneering studies. The impact of the louvres is mostly noticeable during the central hours of the day, with a peak temperature reduction of about 0.46°C between 13:30 and 14:00, and an average reduction of 0.39°C over the entire afternoon. The difference between the two configurations is minimal, with the latter ensuring an average reduction of 0.36°C. Given its

slightly lower impact on temperature but better performance in natural lighting and fewer components required, this second option may be the preferable choice.

The main outcomes of the study can synthesized as it follows considering the various topic addressed

- Optimization of PV Panels:
  A southern exposure of the building is generally preferred for PV installation, but building orientation has a minor impact if facade sizes are comparable. For BIPV the optimal configuration involves PV panels with a tilt angle between -35° and -75°. To maximizee energy production during summer, a layout with PV blades 1.1. m spaced and 55° tilted over the E and W facades, and 25° tilted in the south one is advisable. For winter periods, a tilt angle of 70° and vertical spacing by 1.5 m should be preferred in the Eastern and western oriented façade while the coverage of the southern one should be prioritized recurring to a layout with reduced vertical spacing (-75° tilt, 0.7 m distance between rows). Notably, all these configurations were meant to maximize energy production using a limited amount of panels.

- Daylight and Visual Comfort:
  Daylight simulations and visual comfort assessments focused on daylight factor, daylight autonomy, and useful daylight illuminance (UDI). Different window configurations and the presence of roof skylights were evaluated to enhance indoor lighting conditions, revealing the possible issues in case of large internal volumes and the need for both adequate openings percentages and roof skylights layout. In particular, the latter are crucial in large buildings should be located close to the core of the building, were side windows are not able to guarantee appropriate lighting conditions.

- Shading Systems:
  Design optioneering is used to explore different solar shading solutions, to reduce indoor temperature without compromising natural lighting contribution. The advisable shading solution involves horizontal or nearly horizontal louvres with spacing between 0.2 and 0.4 meters, reducing indoor temperature by 0.46°C.

The integration of photovoltaic panels in intervention of external facades recladding has been evaluated also with reference to buildings characterized by horizontal panels as external walls and ribbon windows. The research was presented at the 10th REHABEND Congress 2024 “Construction

pathology, rehabilitation technology and heritage management" with a contribution entitled "*Solar potential analysis of building integrated photovoltaic panels as retrofitting solution for existing industrial buildings*" [42]. The energy potential of a BIPV façade system as an envelope retrofit for a representative industrial facility in central Italy was evaluated across different building orientations. The building was assumed to present a more pronounced longitudinal development and a reduced height with respect to the facility considered in the study presented before. The SW-NE configuration was proved to yield the highest annual generation rate (18.26 kWh/m²) due to optimal solar radiation exposure. While the N-S orientation was most effective during summer, the E-W orientation performed better in winter but was still insufficient to satisfy the expected heating demand, covering only 22% of the need. However, the E-W layout remains the most advisable for manufacturing facilities, as it maximizes winter energy production when solar angles are low and rooftop PV systems are less effective. Although not the top performer in summer, it is efficient in meeting cooling demands and provides excess energy for machinery.

5.3.4 Heating systems alternatives

In the research carried out, an innovative methodology was applied to comprehensively integrate the various dimensions of energy retrofitting in industrial buildings and to overcome the current limitations of the existing literature in this domain, generally incomplete or limited to case-specific analyses. A Multi-Criteria Decision Making (MCDM) method is employed to determine the most suitable HVAC installation for space heating, seeking a more robust and replicable framework for the energy retrofit intervention in industrial buildings. Even if this methodology allows for the inclusion of diverse and potentially conflicting decision-making factors, the application of MCDM approaches in the energy redevelopment of industrial buildings remains relatively uncommon, with existing studies often being highly specific and with limited practicality of the proposed solutions since many key parameters are often neglected. The Analytical Hierarchical Process (AHP) used in the study encompassed evaluation criteria related to energy demand, human comfort, economics, environmental impact, and practical considerations such as space requirements and reliability.

The research work described in this paragraph is extensively reported in the paper "*Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings*" published in Journal of Building Engineering [43].

Various alternatives were evaluated considering a real case study building in the Mugello area, assuming a renovated state, ensuring compliance with the thermal transmittance values in line with current Italian regulations for external envelope. Adopting this solution, it was possible to focus on the impact of the different alternatives included in the study. An energy model was developed using DesignBuilder, incorporating nine different system solutions and simulations were conducted over winter (November–March). The results were processed in an Excel sheet to derive the relevant values for being implemented in the AHP phase. The latter was carried out using the software Super Decision, freely accessible online, robust and user-friendly thanks to its intuitive interface. Within the Super Decisions software, the predefined evaluation criteria were ranked according to their relevance and the alternatives evaluated based on these parameters. Using the provided inputs, the Super Decisions tool generated statistics instrumental in identifying the most advantageous heating systems based on the specific requirements. Additionally, to further analyse the results, sensitivity analyses on the evaluation criteria were conducted. The methodology workflow exposed in this paragraph is summarized in Figure 5.59.

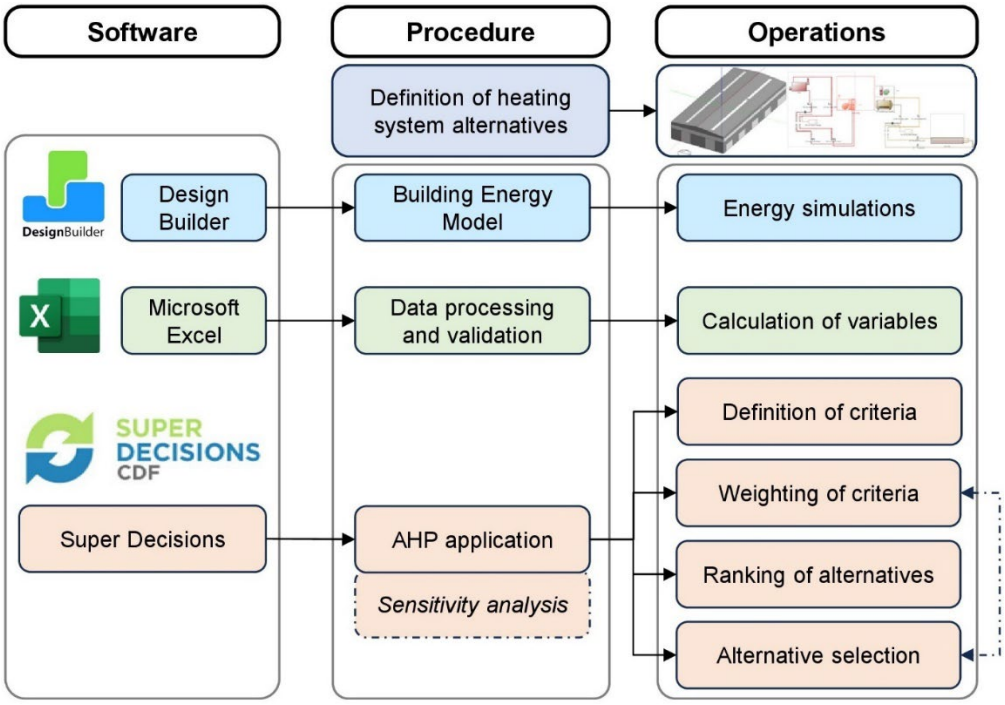


Figure 5.59 Methodological workflow of the research and AHP procedure. *Source: elaboration of the author.*

For the purpose of this study, a building pertaining to the *Sl_rc_slb* variant (buildings with sloped roofs made from precast concrete sloped beams) was selected (Figure 5.60).

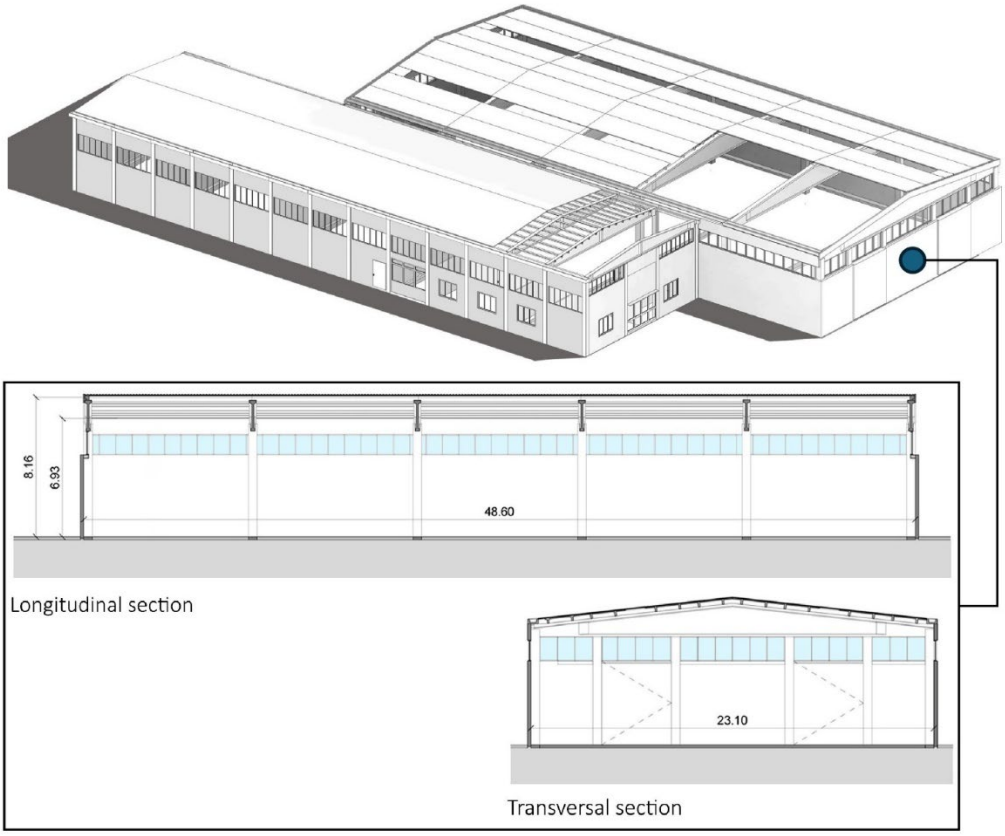


Figure 5.60 Case study building geometry and layout. *Source: elaboration of the author.*

In the energy model of the building, a retrofit state of both external walls and roof was assumed considering a re-cladding intervention using metal PIR sandwich panels as detailed in Table 5.38. The substitution of current windows was also foreseen (Solar Factor 0.51, U 1.20 W/m^{2}K, Light Transmittance 0.74).

Table 5.38 Properties of Building envelope considered in the study. *Source: elaboration of the author.*

External walls				**Roof**			
Stratigraphy [-]	Layer Thick. [m]	U [W/m^2 K]	Surface mass [kg/m^2]	Stratigraphy [-]	Layer Thick. [m]	U [W/m^2 K]	Surface mass [kg/m^2]
Metal-PIR sandwich panel	0.08	0.21	381	Metal-PIR sandwich panel	0.10	0.22	126
Concrete	0.10			Fiber-cement	0.007		
EPS insulation	0.04			Membrane	0.002		
Precast concrete	0.06			Rockwool insulation	0.04		
				Precast concrete	0.05		

In Table 5.39 the heating system alternatives evaluated are collected.

Table 5.39 Alternatives for heating systems in terms of heat source and heat distribution terminals. *Source: Re-elaboration of the authors from Banti N, Krawczyk DA (2024) Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings. Journal of Building Engineering 95:110203. https://doi.org/10.1016/j.jobe.2024.110203.*

Heat distribution and terminals	***Heat source***	***Code***
Heated walls	Gas condensing boiler	*S1*
	Air-to-Water Heat Pump	*S2*
Heated floor	Gas condensing boiler	*S3*
	Air-to-Water Heat Pump	*S4*
	Air-to-Water Heat Pump + PV	*S5_PV*
Fan air heaters	Gas boiler	*S6*
All air system - Mech. Vent.	Air-to-Air Heat Pump	*S7*
	Air-to-Air Heat Pump + Heat recovery	*S8*
	Air-to-Air Heat Pump + Heat recovery + PV	*S9_PV*

These alternatives were preliminary selected to properly deal with the specific characteristics of industrial environments and operational requirements (e.g., overhead cranes, fixed racking). Conversely, other solutions were excluded due to avoid prolonged work suspensions for installation

or spatial constraints. For example, ground-source heat pumps, needing wide areas for geothermal probes, and water-sourced heat pumps, depending on nearby water basins, were not deemed feasible. In total, nine different system configurations were included, varying in heat generation, carriers, and operating temperatures. Fan air heaters, for example, heat spaces by convection thanks to hot water from an external gas boiler circulating in heat exchange units with internal blowers. Proper placement of these terminals is essential to ensure even air temperature distribution. Radiant floors and walls ensure lower working temperatures, with water circulating in embedded pipes. Radiant floors, in particular, are well-suited for industrial environments due to their wide areas and the thermal inertia of the floors. These latter heat distribution strategies were associated with condensing gas boilers and air source heat pumps. The latter can be also used in all-air systems, providing also mechanical ventilation, where heat recovery units can be moreover installed. Heat pump solutions also allow to integrate onsite renewable energy systems, such as photovoltaic (PV) modules.

DesignBuilder software, known for its user-friendly interface and extensive HVAC system library, was used for building energy simulations. Specific internal conditions—such as setpoint temperatures, activities, number of workers, occupancy schedules, and internal loads—were assessed through an on-site survey and a brief interview with the owner of a representative company. The building currently lacks dedicated mechanical ventilation systems. The required illuminance level was set at 300 lux, following the guidelines for typical manufacturing environments set by UNI EN 12464-1 [44]. For the simulation of a fully retrofitted configuration, a LED lighting system with a normalized power density of 0.58 W/m² - 100 lux was included in the simulations. Internal loads from working machinery were not included in the energy model, as the production processes do not release significant heat. To validate the energy model and the consequently the subsequent simulations, real energy bills provided by the company were compared with the model's energy consumption outputs. A conventional gas boiler with an efficiency of 0.7 and a heating setpoint of 18°C was assumed to replicate the heating system currently in use. As a result, the energy model's yearly estimation was only 6% lower than the actual energy consumption derived from the bills and this minor discrepancy was considered acceptable, indicating a reasonable correspondence between the real data and the simulated results in view of the assumptions made about the thermal properties of certain building components, challenges in accurately estimating infiltration rates, uncertainties related to the operation of openings, and the potential impact of internal thermal loads generated by industrial processes.

The Italian regulations do not prescribe specific air temperature values for industrial buildings. The reglementary framework on workplace safety and health generally emphasizes the importance of providing comfortable conditions for workers [45] posing considerable challenges for the definition of uniform standards for such facilities, given the wide variety of industrial activities and the relative working conditions. For this reason, initial tests were conducted to determine the optimal internal setpoint temperature that would ensure worker comfort in the case study facility. Energy simulations in DesignBuilder over a reference winter month (January) were run considering different setpoints and Fanger's indexes, namely Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), were used as key reference parameters. The results indicated that a setpoint of 18°C is sufficient for systems utilizing radiant heat transfer, while air systems require a setpoint of 20°C, both aligning with the requirements of Italian regulations for setpoint temperatures in industrial buildings [46].

To evaluate the different system alternatives, each was modelled in DesignBuilder using the detailed HVAC configuration. For radiant floor and wall solutions, sub-surfaces were introduced in the building model where distribution pipes would likely be located. In case of the heated floor, approximately half of the total available surface area was considered, excluding areas for machinery and loading operations near the building's main openings. Similarly, for radiant walls, a series of heated sections 3 meters high were introduced along the side walls, covering a total heating surface of about 160 m², preserving areas for racking and workstations installation. The main parameters used in the simulations are reported in Table 5.40 while the various energy models generated from these configurations are compiled and illustrated in Figure 5.61.

Table 5.40 Parameters and boundary conditions for the system alternatives adopted in the energy simulations. *Source: Re-elaboration of the authors from Banti N, Krawczyk DA (2024) Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings. Journal of Building Engineering 95:110203. https://doi.org/10.1016/j.jobe.2024.110203.*

Sol.	***Peak nominal power***	***Efficiency / COP***	***Setpoint temp.***	***Schedule***	***Setback temp.***	***Design inlet water/air temp.***	***ΔT***
S1 – S3	49.30 kW	0.95	18 °C	Mon: 5 a.m. – 4 p.m. Tue - Fri: 7 a.m. – 4 p.m.	16 °C	40 °C	6 K
S2 – S4 – S5_ PV	49.95 kW	4.33	18 °C	Mon: 5 a.m. – 4 p.m. Tue - Fri: 7 a.m. – 4 p.m.	16 °C	40 °C	6 K

S6	49.00 kW	0.85	20 °C	Mon: 6 a.m. – 5 p.m. Tue - Fri: 7 a.m. – 5 p.m.	12 °C	85 °C	15 K
S7 – S8 – S9_ PV	60.00 kW	4.06	20 °C	Mon: 6 a.m. – 5 p.m. Tue - Fri: 7 a.m. – 5 p.m.	12 °C	28 °C	-

For solution S8 featuring an air-to-air heat pump, an efficiency of 75% was assumed for the heat recovery unit. In the case of solutions S5_PV and S9_PV including air to water and air to air heat pumps respectively, the presence of photovoltaic (PV) crystalline silicon modules, with a rated electric power output of 390 W and an efficiency of 22.1%, was simulated in the DesignBuilder model. The total installed power for these PV modules was set at 29.64 kWp, in accordance with national regulations [47].

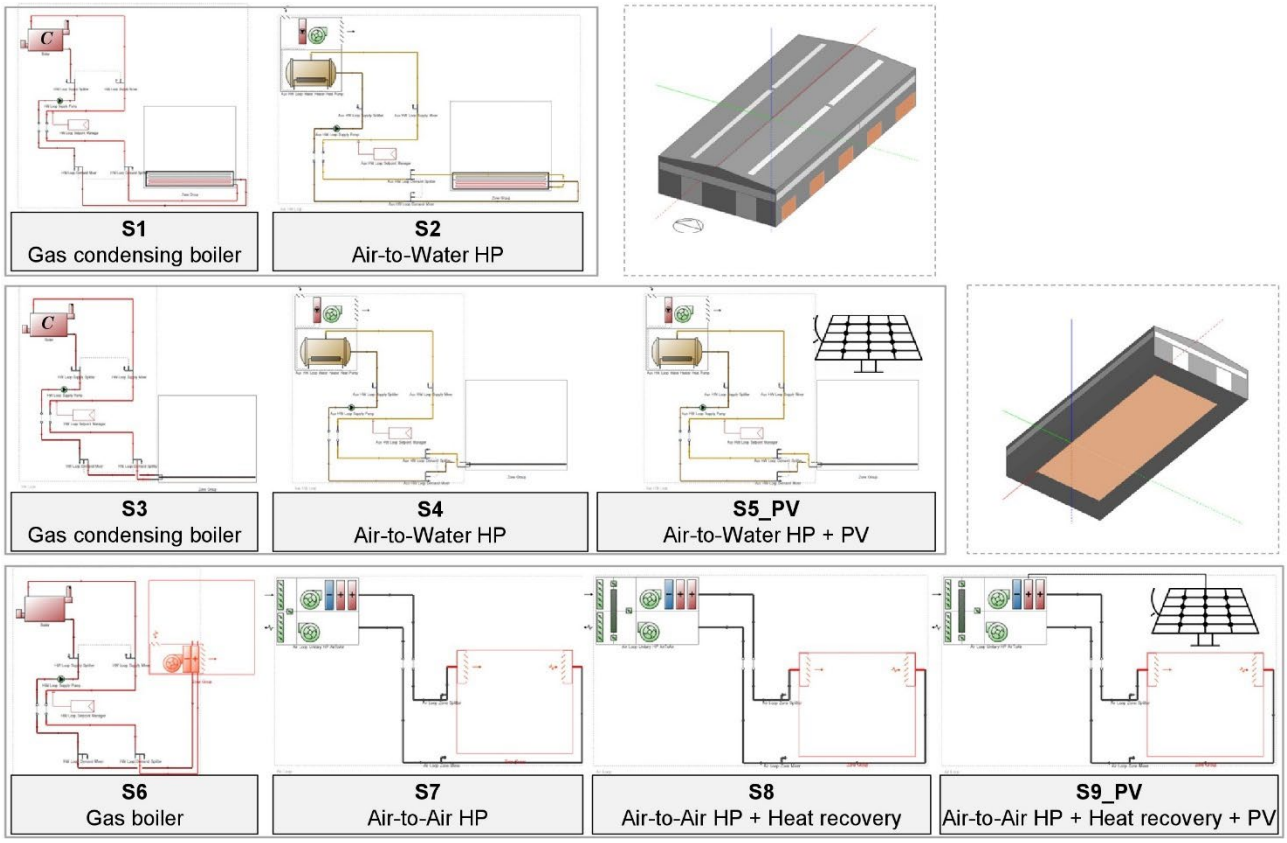


Figure 5.61 DesignBuilder energy models encompassing the different evaluated system alternatives. The portions coloured in orange represent the areas where radiant surfaces are installed in the models Source: Re-elaboration of the authors from Banti N, Krawczyk DA (2024) Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings. Journal of Building Engineering 95:110203. https://doi.org/10.1016/j.jobe.2024.110203.

To ensure an effective application of the Analytic Hierarchy Process, the problem was analysed by imposing various evaluation criteria, as HVAC systems impact multiple aspects of a building's lifecycle and affect numerous factors during both installation and daily operation. These criteria were chosen based on the authors' expertise, findings from similar studies [48][49], and evidence gathered from interviews conducted with manufacturing companies during field inspections of existing buildings carried out n approximately ten industrial buildings in the Mugello area, based on the availability provided by local companies. These buildings were selected to ensure a diverse sample, representing various industrial sectors such as metalworking, plastics, textiles, and electrical components production, with a range of building sizes, employee numbers, and shift patterns. Interviews with company representatives aimed to address aspects within the five main parameter categories covered by the study: comfort, cost, environment, space, and reliability. Discussions with entrepreneurs provided insights into their requirements, including working conditions, logistical limitations, constraints, and economic feasibility. As rapidly mentioned, the selected parameters for evaluation pertain to five thematic categories, and can be detailed as it follows:

- Comfort-Related Criteria:
    - Acoustic comfort: Assessed based on current noise levels recorded for different installations;
    - Thermal comfort: evaluated to reflect general preferences related to specific working conditions;
    - Air temperature distribution: analysed through simulations meant to identify potential stagnation effects within the workspace;
    - Flexibility and integration of the heating system: to express the potential for the system to be integrated with indoor air quality management, air change rates, dehumidification, or summer cooling.
- Cost-Related Criteria:

- Installation costs: based on recognized price lists in Italy [50][51], including the purchase of components, transportation, and installation, with an additional 15% imposed to cover extra components not listed in the price schedules;

- Operational costs: estimating the average fuel expenses during heating periods using current rates for natural gas (€0.47/scm) and electricity (€0.18/kWh) [52], excluding taxes and additional fees.

- Environment-Related Criteria:

  - Primary energy consumption: assessed through energy simulations and the conversion factors in Table 5.41;

  - CO_2 emissions: calculated using the CO_2 conversion factors provided in Table 5.41.

Table 5.41 Conversion factors for Primary Energy and CO_2 calculation. *Source: Banti N, Krawczyk DA (2024) Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings. Journal of Building Engineering 95:110203. https://doi.org/10.1016/j.jobe.2024.110203..*

Energy Source	**Primary Energy Conversion Factor**	**CO_2 Conversion Factor**
Natural Gas	1.05	0.19 kgCO2/smc
Electricity from Grid	1.90	0.27 kgCO2/kWh
On-site Generation from Renewables	1.00	0 kgCO2/kWh

- Space-Related Parameters:.

  - Indoor and outdoor required Area: account for the space required to host the components internally or externally;

  - Layout flexibility: rate the system's adaptability according to changes in the building's internal layout;

  - Installation procedures: to evaluate the interference of installation activities on production processes;

- Compatibility with working activities: considers potential interference of distribution pipes and heating units with production-related equipment.

- Reliability:

  - Lifetime: indicates the expected lifetime of the installed components, reflecting the system's long-term reliability;

  - Maintenance: expresses the frequency and complexity of maintenance operations. Maintenance costs were not included in the study because, in absence of detailed estimations they would have been simply factored as a percentage of the initial cost, not significantly affecting the AHP study results.

For each parameter, a qualitative or quantitative judgment was expressed taking into account the results of energy simulations carried out. At the same time, a pairwise comparison procedure let to assign a weight to each evaluation criteria to prioritize the final selection, whose consistency was ensured by the built-in checking scheme. Considerations were derived in this phase following the inputs from the companies interviewed, as well as insights drawn from similar applications documented in the literature. As reported in Table 5.42, cost-related parameters were identified as the most influential and the initial investment in particular emerged as the most critical criterion. The impact on operational activities also required careful consideration, as highlighted by the relevance of parameters Sp5 (compatibility with working activities) and Sp4 (installation procedures). Thermal comfort criteria were addressed due to their impact on workers' well-being and the distinct characteristics of the evaluated systems, such as thermal inertia, air temperature distribution, and the potential use of internal heat gains. In contrast, CO_2 emissions, often overlooked by industrial company owners, were found to be a minimally influential factor.

Table 5.42 Evaluation parameters: classification, unit and weight for the final selection of the solution of interest. *Source: Banti N, Krawczyk DA (2024) Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings. Journal of Building Engineering 95:110203. https://doi.org/10.1016/j.jobe.2024.110203..*

Category	***Evaluation parameter***	***ID***	***Unit (for quantitative criteria)***	***Weight***
Comfort	Acoustic comfort	C1	-	0.02
	Thermal comfort	C2	-	0.08
	Air temperature distribution	C3	-	0.02
	Integration and flexibility	C4	-	0.03
Cost	Initial investment	Co1	€/m²	0.19
	Operational cost	Co2	€/m²y	0.13
Environment	Energy consumption	E1	kWh/m²y	0.09
	CO_2 emissions	E2	$kgCO_2/m^2y$	0.01
Space	Indoor area	Sp1	-	0.06
	Outdoor area	Sp2	-	0.02
	Layout flexibility	Sp3	-	0.03
	Installation procedures	Sp4	-	0.09
	Compatibility with working activities	Sp5	-	0.13
Reliability	Lifetime	R1	Years	0.05
	Maintenance	R2	-	0.03

The results of energy simulations were processed to derive outputs on the environmental performance of the alternatives considered in the study. Solutions exploiting natural gas for heat generation (S1, S2, S6) demonstrated the highest environmental impact, with elevated energy consumption and emissions. Although incorporating high-efficiency gas condensing boilers and radiative heating in the S1 and S3 configurations can reduce both carbon emissions and energy use, heat pump-based solutions proved to guarantee better performance standards. In particular, heated floors (S4) are more energy-intensive than heated walls (S2) due to the larger radiant surface area. The inclusion of heat recovery systems in the S8 configuration, emerged as highly effective, cutting energy demand by 46% compared to the S7 configuration and ensuring higher efficiency with respect to radiative systems. The inclusion of PV systems can further enhance energy savings by approximately 15% in both S5_PV and S9_PV cases, decreasing reliance on the grid and reducing CO2 emissions by 30% in radiant floor systems and by 35% in all-air systems. It's important to underline that the analysis focused solely on heating-related energy demand, not accounting for the energy use associated with circulation pumps and fans. Even if these components have a relatively smaller impact on the overall energy balance, especially in view of their modern high-efficiency levels, this aspect should be explored further. In particular, fans can be significant energy consumers in case of mechanical ventilation, when their operation schedule is meant to meet necessary air exchange rates and is not directly connected with the heating demand.

If environmental criteria were considered as secondary in influencing the final selection of the solution of interest, economic feasibility emerged as crucial and cost related parameters were hence examined carefully. The installation of a heat pump in the S2 scenario increases the initial cost by about 57% compared to the gas condensing boiler used in S1, but it offers an annual energy savings of approximately 11%. A similar trend is observed in the S3 and S4 configurations, where the higher costs associated with constructing an industrial heated floor are offset by the modest increase in initial investment when using a heat pump. This results in an associated reduction in annual energy costs of about 15%. The S6 configuration emerged as the most economical in terms of installation, due to minimal procedures required and the lower costs of the components involved; however, the lower efficiency of the traditional gas boiler in this setup leads to the highest operational costs. All-air systems offer a balanced solution, with moderate initial investments and yearly energy expenses comparable to other configurations. In this case, incorporating heat recovery is highly advisable from an economic standpoint, as it significantly reduces operational costs. The addition of a PV system (S5_PV and S9_PV), further decreases the dependency on the electrical grid, reducing energy costs for heating by 30% to 35%. For these setups, the impact on the initial investment varies significantly: the PV system increases costs by 36% in S5_PV but more than doubles them in S9_PV. Remarkably, the potential economic benefits of surplus energy production were not accounted for, as the viability of compensation mechanisms requires specific studies and continuous updates given the constantly evolving regulatory framework. Additionally, the economic impact of interrupting production activities during installation was not considered due to the uncertainties in generalizing these findings. When analysing in a combined way the environmental and economic performance of the different alternatives, it is evident that lower-emission solutions typically require significant investment costs, as highlighted in the graph of Figure 5.62. This financial barrier could hinder the widespread adoption of system upgrades aimed at enhancing the overall sustainability of industrial buildings.

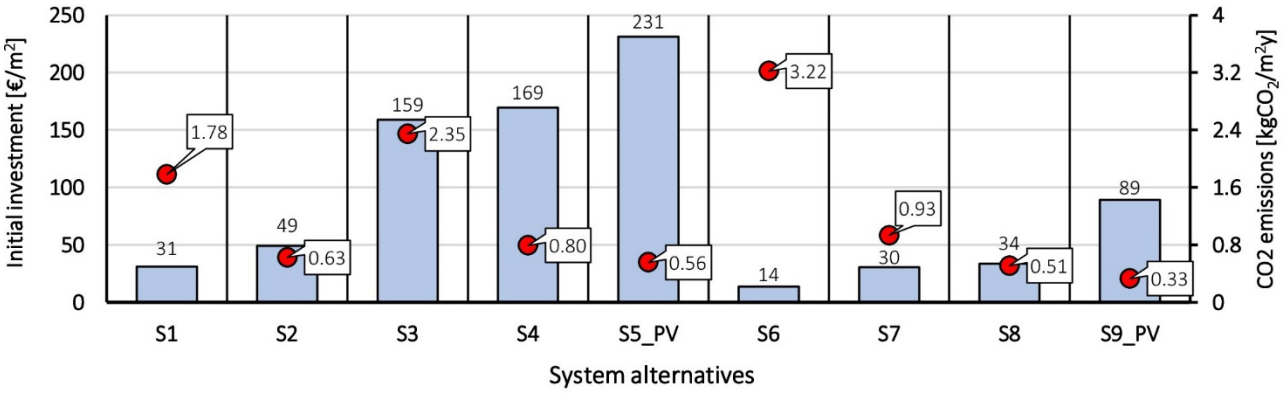


Figure 5.62 Evaluation of economic and environmental criteria considering initial investment (Co1) in blue boxes and emissions (E2) in red dots. S1. *Source: Re-elaboration from Banti N, Krawczyk DA (2024) Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings. Journal of Building Engineering 95:110203. https://doi.org/10.1016/j.jobe.2024.110203..*

As for comfort related performance, the different types of heating distribution solutions and terminals considerably influence the expected results for the various aspects considered (Acoustic, Thermal, Air temperature distribution, Integration and flexibility). Additional noise from HVAC systems can be critical in industrial environments, particularly where noisy machinery is installed. However, while these issues are well-documented in the context of office buildings, they are less frequently addressed for large industrial halls. On-site measurements and comfort surveys revealed no significant differences in acoustic comfort between radiant and all-air heating systems, except in open spaces [53]. Generally, while radiant systems contribute minimally to rising internal noise levels since they do not involve air flows or moving components [54], air handling units (AHUs) in large industrial spaces can produce significant noise, influenced by factors like duct size, airflow rate, and air pressure [55]. Without specific measurement data available, qualitative judgments were made: radiant walls and heated floors were deemed optimal for acoustic comfort, while systems like S6 and S7-S9_PV, which involve moving components, were considered responsible of variable noise levels and rated as less effective from this point of view.

As for the integration and flexibility aspects, all-air systems are the most versatile, capable to be easily integrated with technologies for cooling, air quality control, and humidification. Radiant surfaces can also be used for cooling but are less effective, while the S6 configuration would require additional dedicated systems for these functions. Considering thermal comfort, the unique characteristics of industrial buildings make traditional comfort indexes like PMV and PPD not adequate [56], and were hence only used to set preliminary temperatures. For this reason, comfort related judgments were expressed following a qualitative approach. The analysis of air temperature distribution in DesignBuilder simulations provided clearer insights into the efficacy of each heating solution.

Simulations were set considering typical site and operating conditions, including infrequent door and window openings, minimal thermal fluctuations, and low internal heat gains exclusively connected with the presence of employees. Heated floors offer uniform heating by effectively warming the lower areas where workers are standing at machinery and working desks. The substantial thermal inertia of the precast concrete structure helps retain heat, making this option particularly beneficial for companies operating on 24h schedules. In addition, radiant floors prevent dust dispersion and noise emissions, as they do not induce air movement. However, they may be less effective in scenarios with sudden thermal loads or frequent door opening due to the high thermal inertia of the system. On the other hand, radiant walls solutions are less effective as they primarily heat perimeter areas and in large buildings, or in those with multiple sections, this can limit overall comfort. Radiant walls are more suitable for buildings with high-located ribbon windows, which provide a larger surface area for maintaining comfort within the worker-occupied height range. Configurations relying on convective heating (S6, S7-S9_PV) may result in hot air stagnation in upper building regions. In particular, the S6 setup, with localized fan heaters can induce non-uniform temperature distribution, requiring careful placement of the terminals to ensure comfort in all the occupied zones.

In Figure 5.63 the results related to comfort performance are expressed along with the findings of the internal temperature distribution simulations.

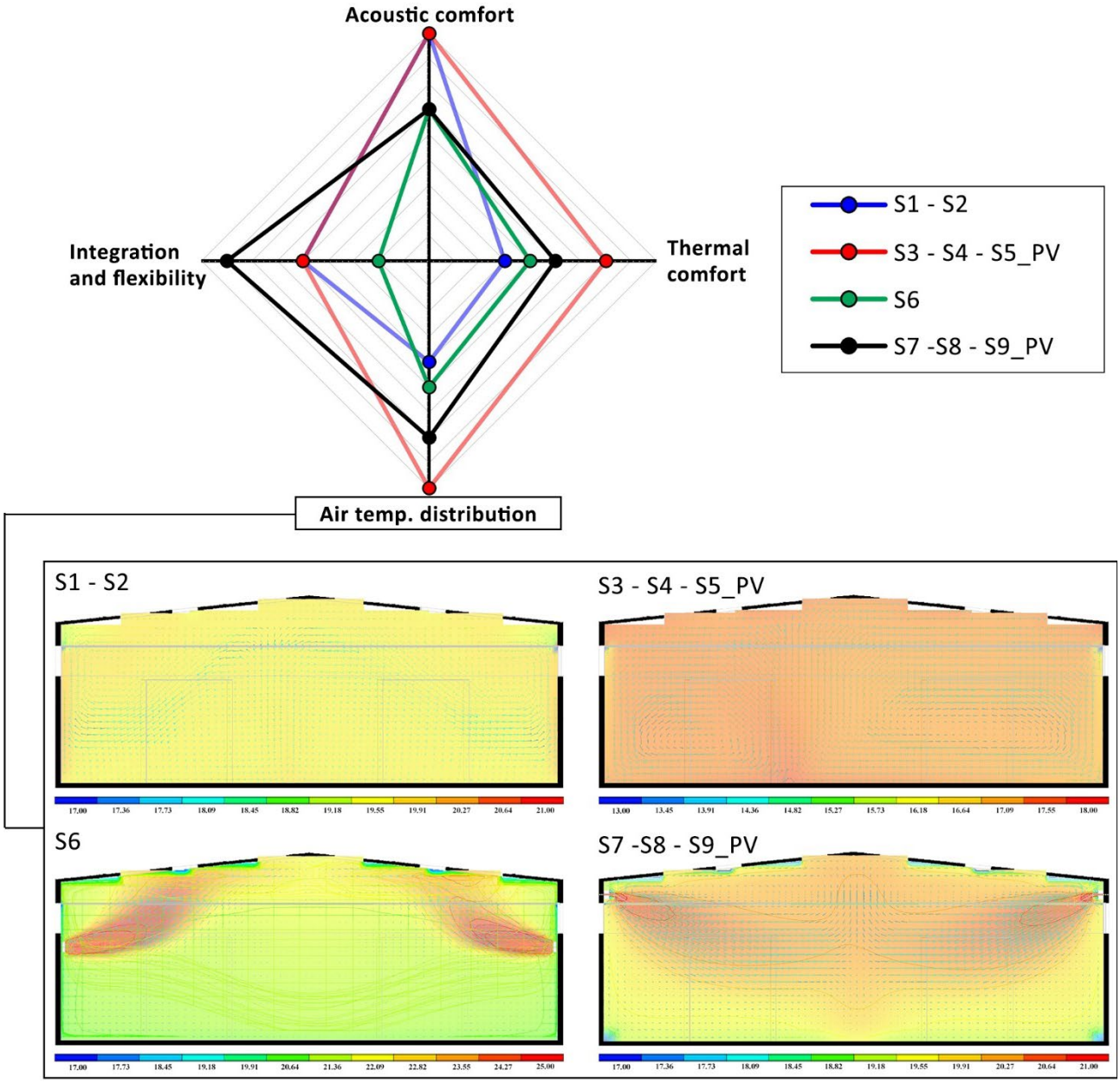


Figure 5.63 Comfort related performances of the alternative system configurations evaluated. *Source: elaboration of the author.*

The analysis of space and logistics-related criteria, performed expressing qualitative judgments in pairwise comparisons, revealed notable differences among the heating solutions. In terms of installation procedures, radiant heating solutions, and radiant floors in particular, involve intrusive installation processes that significantly interfere with industrial operations, as they require the complete displacement of machinery and stored materials. On the other hand, the S6 solution, featuring localized air heaters, is the easiest to deploy due to its minimal assembly requirements.

Radiant heating solutions (S1 – S5_PV) are however preferable for the indoor space occupancy, as they avoid introducing obstacles in the working area, allowing unrestricted use of the building's internal space. In contrast, S6 and all-air systems (S7-S9_PV) require suspended components, which can collide with process machinery and were therefore penalized when evaluating their compatibility with industrial operations. S1 and S2 are particularly unfavourable as they limit the use of wall space for machinery or shelving, that is a common requirement in manufacturing facilities. Industrial buildings often need flexible layouts to accommodate changes in production processes and machinery arrangements. Solutions S1-S5_PV, which involve radiant heating, are less adaptable as modifying the distribution of heating pipes embedded in walls or floors would lead to extremely invasive procedures. Conversely, S6 and S7-S9_PV offer greater flexibility, allowing easier rearrangement in response to layout changes. With reference to the last criteria, the outdoor area required by each alternative, the different systems are more or less comparable and this parameter does not play a significant role in the final decision-making process.

To properly analyse the reliability of the different system setups, the expected lifetime of the various components foreseen in every layout was derived from the available publications, for heating sources [57][58][59] and PV related elements [60]. Solutions featuring PV energy generation were rated lower due to their higher maintenance demands and the relatively shorter lifespan of inverters. Similarly, all-air HVAC configurations require more frequent replacement of accessory components compared to primary generation units, with scheduled maintenance, and evolving standards driving these replacements. Regular air filter replacement is pivotal to ensure effective filtration and overall system efficiency. On the other hand, radiant heating solutions are recognized for their reliability, with maintenance needs primarily limited to the heating source components. Heat pumps, for example, require less maintenance than combustion-based heating sources [61]. However, systems incorporating Air Handling Units (AHUs), including those with heat pumps, necessitate additional inspections and maintenance for components like air filters, control valves, sensors, thermostats, and ventilation units to maintain system performance. The S6 scenario, which fosters moving components such as fans, was further penalized because of the increased risk of mechanical failures, underscoring the maintenance benefits of simpler, static systems like radiant heating.

The evaluations of the alternatives were integrated with the weights of each criterion to identify the most recommendable configurations. The results of the final evaluation are illustrated in Figure 5.64.

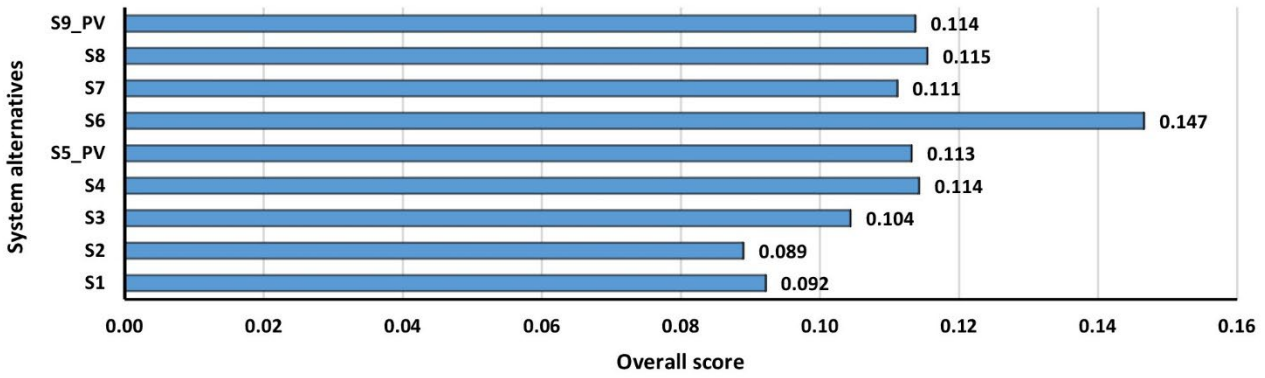


Figure 5.64 Final ranking of system solutions evaluated. *Source: Re-elaboration from Banti N, Krawczyk DA (2024) Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings. Journal of Building Engineering 95:110203. https://doi.org/10.1016/j.jobe.2024.110203..*

According to the adopted boundary conditions, configuration S6 was identified as the most advisable solution, whereas configurations featuring radiant walls (S1 and S2) exhibit overall scores that were 37% and 39% lower than the optimal performance. The preference for configuration S6 is supported by its reduced investment costs, the minimal disruption to working activities caused by installation, and greater flexibility to face evolutions in the internal layout, without significative interferences with production processes. It is important to note, however, that while similar heating systems are commonly employed in several industrial buildings, the heat generators currently in use are often outdated. The analysis reveals a pronounced prevalence of economic needs over environmental considerations: for this reason, configurations with PV systems (S5_PV, S9_PV) are penalized by their costs, which overshadow their sustainability benefits. Scenarios with radiant floors (S3-S5_PV) and all-air systems (S7-S9_PV), despite demonstrating comparable overall indices, exhibit substantial differences in expenditures and logistic.

To facilitate the generalization of the research findings, further analyses were deemed necessary. An extensive sensitivity analysis was subsequently conducted using SuperDecisions software to assess how varying boundary conditions or specific manufacturer requirements could influence the decision-making process. Different weights were assigned to each evaluation criterion to explore their impact. The analysis mainly focused on key factors, including economic parameters (initial investment), environmental impact (CO2 emissions), and installation procedures. The weights of these parameters were adjusted within a range from 0 (indicating no influence, as if the parameter were excluded from the analysis) to 0.65. The outputs of this deepening are illustrated in Figure 5.65.

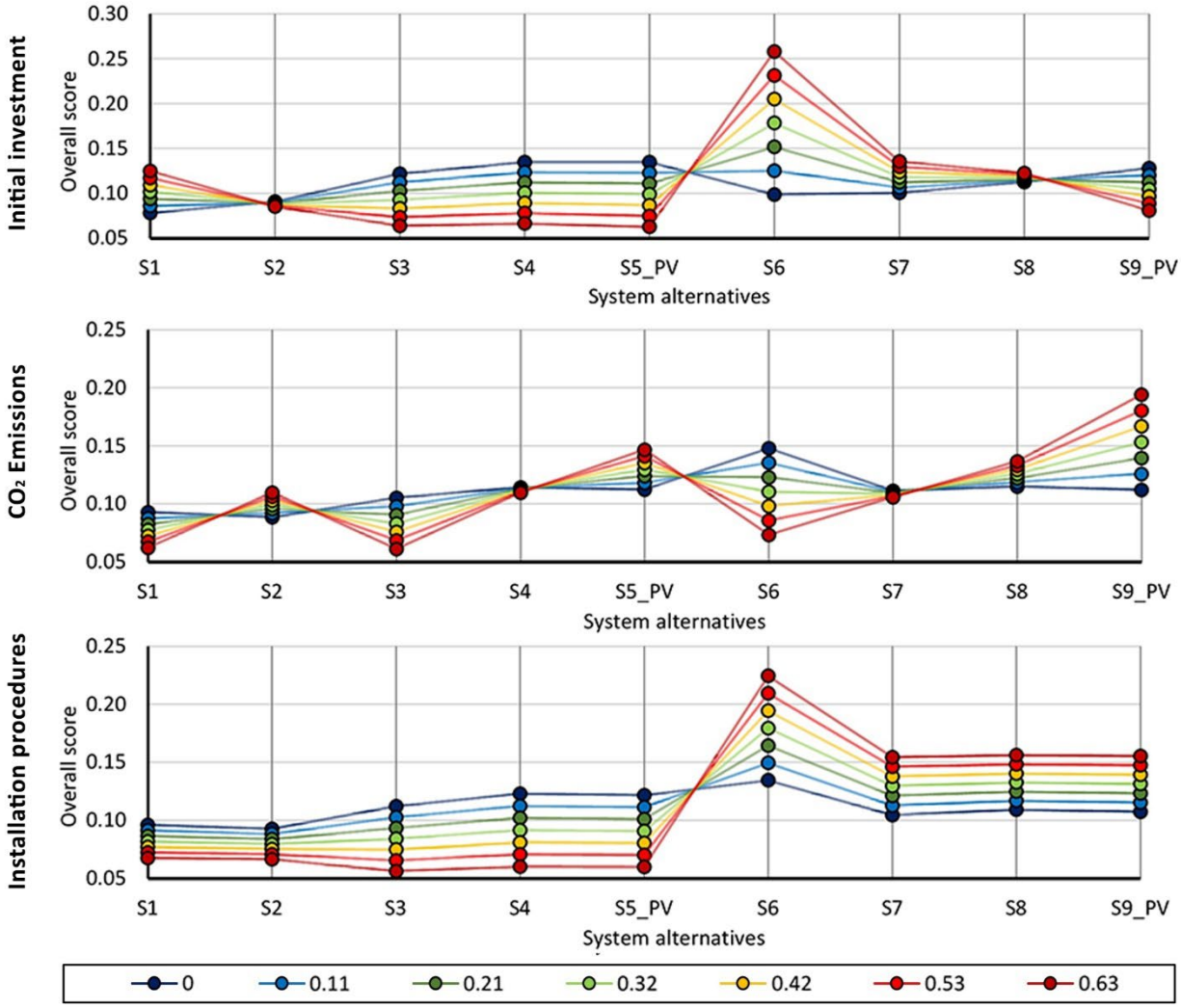


Figure 5.65 Results of the sensitivity analysis carried out with respect to the Initial investment, CO2 emissions, and Installation procedures criteria. The weight assigned to each parameter varies according to the values shown in the legend and the overall score for each configuration is reported in the y-axis of each graph. *Source: Re-elaboration from Banti N, Krawczyk DA (2024) Integrating energy simulations and analytical hierarchy process procedure in multi-criteria evaluation of heating systems for industrial buildings. Journal of Building Engineering 95:110203. https://doi.org/10.1016/j.jobe.2024.110203..*

The sensitivity analysis initially focused on the initial investment, identified as the most influential parameter and currently weighted at approximately 0.20. Given that industrial companies may have varying budgets and resources, it is reasonable to expect for choices that could favour also more expensive solutions. If the initial investment is not a major constraint, radiant floor solutions are particularly attractive due to the comfort standards guaranteed, the low maintenance required, and the prevention of internal obstructions. On the opposite, the S6 solution becomes the preferred one when budget constraints are significant, and its appeal is notably affected by variations in the relevance assigned to this criterion. S9_PV exhibits an almost opposite trend, while S2 and S8 show only minor variations. It is important to note that these setups shows considerably different trends when considering the operational costs connected to annual energy expenses. S6 is notably affected by

higher operational energy costs, which may prompt reconsideration if this criterion gains greater weight, especially with rising natural gas prices. In contrast, PV-based solutions are advantageous due to their use of self-generated energy, reducing reliance on grid electricity.

Even if CO2 emissions were investigated in the sensitivity analysis, they are marginal in decision-making for companies. Heat pump solutions are preferred in terms of CO2 emissions, and their environmental performance can be further improved with a dedicated PV system. The graph highlights that S6 has the highest emission rate, underscoring the need for retrofitting existing heat sources in many industrial buildings to improve environmental sustainability.

Logistical aspects were also considered, focusing on installation procedures. The trends across all alternatives for these criteria are comparable, with S6 consistently performing the best. Radiant floor configurations are penalized in terms of installation procedures, making them suitable only in cases where the industrial hall is empty, installation deadlines are flexible, or significant additional interventions are required, such as structural reinforcements, leading to a unavoidable interruption of working activities.

In conclusion, the research utilized in this stage an Analytic Hierarchy Process (AHP) to evaluate various heating system alternatives for a representative manufacturing building, following an approach meant to facilitate the generalization of the study's outcomes. Pairwise comparisons were conducted among 15 evaluation criteria to rank their priorities, reflecting the industrial sector's perspectives, including direct feedback from entrepreneurs.

The main findings can be summarized as follows:

- In the context of industrial buildings, the initial investment parameter is the most influential one, followed by installation procedures and compatibility with operational needs, which impact manufacturing processes and company operations. All of these aspects should be hence addressed with particular attention and discussed through case specific assessments;

- For the scenario analysed, which aligns with the majority of real enterprises in Tuscany, a heating system based on a gas boiler and localized hot-water fan heaters proved to be recommendable. This can be justified considering the flexibility, the low initial costs, and straightforward installation procedures of this solution.

- The sensitivity analysis led to further insights. To enhance environmental sustainability, solutions incorporating heat pumps are recommended, and integrating renewable energy through photovoltaic (PV) systems should be encouraged despite higher initial costs. Configurations similar to S6, prevalent in current industrial buildings, should ideally be replaced with more sustainable options. Given the expected higher yearly energy costs and inefficiency of boilers, solutions like heated floors become particularly attractive due to their reliability, uniform air distribution, comfort, quiet operation, and lack of obstructions in work areas.

The research addresses a gap in the existing literature through an innovative method that allows to perform multi-objective evaluations of energy retrofitting strategies, based on scientific literature, expert input, and local company feedback. The research, while providing valuable insights, has some limitations and areas for further development. The alternatives and evaluation criteria used may need to be adjusted for different scenarios with varying requirements and boundaries, as the conditions of manufacturing facilities can vary significantly due to different industrial processes. In this regard, broader and standardized audit campaigns across larger sets of companies could enhance the systematic collection of requirements. Including data on internal heat gains from machinery or production processes in energy models would further refine decision-making accuracy, especially in case of highly heat-emitting industrial activities. Future research should also consider more precise estimations financial aspects, including available incentives and the monetization of surplus energy production. Integrating Life Cycle Costs (LCC) and Life Cycle Analyses (LCA) could provide a more comprehensive assessment of the economic and environmental impacts over the solutions' lifespan and aid in determining their payback periods.

5.3.5 PV energy production and storage potential

Existing industrial facilities are characterized by large, still largely under-utilized roof surfaces with significant potential for renewable energy integration, particularly solar energy. Considering the buildings surveyed in the first stages of the research, only about 10% have solar thermal panels or PV modules installed, generally retrievable only in recently built or renovated facilities given the reglementary prescriptions currently in force.

In addition to the wide roof surface available, industrial buildings exhibit a series of favourable characteristics for exploiting solar radiation. For instance, industrial districts often have uniform building heights, minimizing the shading effect on rooftops. Moreover, the latter are low-tilted, reducing the influence of building orientation on the total energy production in both winter and summer seasons. The decarbonization contribution achievable by installing roof-mounted PV modules in commercial and manufacturing facilities was documented in the literature for Northern European contexts, letting to foresee even more considerable impacts at the Mediterranean latitudes. To further maximize energy production and reduce reliance on the grid, energy storage systems can be implemented to store surplus energy for use during nighttime or periods of insufficient generation.

These aspects were analysed in the research by first evaluating the energy production from PV modules installed on the rooftop of the case study building already addressed. The energy balance of the building was determined by comparing this production with the energy demand for heating, assuming the installation of an all-air heat pump system. To conclude, the economic feasibility of storage system adoption was assessed through dedicated simulations and financial forecasts. The methodological approach is synthesized in Figure 5.66.

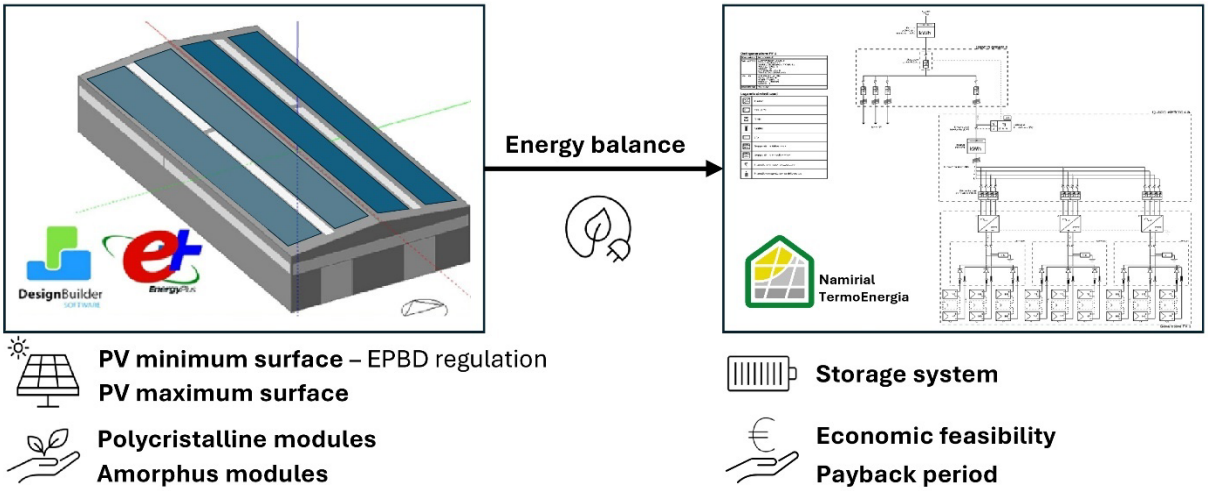


Figure 5.66 Method of the research for PV potential production analysis. *Source: elaboration of the author.*

Two different solutions for PV modules have been tested, considering both traditional and amorphous panels. The latter presents numerous advantages, making it a highly versatile option for various applications to overcome possible limitations induced by the peculiarities of industrial buildings. The installation, possible also on vaulted cupels or curved roofs thanks to the flexibility of the possible, does not require perforating the waterproofing layer, and the modules are both walkable and shatterproof. Furthermore, no dedicated supporting substructure is needed. Notably, from an energy production point of view, the system is particularly effective even at high temperatures and under low irradiation conditions because, in the event of shading, each cell is equipped with a bypass diode. However, the peak power production is currently lower when compared to traditional panels and can be only enhanced by covering a wider roof area. The properties of the PV modules were set in the models making reference to products available in the market, collected in Table 5.43.

Table 5.43 PV panels properties adopted in the model. *Source: elaboration of the author.*

Properties	**Traditional monocrystalline panels**	**Amorphous flexible monocrystalline panels**
Panel size [mm]	1046 x 1690	1386 x 994
Cells per module	104	48
Rated electric power output per module [W]	390	240
Short circuit current [A]	6.55	9.8
Module current at max power [A]	6.05	9.5
Open circuit voltage [V]	75.3	32
Module voltage at max power [V]	64.5	25.3

In the case of new buildings or facilities undergoing major renovations, the electrical power of the systems powered by renewable energy sources that must be installed mandatorily on or within the building or its appurtenances, measured in kW, is calculated according to the following formula proposed by the Decreto Legislativo n. 199/2021:

$$P = k * S$$

- S [m^2], footprint area of the building at ground level;
- k [kW/m^2], parameter equal to 0.025 and 0.05 for existing and new buildings, respectively.

According to this prescription, the minimum amount of electrical power to be installed for the building under consideration is equal to:

$$P = 0.025 * 1120 = 28\ kW$$

Based on this result, the minimum number of modules for both solutions was calculated. To also evaluate the total solar potential of the roof, the exploitation of the whole surface available was considered. In this case the layout of the panels was assumed to preserve adequate areas for maintenance operations. The key features of the different scenarios evaluated, encompassing minimum and maximum area for both traditional and thin-film flexible modules, are collected in the following Table 5.44.

Table 5.44 PV layouts considered in the analysis. *Source: elaboration of the author.*

Properties	Trad_min	Flex_min	Trad_max	Flex_max
Area covered by PV panels [m²]	128	167	348	333
Number of panels installed	72	120	232	240
Total power installed [kW]	28.08	28.80	90.48	57.60

In Figure 5.67, the energy production ensured by the different layouts is illustrated on a monthly basis.

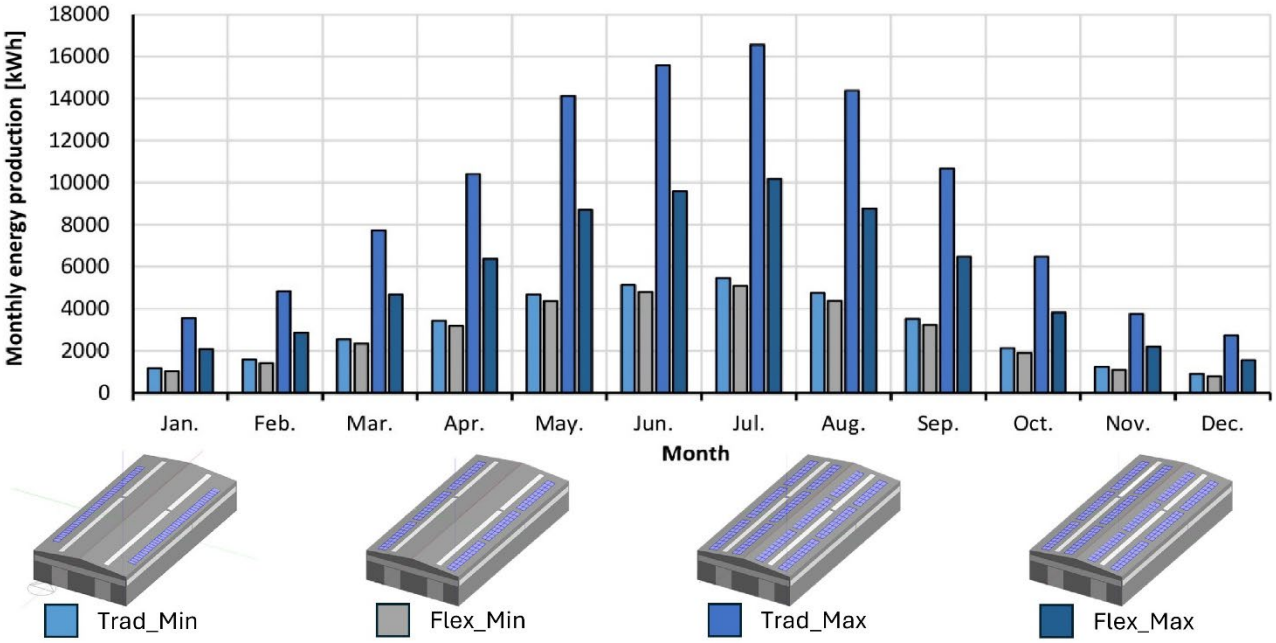


Figure 5.67 Monthly energy production in the different scenarios. *Source: Elaboration of the authors*

All configurations exhibit maximum energy production potential in July, while PV systems are least effective in December. Comparing scenarios based on minimum regulatory requirements, traditional modules can produce up to 15% more energy than flexible ones during summer months. This difference decreases in winter, ranging between 7-9%. Focusing on layouts that maximize PV surface, the gap is more pronounced: the Trad_max option can produce 40% more than the Flex_max layout. This is because the number of flexible panels doubles in the maximum coverage layout compared to

the minimum one, while the number of traditional modules nearly triples. Besides energy considerations, the load induced by the PV systems must also be addressed when evaluating the feasibility of interventions. The lightweight nature of flexible modules (approximately 2.2 kg/m²) helps avoid compromising the building's structural integrity and seismic performance, whereas the extensive use of traditional panels may be problematic due to excessive weight. Referring to the two extreme configurations (Flex_min, Trad_max), comparisons were produced with the expected energy consumption in case of a system retrofitting with an all-air system, featuring air source heat pump, mechanical ventilation, and heat recovery units. This system configuration has been already evaluated in section 5.3.4. In Figure 5.68, the energy balance of the building is illustrated on a monthly basis for the winter period, highlighting the demand connected with lighting, ventilation, and heating systems for both the PV modules layouts and their electricity generation.

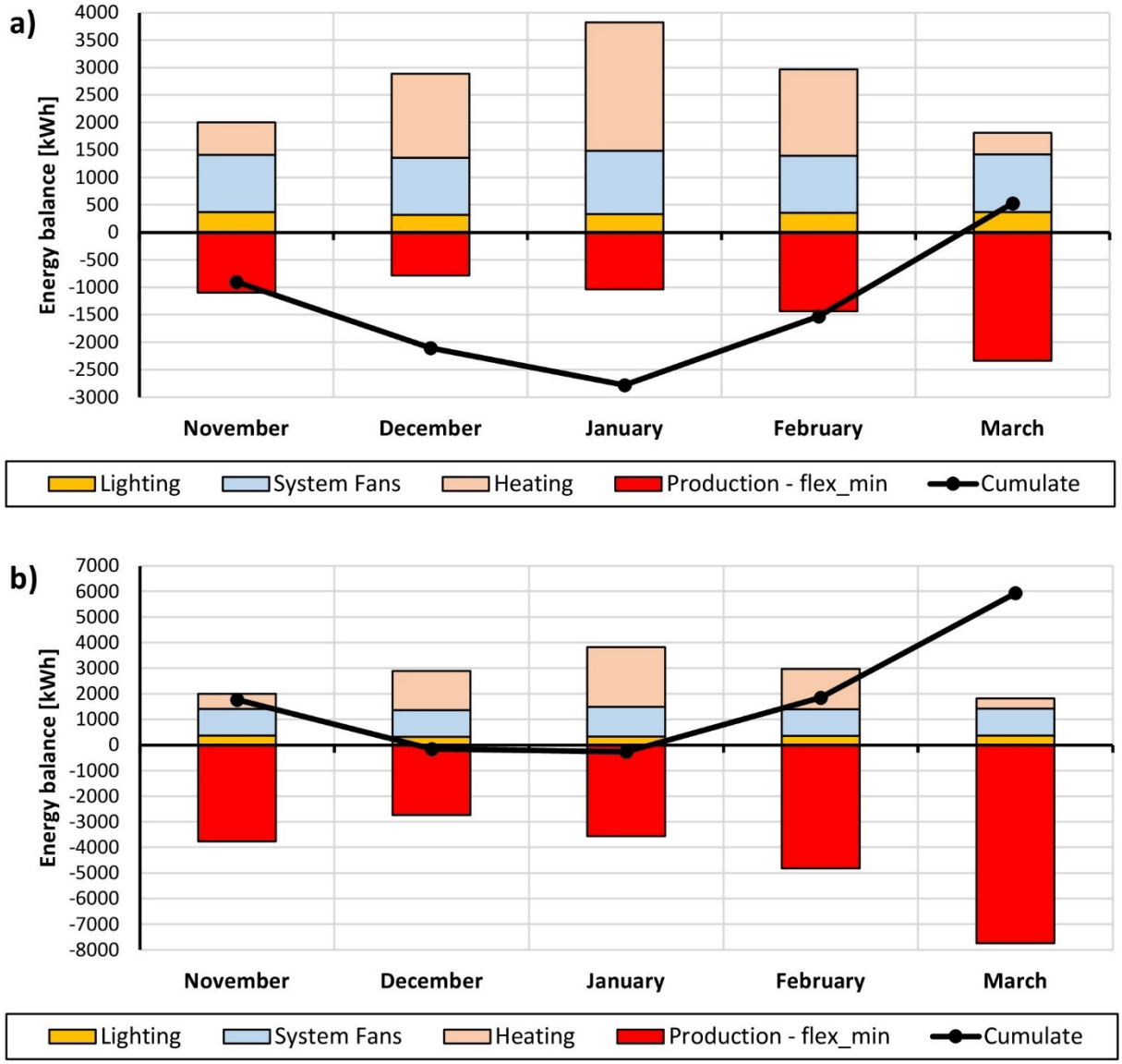


Figure 5.68 Energy balance for Flex_min (a), Trad_max (b) layouts. *Source: elaboration of the author.*

When considering the global values over each months, the installation of the minimum amount of flexible panels appears to be insufficient during the coldest months, resulting in a positive balance only during March. On the other hand, the maximization of PV surface on the roof allows to ensure relevant gains starting from February and to substantially equal the energy demand during both December and January.

However, to effectively account for the contemporaneity of energy generation and demand, more detailed insights were produced referring to hourly distributions thanks to dedicated energy simulations. The outputs of simulations were postprocessed in a series of specifically intended calculation sheets to provide a better understanding of the results achieved.

In Figure 5.69 and Figure 5.70 the results are illustrated for Flex_min and Trad_max scenarios respectively making reference to the month of January, that proved to be characterized by the most challenging conditions. Hourly trends were derived for the whole month and the reference design week.

As emerging from the graphs, in case of flexible panels providing the minimum peak power, the energy production achieved is not sufficient to cover the total demand, even if it could be enough to satisfy the consumption connected with lighting and ventilation. The heating energy demand is characterized by a peak in the first half of the morning, mismatching with the trend of energy production that reaches the maximum in the central hours of the day. This is particularly evident when analysing the Trad_max alternative: in this case the electricity produced generally outset the energy demand but in the morning it is not sufficient to assist the activation of the heating system.

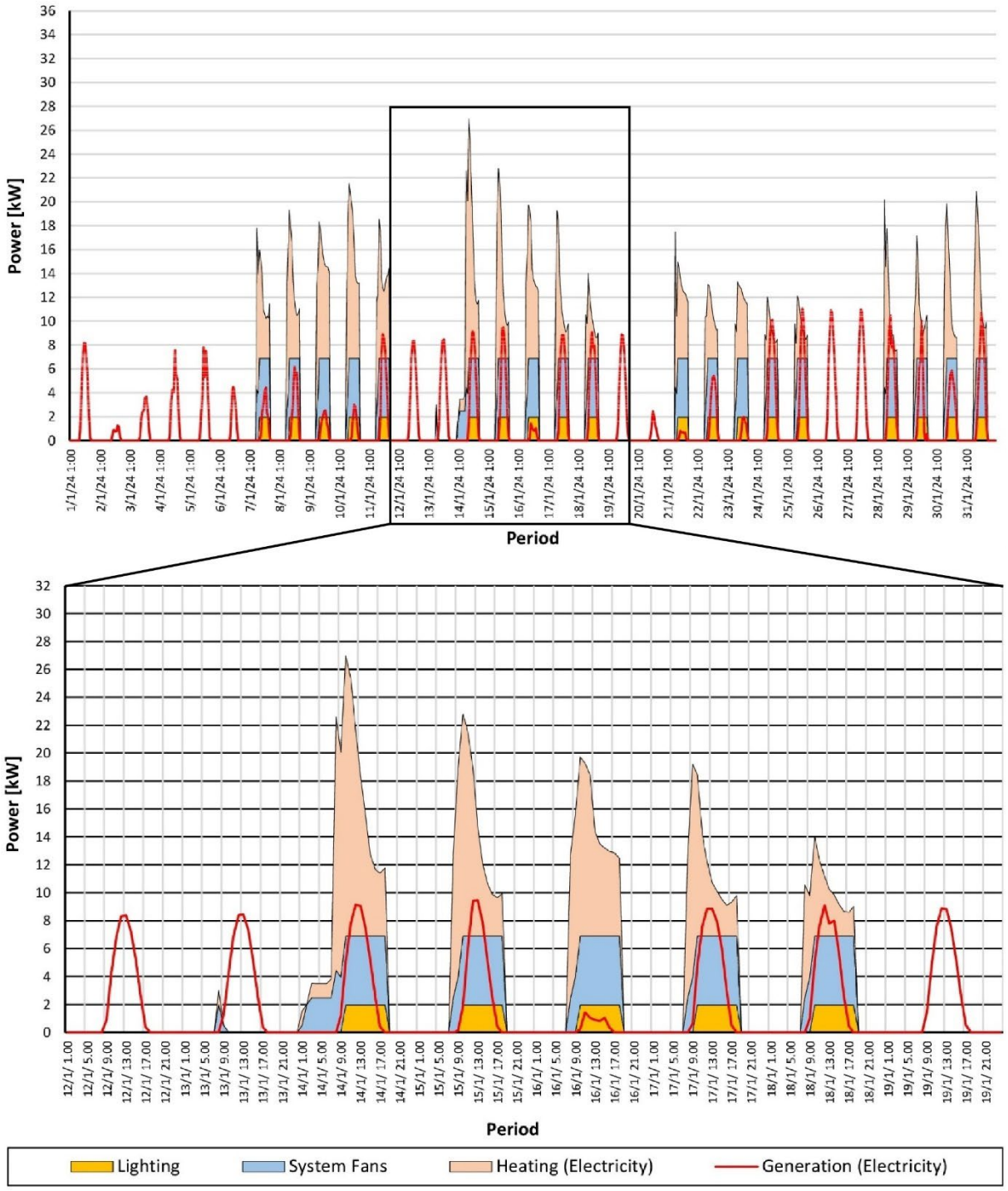


Figure 5.69 Hourly trend of energy consumption and production over January and the reference week selected (12-19 January) in case of Flex_min configuration for PV panels. *Source: elaboration of the author.*

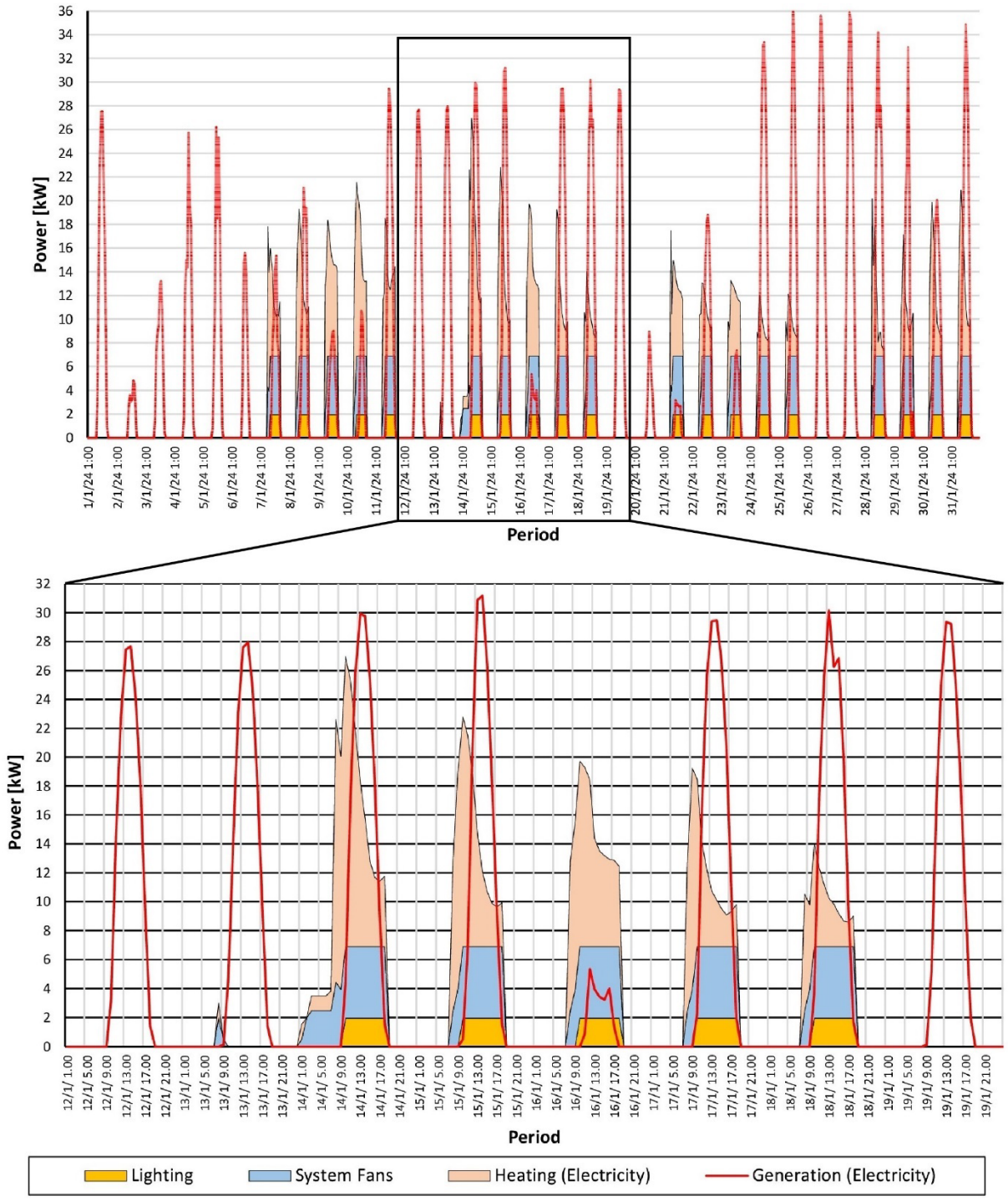


Figure 5.70 Hourly trend of energy consumption and production over January and the reference week selected (12-19 January) in case of Trad_max configuration for PV panels. *Source: elaboration of the author.*

However, industrial buildings are characterized by utilization patterns usually coinciding with the hours of energy production and this represent a possible enhancing factor for solar source exploitation. On the other hand, the interruption of working activities during the weekend prevents the direct exploitation of the energy produced in these periods as well as during late afternoon hours in the summer periods. The unpredictability of solar source can be stressed out making reference to the day of 16th January when energy generation drops because of adverse weather conditions.

Following these considerations, the analysis of the results was deepened to assess the amount of energy produced when building's systems are turned off, the one to be fed from the grid, the one simultaneously consumed and produced, and the extra production during working days. Table 5.45 and Table 5.46 synthesize the findings produced for the whole winter period, once again distinguished for configurations Flex_min and Trad_max. In the first scenario, systems still largely rely on energy fed from grid as the PV modules can only cover about 23% of the demand during December and January, when only a negligible extra production is guaranteed. On the other hand, a considerable amount of energy is produced during unoccupied periods but not directly exploited, as for the extra production during March. These aspects become even more significant in the Trad_max configuration: in this case extra generation in both working and resting days is relevant and only during December and January the energy fed from grid exceeds the one ensured by the PV system. Maximizing the PV surface allows to satisfy at least the 45% of the energy demand by renewables.

Table 5.45 Energy balance based on simultaneous consumption and production for Flex_min scenario. *Source: elaboration of the author.*

	Production when systems turned off [kWh]	**Fed from grid [kWh]**	**Simultaneous consumption and production [kWh]**	**Extra production [kWh]**	**Share of energy demand covered by the PV system**
November	353.33	970.56	656.28	87.24	40%
December	244.48	1'776.66	532.48	7.66	23%
January	414.84	2'127.12	615.98	8.19	22%
February	366.11	1'390.92	961.67	105.96	41%
March	745.91	588.63	982.77	517.41	63%

Table 5.46 Energy balance based on simultaneous consumption and production for Trad_max scenario. *Source: elaboration of the author.*

	Production when systems turned off [kWh]	**Fed from grid [kWh]**	**Simultaneous consumption and production [kWh]**	**Extra production [kWh]**	**Share of energy demand covered by the PV system**
November	1'208.52	567.10	1'059.74	1'498.83	65%
December	854.83	1'143.03	1'166.11	712.00	50%
January	1'424.30	1'518.29	1'224.81	910.99	45%
February	1'243.67	847.61	1'504.99	2'069.73	64%
March	2'778.01	245.48	1'325.92	3'637.42	84%

Given the promising results obtained, the research was deepened performing dedicated energy and financial scenarios simulations using the Namirial Termo Energia software [62], designed for planning solar energy systems complying with the standard UNI EN 15316-4-3:2018.

At first, for both the configurations tested, the PV system layout was recreated in the new modelling environment making reference to the built-in extensive database available. Both the photovoltaic modules and the inverters were selected to reproduce the configurations foreseen in the DesignBuilder models. Specifically, the PV alternatives were modelled according to the electric schemes of Figure 5.71 and the properties reported in Table 5.47.

Table 5.47 Namirial settings for PV systems. *Source: elaboration of the author.*

	Number of panels	**Panel power [W]**	**Inverters**
Flex_min	120	240	4 inverters, 7.5 kW each
Trad_max	230	340	10 inverters, 10 kW each

To evaluate the profitability of the PV system on a long-term basis, assumptions were made about the possible deployment of an air conditioning system to provide cooling during summer months by exploiting the same system solution already included in the DesignBuilder models (reversible heat pump and mechanical ventilation through an all-air system). The cooling set point was set at 26°C during the working hours and an EER equal to 4 assumed for the heat pump efficiency.

The energy demand profile accounting for heating and cooling with heat pump, mechanical ventilation, and LED lighting was hence derived from new DesignBuilder simulations performed over a yearly period and imported in the PV analysis software. These outputs were compared with the data retrievable online on the ARERA website, the Italian authority for the regulation of energy, grids, and environment. By exploring this portal, it was possible to derive information on the average energy consumption for non-domestic users [331]. Filters were set to focus on the Province of Florence and on manufacturing activities profiles with a power demand over 16 kW. In Figure 5.72 the results of energy simulations and actual average data derived from ARERA are presented. Even if a significative discrepancy in terms of total energy demand can be outlined, the qualitative trend over the year is validated. The different energy demand levels can be moreover justified by considering that the energy simulations carried out do not include the consumption for production machinery and the average data are not related to the building's dimensions and characteristics.

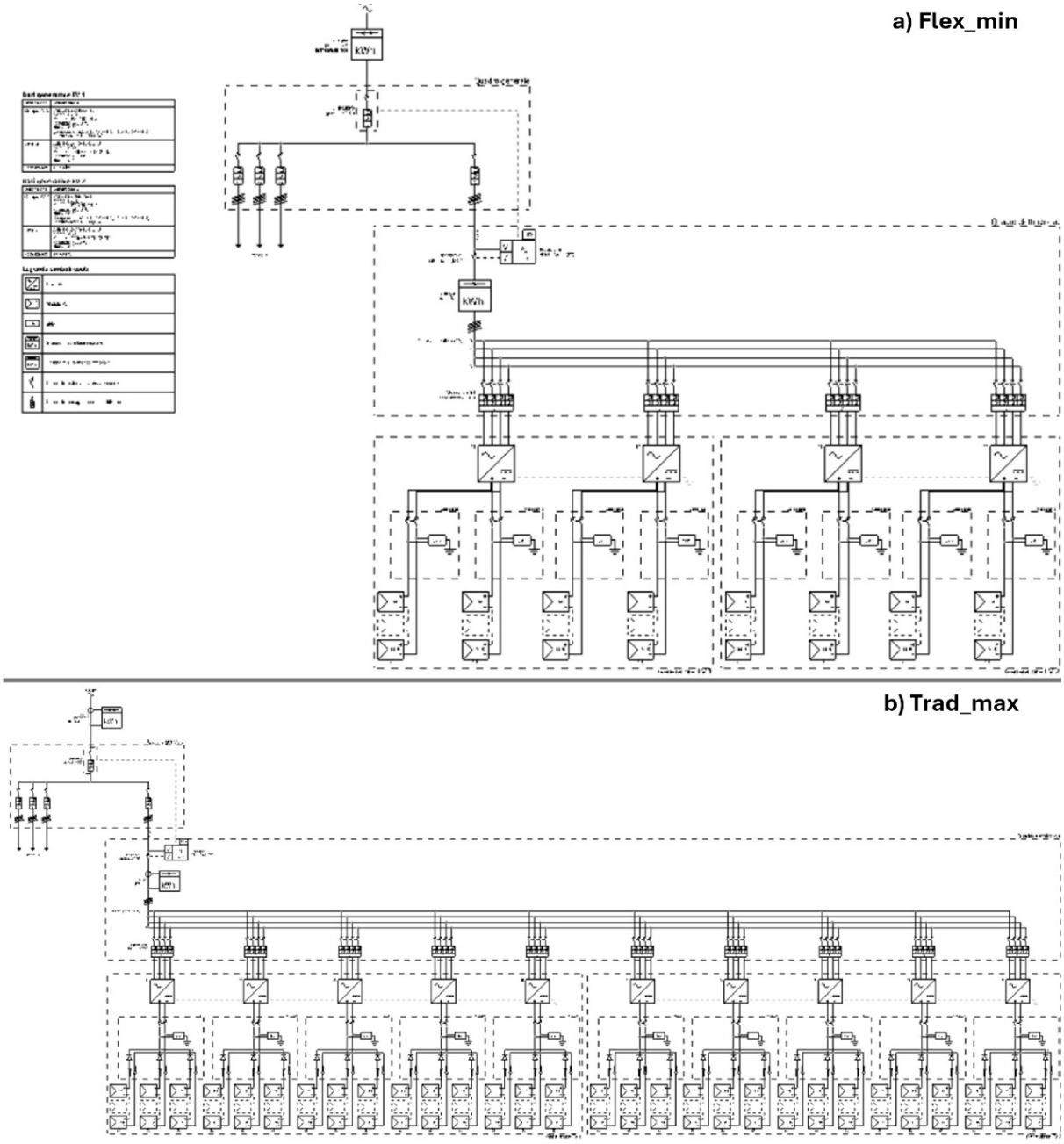


Figure 5.71 Electric schemes of Flex_min and Trad_max layout. *Source: elaboration of the author.*

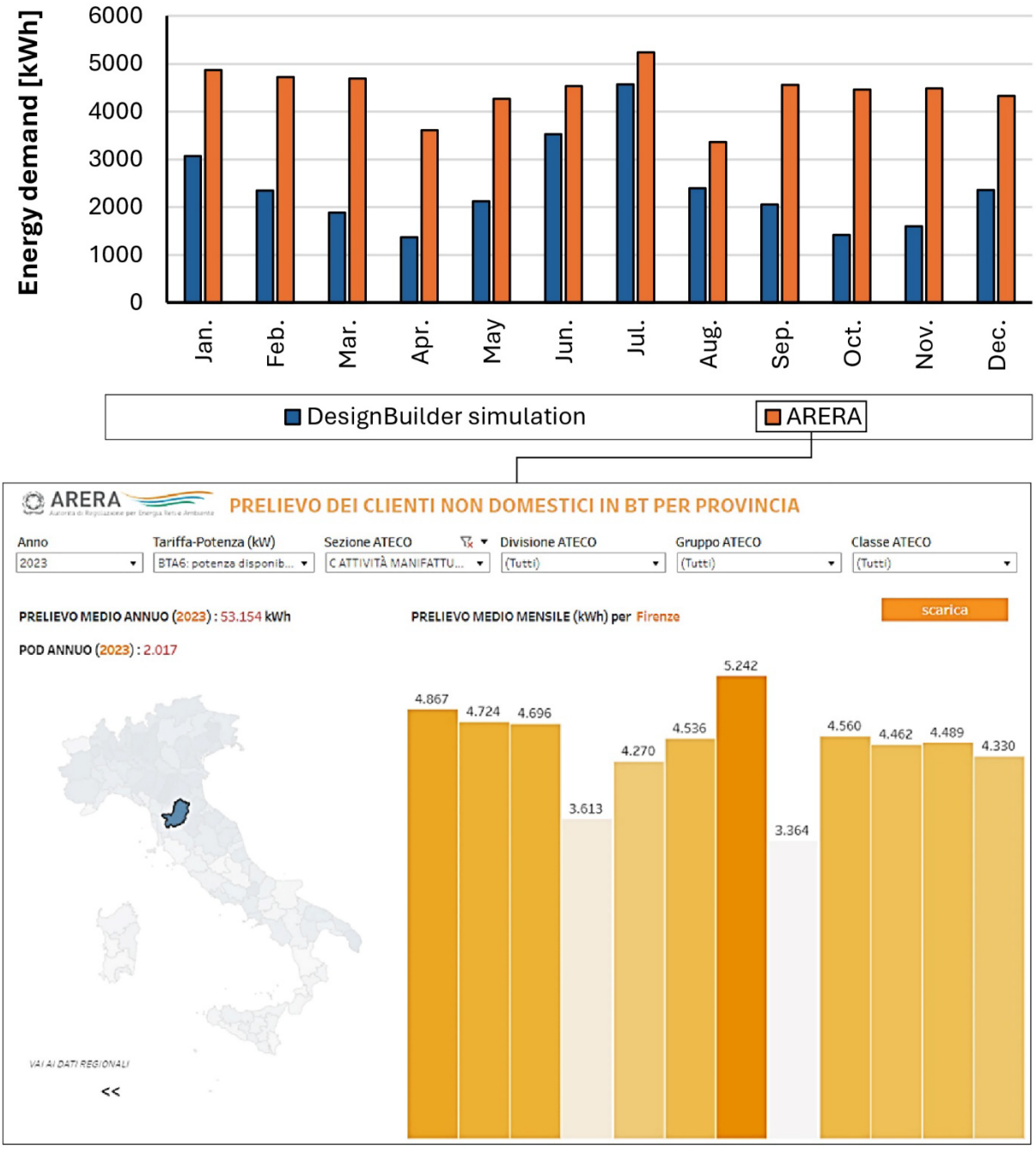


Figure 5.72 Energy demand: comparison between DesignBuilder simulations and ARERA average data for manufacturing activities in the Florence province in 2023. *Source: Elaboration of the author from ARERA*.

To assess the economic impact of PV solutions, the energy costs, the initial investments required for the installation, and the financial parameters had to be considered.

For the former, both the buying and selling tariffs were investigated. For the energy price purchased from the grid, reference was made to a time-of-use (TOU) tariff with three pricing bands, commonly adopted by many companies contacted during the research stages. The rates were averaged on the ARERA data over the past 4 years to account for the substantial fluctuations in energy prices and providing a forecast for potential values in unpredictable future scenarios. The last years were characterized by particularly unstable pricing levels due to the international context, as well as by rapid evolutions in the market policies. For these reasons, obtaining data on the energy pricing for industrial users was challenging and the energy bills shared by the companies often reflected outdated market systems and pricing procedures. Following this method, a pricing policy structured as follows was adopted:

- Energy component:
    - Fixed share price: 106.27 €;
    - F1 band: 30.79 €cent/kWh;
    - F1 band: 28.03 €cent/kWh;
    - F1 band: 22.42 €cent/kWh;
- Transport component:
    - Fixed share price: 25.07 €;
    - Quantity share price: 0.86 €cent/kWh.

As for the costs related to the selling of surplus energy to be fed into the grid, a preliminary review of the current reglementary framework was necessary. Until the end of 2024 two different mechanisms are available for the economic valorisation of surplus energy: the “scambio sul posto” net metering solution and “ritiro dedicato”. However, the former is set to be no more available starting from 2025, replaced by other kinds of solutions to promote the diffusion of Renewable Energy Communities (CER). For this reason, reference was made to the “ritiro dedicato” framework, that basically represents an alternative to the free market, featuring simplified procedures and market-based economic ratings. The price paid to producers is based on the electricity market price referring

to the hourly zonal price and is determined according to the individual producer's hourly energy production and cession profile. This mechanism allows for the actual buying and selling of electricity under streamlined terms, making it more accessible for users seeking efficient energy transactions. This solution was introduced in 2008 [63] [64] and starting from 2014 guaranteed minimum prices have been introduced to supports small producers by providing economic protection against market price instability and ensure more stable revenues. For the purpose of this study, a guaranteed minimum price set at the current rate (46.4 €/MWh) was assumed.

As for the costs related to the systems components and installation, extensive research were performed consulting online pricing lists of manufacturers and Regional reference documents such as the Prezzario Lavori 2024 of Tuscany Region [65]. However, the latter only provides indications for small-medium sized solutions and further considerations have been hence requested to adequately scale the pricing suggested. In Table 5.48 the main pricing assumptions made for both of the scenarios are reported. It has to be remarked that the purchase of modules, inverters, cables, and accessory elements were included in the system costs. For the inverters, an expected lifetime of 10 years was assumed leading to a double substitution over the period considered for the analysis. The other key parameters are reported in Table 5.49.

Table 5.48 Pricing settings for the costs related to the system installation and operative expenses over time. *Source: elaboration of the author.*

	System Cost	Incidence of inverters on total cost	Design and technical expenses	Maintenance
Flex_min	1000 €/kW	15 %	20 %	67 €/kW
Trad_max	1485 €/kW	12 %	20 %	70 €/kW

Table 5.49 Settings for the profitability analysis. *Source: elaboration of the author.*

Time of the analysis	Amortization of the initial cost	IRAP fee	Inflation	Energy inflation	Actualization rate
25 years	10 %	3.90 %	2.30 %	2.50 %	4 %

The results of the economic forecasts are reported in Figure 5.73 for both the configurations investigated. As clearly emerging from the graphs, the two different PV layouts lead to remarkably different energy generation production and also financial conditions. Installing the minimum amount of PV panels required by the energy regulation, ensure a more profitable economic return of the investment. Due to the reduced initial investment required, the payback period is reduced to 7 years and this also allows to limit the impact of the expenses related to substitution of the inverters occurring

after the first decade. The economic profitability of this solution is hence assessed assuring at the same time both financial savings and environmental benefits. On the other hand, the higher energy production rate is not sufficient to compensate the considerable installation costs of the Trad_max configuration. In this case the energy savings ensured and the economic compensation of surplus energy appear to be inadequate to offset the initial investment, resulting in a payback time equal to 22 years, given also to the replacement of components occurring at the year 10 and 20. To make this significative investments attractive for industrial investors, dedicated incentive mechanisms are necessary to guarantee both financial support in the initial stages and awarding valorisation of the energy produced.

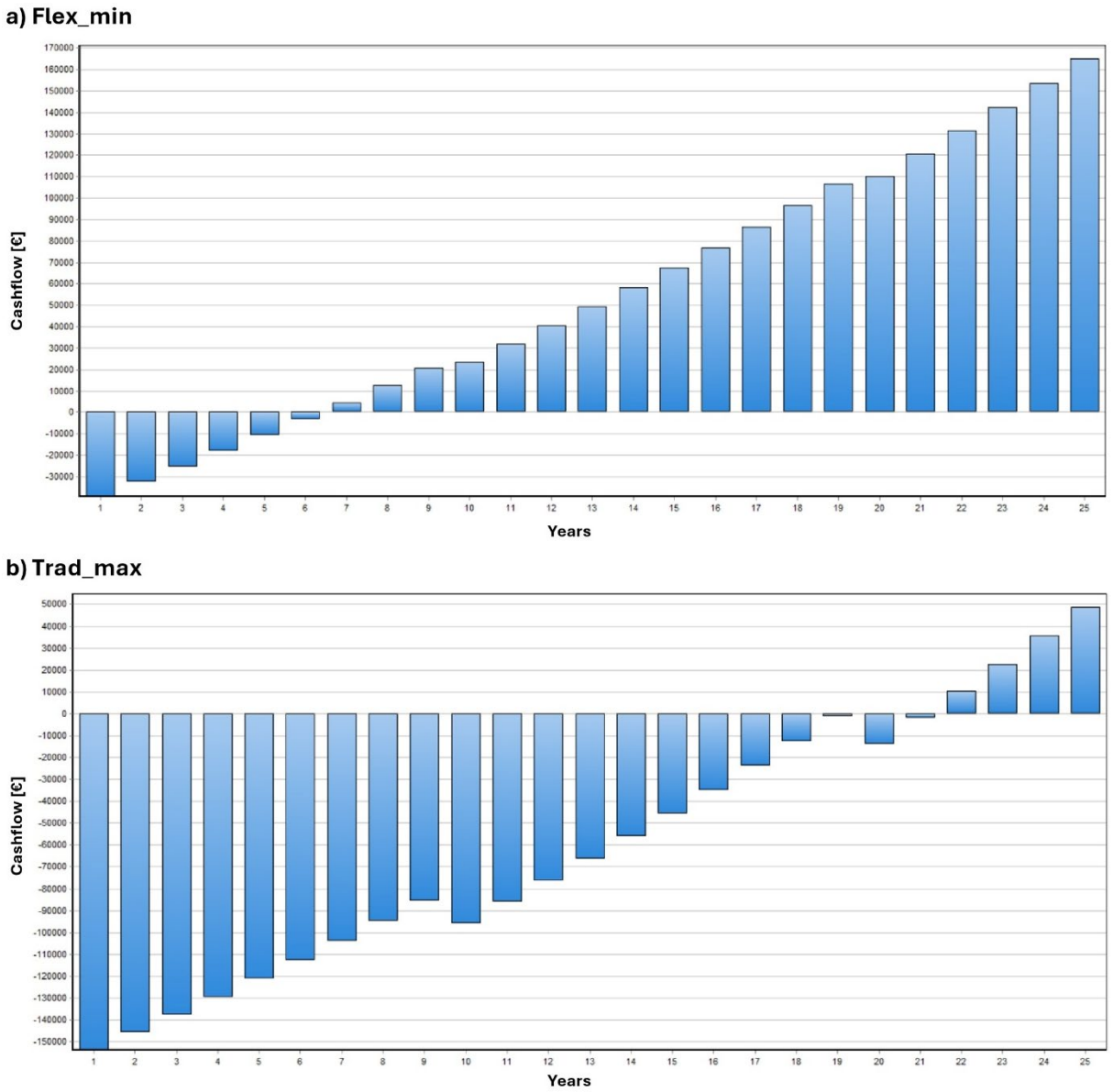


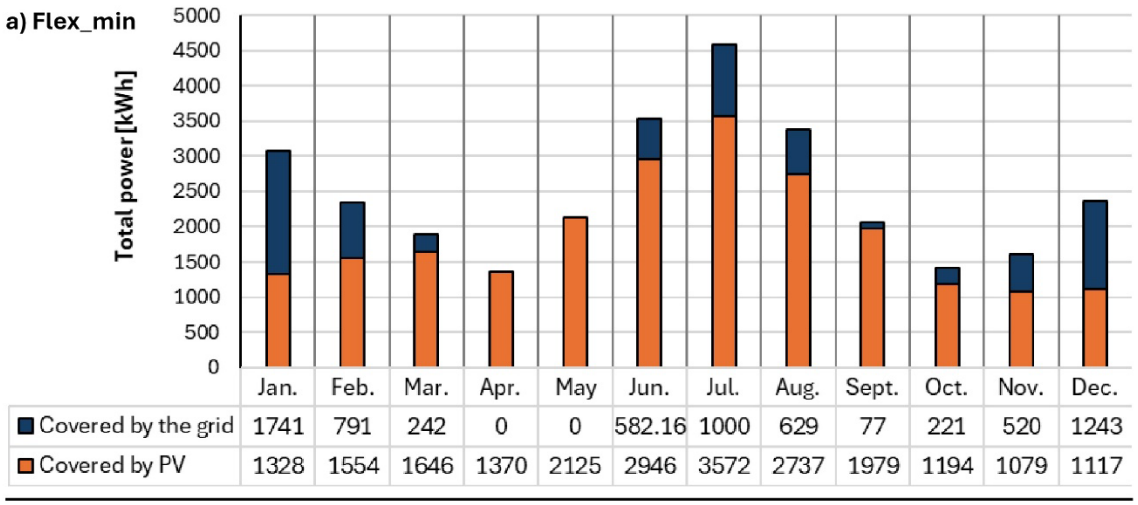
Figure 5.73 Cashflow analysis for the economic profitability of both the PV scenarios. *Source: elaboration of the author.*

To produce a more comprehensive assessment, also the effects on the environmental impact of the operational activities of the building were considered by referring to the CO2 emissions savings. Considering this performance parameter, the installation of a PV system can produce substantial benefits, leading to avoid the emission of 9954.56 kg of CO2 every year in case of the Flex_min layout and 31316.94 kg for the Trad_max configuration.

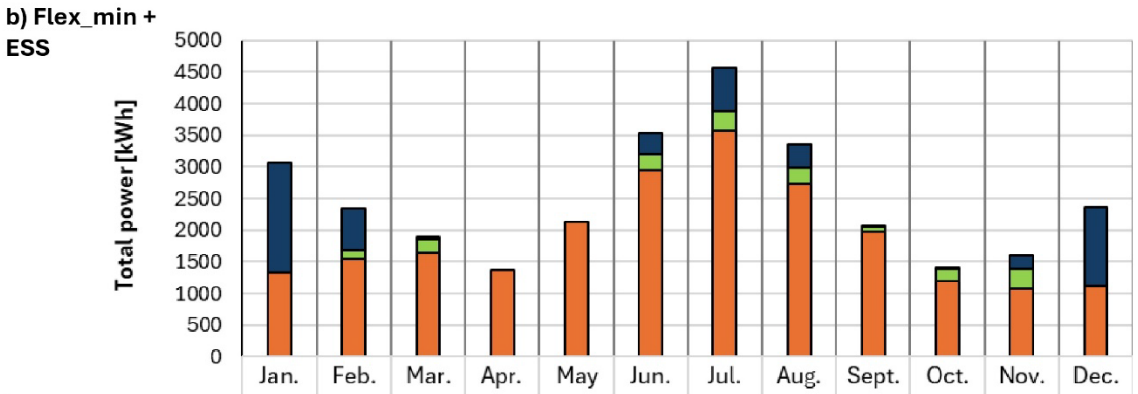
In both the configurations analysed, the energy produced over a yearly period exceeds the energy requested and the possible benefits achievable through the installation of dedicated energy storage systems (ESS), from both an economic and environmental point of view. For this application, the research was focused on the Flex_min layout that emerged as the most promising from a financial standpoint because the adoption of storage solutions would require extra costs to be faced in the initial stages. Acting on the Trad_max scenario that is already characterized by consistent initial expenses would results in an unstainable economic burden.

As for the selection of the storage technology, reference was made to Litium-Ion batteries. This solution, compared to the other tradition ones fostering Nichel-Cadmium or lead-acid, is nowadays emerging as one of the most favourable given the reduced environmental impact of the components, the longer life expectancy, the reduced size and weights, and the extended depth of discharge (DOD) [66]. Technical data were derived from real products available in the market to produce reasonable simulations. As for the sizing of the storage capacity, the one suggested by the simulation software was adopted, as it was produced based on the production rates calculated and the energy demand profiles set. According to these data, a 42 kWh storage emerged as preferrable. 13 batteries characterized by a nominal capacity of 37 Ah and a DOD equal to 95% were introduced in the model. Following another pricing estimation through the same sources introduced before, an average price of 530 €/kWh was derived, increased once again by 20% to account for installation costs and technical related expenses.

In Figure 5.74 the energy balance of the Flex_min scheme, both with and without ESS, are reported. As emerging from the graph, the storage system seems to be effective only during the summer months while during the coldest period it remains substantially unexploited due to frequent complete charging and discharging cycles, excepts for the weekend closings. For this reason, the recurs to seasonally scaled storage solutions may be more profitable for industrial facilities given their peculiar occupancy and usage schedule in which the demand and production hours are practically overlapping.



	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Covered by the grid	1741	791	242	0	0	582.16	1000	629	77	221	520	1243
Covered by PV	1328	1554	1646	1370	2125	2946	3572	2737	1979	1194	1079	1117



	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Covered by the grid	1741	658	35	0	0	318	681	373	0.38	27	209	1241
Covered by the ESS	0	133	207	0	0	263	319	256	77	195	310	3
Covered by PV	1328	1554	1646	1370	2125	2946	3572	2737	1979	1194	1079	1117

Figure 5.74 Energy balance and share of energy from grid, PV, and ESS. *Source: elaboration of the author.*

Economic forecasts where produced also in this case to evaluate the financial profitability of the ESS installation. The cashflow trend is illustrated in Figure 5.75. In this configuration, the higher initial investment needed results in a longer payback period, because the yearly extra savings ensured are not enough to cover it (1762 kWh saved from the grid). A first breakeven point is registered after 12 years but the incomes are basically outset by the costs of batteries substitution after few years.

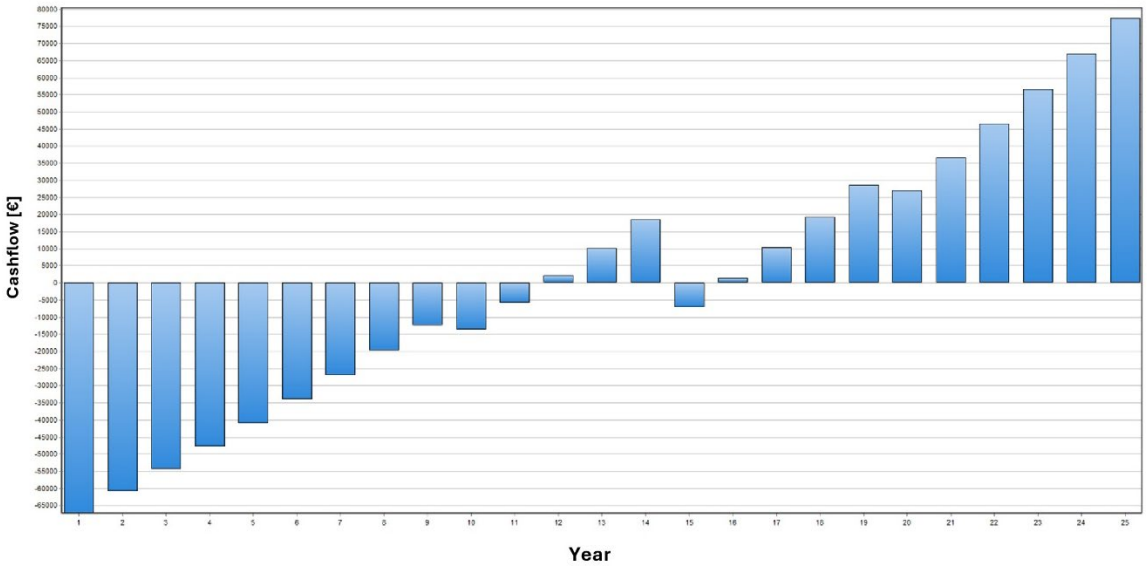


Figure 5.75 Economic cashflow trend to evaluate the economic profitability of the Flex_min layout coupled with ESS. *Source: elaboration of the author.*

In conclusion, the research let to achieve the main findings synthesized below:

- Thin film PV modules, despite being characterized by a generally lower peak power production, can represent a valuable solution as they induce lower static load on existing structures and can allow to exploit greater roof surface;

- The installation of PV system with a considerable peak power can be not profitable from an economic point of view given the longer payback period associated;

- Specifically meant financial incentives and awarding mechanisms are needed to make the energy transition to renewables captivating for business stakeholders such as industrial or manufacturing companies;

- The recurs to seasonal storage system may be more recommendable than traditional systems due to their ineffectiveness in the periods characterized by lower solar radiation;

- The significative de-carbonization potential of PV based energy production in industrial buildings was assessed, with CO_2 savings ranging from about 9500 up to over 30000 kg per year according to the size of the system installed.

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6 INTEGRATED REDEVELOPMENT PROTOCOL

Based on the measures previously introduced, a comprehensive retrofit protocol to be applied for existing industrial buildings was defined. The peculiarities of the different typological variants in terms of external walls and roof solutions were considered to select the most appropriate redevelopment measures to be adopted. For this reason, some of the retrofit interventions can be repeated for different typological variants while others are exclusively addressing the criticalities connected to one of them. For each variant, a dedicated sheet has been produced to collect the most suitable retrofit solutions to tackle criticalities associated with external areas, external walls and relative openings, and roof and skylights. As for the actions on systems, the substitution of currently installed equipment for both heating, cooling, ventilation, and lighting is generally recommended given the outdated technologies commonly used. In this regard, the possible alternatives are likely independent from the typological variant given the common characteristics of working areas, not affected by the structural or technological features of the building.

The proposed protocol outlines a series of multidisciplinary interventions aimed at achieving an integrated building retrofit, with the objectives of optimizing energy performance, reducing environmental impact, enhancing indoor environmental conditions, and improving the architectural quality of both the facility and the surrounding built environment. These interventions can be implemented either individually or in combination, offering flexibility and adaptability to the specific needs of the companies housed within the buildings. By addressing varying levels of design and implementation complexity, retrofit solutions can be tailored to case-specific factors, such as optimizing the use of available financial resources or minimizing disruptions to ongoing activities within the building. This approach enables customized interventions that maximize benefits while considering project priorities and constraints.

In addition, energy production through PV system installation must be necessarily integrated to limit energy dependency from grid and to reduce the carbon footprint of industrial buildings. The wide roof surfaces available, not depending on the typological variant, allow for a great energy saving potential through solar energy generation on site. In this case attention should be paid to select the most suitable module solutions, considering also the opportunity of installing flexible panels to limit the load induced on existing structures.

6.1 Vaulted roof with metal arch trusses (V_m_ar variant) and Sloped roof with metal trusses (Sl_m_tr variant)

Table 6.1 Retrofit protocol for V_m_ar variant and Sl_m_tr variant buildings. *Source: elaboration of the author.*

DISTRICT SCALE and OUTDOOR AREAS						
Retrofit strategy				**Target performance**		
Code	**Measure**			**Env. / Climate**	**Energy**	**Struct.**	**Archit.**
Ur.1	Cool pavement installation			X			
Ur.2	Trees planting / Vegetation implementation			X	X		
Ur.3	De-paving and flowerbeds installation			X			
EXTERNAL WALLS						
Current state		**Retrofit strategy**		**Target performance**		
Technology	**Position**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Masonry / Built in place infills	Inserted	EW.1	Substitution with sandwich panels	X	X	X
Horizontal precast panels		EW.2	Substitution with Aquapanel panels	X	X	X
Windows and openings						
Current state		**Retrofit strategy**		**Target performance**		
Element	**Criticalities**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Windows	Single glass pane Wired glass panes Frame no thermal break Bad airtightness	W.1	Substitution of existing windows with new ones featuring insulated stratified glazing and frames with thermal break	X		
	Manual opening	W.2	Adoption of automatic opening systems	X		
	Lack of shading solutions	W.3	Installation of solar shading systems, both fixed or automatized	X		X

Industrial doors	Inadequate thermal insulation Compromised airtightness	W.4	Installation of new insulated sectional doors or industrial openings	X		X
ROOFING STRATIGRAPHY						
Current state		**Retrofit strategy**		**Target performance**		
Structure	**Completion solution**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Metal double sloped or arched trusses	Asbestos panel + thermal insulation + asbestos corrugated panel	RS.3	Existing trusses removal and substitution with newly designed ones		X	
		R.4	Insulated false-ceiling installation	X		X
		R.5	Substitution of completion stratigraphy with metal sandwich panels	X	X	X
		R.6	R.5 + cool roof membrane finishing	X		
Skylights						
Current state		**Retrofit strategy**		**Target performance**		
Skylight configuration		**Code**	**Measure**	**En.**	**Str.**	**Ar.**
Inserted skylights		Sk.1	Redefinition of skylights layout	X	X	X
		Sk.2	Substitution of transparent portions with state-of-the-art polycarbonate panes	X	X	
		Sk.3	Replacement of frames components	X		

6.2 Sloped roof with precast double slope beams (Sl_rc_slb variant)

Table 6.2 Table 6.1 Retrofit protocol for Sl_rc_slb variant buildings. *Source: elaboration of the author.*

DISTRICT SCALE and OUTDOOR AREAS					
Retrofit strategy		**Target performance**			
Code	**Measure**	**Env. / Climate**	**Energy**	**Struct.**	**Archit.**
Ur.1	Cool pavement installation	X			
Ur.2	Trees planting / Vegetation implementation	X	X		
Ur.3	De-paving and flowerbeds installation	X			

EXTERNAL WALLS						
Current state		**Retrofit strategy**		**Target performance**		
Technology	**Position**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Masonry / Built in place infills	Inserted	EW.1	Substitution with sandwich panels	X	X	X
Horizontal precast panels		EW.2	Substitution with Aquapanel panels	X	X	X
Horizontal precast panels or Vertical precast panels	External	EW.1	Substitution with sandwich panels	X	X	X
		EW.2	Substitution with Aquapanel panels	X	X	X
		EW.3	Installation of internal insulated counter-walls	X		
		EW.4	External recladding with sandwich panels	X		X
		EW.5	External recladding with ETICS	X		X
		EW.6	External recladding with Vêture system	X		X
		EW.7	Recladding with rainscreen façades			X
		EW.8	Recladding with metal meshes			X
		EW.9	Recladding with BIPV components	X		X
		EW.10	Addition of indirect green façades	X		X
		EW.11	Partial substitution with curtain walls	X		X
Windows and openings						

Current state		Retrofit strategy		Target performance		
Element	**Criticalities**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Windows	Single glass pane Wired glass Frame no thermal break Bad airtightness	W.1	Substitution of existing windows with new ones featuring stratified glazing and frames with thermal break	X		
	Manual opening	W.2	Adoption of automatic opening systems	X		
	Lack of shading solutions	W.3	Installation of solar shading systems, both fixed or automatized	X		X
Industrial doors	Inadequate thermal insulation Compromised airtightness	W.4	Installation of new insulated sectional doors or industrial openings	X		X
ROOFING STRATIGRAPHY						
Current state		**Retrofit strategy**		**Target performance**		
Structure	**Completion solution**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
π slabs (+r. c. slab)	+ finishing Or +thermal insulation + finishing	RS.1	Precast beams removal and substitution with metal trusses		X	
		RS.2	π slabs removal and substitution with metal sandwich panels	X	X	
		R.1	Insertion/substitution of thermal insulation and external finishing	X		X
		R.2	Recladding with metal sandwich panels	X	X	X
		R.3	RS.2 + Extensive green roof installation	X	X	X
		R.4	Insulated false-ceiling installation	X		X
		R.5	RS.2/R.1/R.2 + cool roof membrane installation	X		
Precast reinforced concrete purlins	+ asbestos panel + thermal insulation + asbestos	RS.1	Precast beams removal and substitution with metal trusses		X	
		R.5	Substitution of completion stratigraphy with metal sandwich panels	X	X	X

	corrugated panel Or + asbestos panel + asbestos corrugated panel	R.3	R5. + Extensive green roof installation	X	X	X
		R.4	Insulated false-ceiling installation	X		X
		R.6	R.5 + cool roof membrane installation	X		
Skylights						
Current state		**Retrofit strategy**		**Target performance**		
Skylight configuration		**Code**	**Measure**	**En.**	**Str.**	**Ar.**
Inserted skylights		Sk.1	Redefinition of skylights layout	X	X	X
		Sk.2	Substitution of transparent portions with state-of-the-art polycarbonate panes	X	X	
		Sk.3	Replacement of frames components	X		

6.3 Plain roof with precast beams (P_rc_b variant)

Table 6.3 Retrofit protocol P_rc_b variant buildings. *Source: elaboration of the author.*

DISTRICT SCALE and OUTDOOR AREAS					
Retrofit strategy		**Target performance**			
Code	**Measure**	**Env. / Climate**	**Energy**	**Struct.**	**Archit.**
Ur.1	Cool pavement installation	X			
Ur.2	Trees planting / Vegetation implementation	X	X		
Ur.3	De-paving and flowerbeds installation	X			

EXTERNAL WALLS						
Current state		**Retrofit strategy**		**Target performance**		
Technology	**Position**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Masonry / Built in place infills	Inserted	EW.1	Substitution with sandwich panels	X	X	X
Horizontal precast panels		EW.2	Substitution with Aquapanel panels	X	X	X
Horizontal precast panels or Vertical precast panels	External	EW.1	Substitution with sandwich panels	X	X	X
		EW.2	Substitution with Aquapanel panels	X	X	X
		EW.3	Installation of internal insulated counter-walls	X		
		EW.4	External recladding with sandwich panels	X		X
		EW.5	External recladding with ETICS	X		X
		EW.6	External recladding with Vêture system	X		X
		EW.7	Recladding with rainscreen façades			X
		EW.8	Recladding with metal meshes			X
		EW.9	Recladding with BIPV components	X		X
		EW.10	Addition of indirect green façades	X		X
		EW.11	Partial substitution with curtain walls	X		X

Windows and openings						
Current state		**Retrofit strategy**		**Target performance**		
Element	**Criticalities**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Windows	Single glass pane Wired glass Frame no thermal break Bad airtightness	W.1	Substitution of existing windows with new ones featuring stratified glazing and thermal break	X		
	Manual opening	W.2	Adoption of automatic opening systems	X		
	Lack of shading solutions	W.3	Installation of solar shading systems, both fixed or automatized	X		X
Industrial doors	Inadequate thermal insulation Compromised airtightness	W.4	Installation of new insulated sectional doors or industrial openings	X		X
ROOFING STRATIGRAPHY						
Current state		**Retrofit strategy**		**Target performance**		
Structure	**Completion solution**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Y-section arched beams	Extrados: fibre cement vaulted panels Intrados: : fibre cement panels counter-ceiling with insulation layer	RS.1	Precast beams removal and substitution with metal trusses		X	
		R.2	RS.1 + Recladding with metal sandwich panels	X	X	X
		R.4	Insulated false-ceiling installation	X		X
		R.6	Substitution of extrados completion panels with sandwich panels with TPO finishing; internal counter-ceiling removal.	X	X	X
		R.7	R.6 + installation of fire-proof false-ceiling	X	X	X
Skylights						
Current state		**Retrofit strategy**		**Target performance**		
Skylight configuration		**Code**	**Measure**	**En.**	**Str.**	**Ar.**

Inserted skylights	Sk.1	Redefinition of skylights layout	X	X	X
	Sk.2	Substitution of transparent portions with state-of-the-art polycarbonate panes	X	X	
	Sk.3	Replacement of frames components	X		
	Sk.4	Replacement of existing skylights with shed-ones	X	X	x

6.4 Plain roof with precast tiles (P_rc_t variant)

Table 6.4 Retrofit protocol for P_rc_t variant buildings. *Source: elaboration of the author.*

DISTRICT SCALE and OUTDOOR AREAS						
Retrofit strategy				**Target performance**		
Code	**Measure**			**Env. / Climate**	**Energy**	**Struct.**	**Archit.**
Ur.1	Cool pavement installation			X			
Ur.2	Trees planting / Vegetation implementation			X	X		
Ur.3	De-paving and flowerbeds installation			X			
EXTERNAL WALLS						
Current state		**Retrofit strategy**		**Target performance**		
Technology	**Position**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Masonry / Built in place infills	Inserted	EW.1	Substitution with sandwich panels	X	X	X
		EW.2	Substitution with Aquapanel panels	X	X	X
Horizontal precast panels or Vertical precast panels	External	EW.1	Substitution with sandwich panels	X	X	X
		EW.2	Substitution with Aquapanel panels	X	X	X
		EW.3	Installation of internal insulated counter-walls	X		
		EW.4	External recladding with sandwich panels	X		X
		EW.5	External recladding with ETICS	X		X
		EW.6	External recladding with Vêture system	X		X
		EW.7	Recladding with rainscreen façades			X
		EW.8	Recladding with metal meshes			X
		EW.9	Recladding with BIPV components	X		X
		EW.10	Addition of indirect green façades	X		X
		EW.11	Partial substitution with curtain walls	X		X
Windows and openings						

Current state		Retrofit strategy		Target performance		
Element	**Criticalities**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Windows	Single glass pane Wired glass Frame no thermal break Bad airtightness	W.1	Substitution of existing windows with new ones featuring stratified glazing and thermal break	X		
	Manual opening	W.2	Adoption of automatic opening systems	X		
	Lack of shading solutions	W.3	Installation of solar shading systems, both fixed or automatized	X		X
Industrial doors	Inadequate thermal insulation Compromised airtightness	W.4	Installation of new insulated sectional doors or industrial openings	X		X
ROOFING STRATIGRAPHY						
Current state		**Retrofit strategy**		**Target performance**		
Structure	**Completion solution**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Precast roofing tiles	Fibre-cement vaulted panels Or Sandwich completion panels	R.1	Insertion/substitution of thermal insulation and external finishing	X		
		R.4	Insulated false-ceiling installation	X		X
		R.5	Substitution of completion elements with metal sandwich panels	X	X	X
		R.6	R1 / R.5 + cool roof membrane installation	X		
Skylights						
Current state		**Retrofit strategy**		**Target performance**		
Skylight configuration		**Code**	**Measure**	**En.**	**Str.**	**Ar.**

Inserted skylights	Sk.1	Redefinition of skylights layout	X	X	X
	Sk.2	Substitution of transparent portions with state-of-the-art polycarbonate panes	X	X	
	Sk.3	Replacement of frames components	X		
	Sk.4	Replacement of existing skylights with shed-ones	X	X	x

6.5 Shed roof with precast tiles (Sh_rc_t variant)

Table 6.5 Retrofit protocol for Sh_rc_t variant buildings. *Source: elaboration of the author.*

DISTRICT SCALE and OUTDOOR AREAS						
Retrofit strategy			**Target performance**			
Code	**Measure**		**Env. / Climate**	**Energy**	**Struct.**	**Archit.**
Ur.1	Cool pavement installation		X			
Ur.2	Trees planting / Vegetation implementation		X	X		
Ur.3	De-paving and flowerbeds installation		X			
EXTERNAL WALLS						
Current state		**Retrofit strategy**		**Target performance**		
Technology	**Position**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Horizontal precast panels or Vertical precast panels	External	EW.1	Substitution with sandwich panels	X	X	X
		EW.2	Substitution with Aquapanel panels	X	X	X
		EW.3	Installation of internal insulated counter-walls	X		
		EW.4	External recladding with sandwich panels	X		X
		EW.5	External recladding with ETICS	X		X
		EW.6	External recladding with Vêture system	X		X
		EW.7	Recladding with rainscreen façades			X
		EW.8	Recladding with metal meshes			X
		EW.9	Recladding with BIPV components	X		X
		EW.10	Addition of indirect green façades	X		X
		EW.11	Partial substitution with curtain walls	X		X
Windows and openings						
Current state		**Retrofit strategy**		**Target performance**		
Element	**Criticalities**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**

Windows	Single glass pane Wired glass Frame no thermal break Bad airtightness	W.1	Substitution of existing windows with new ones featuring stratified glazing and thermal break	X		
	Manual opening	W.2	Adoption of automatic opening systems	X		
	Lack of shading solutions	W.3	Installation of solar shading systems, both fixed or automatized	X		X
Industrial doors	Inadequate thermal insulation Compromised airtightness	W.4	Installation of new insulated sectional doors or industrial openings	X		X
ROOFING STRATIGRAPHY						
Current state		**Retrofit strategy**		**Target performance**		
Structure	**Completion solution**	**Code**	**Measure**	**Energy**	**Struct.**	**Archit.**
Precast roofing tiles	Fibre-cement vaulted panels Or Sandwich completion panels	R.1	Insertion/substitution of thermal insulation and external finishing	X		
		R.4	Insulated false-ceiling installation	X		X
		R.5	Substitution of completion elements with metal sandwich panels	X	X	X
		R.6	R.5 + cool roof membrane installation	X		
Skylights						
Current state		**Retrofit strategy**		**Target performance**		
Skylight configuration		**Code**	**Measure**	**En.**	**Str.**	**Ar.**
Emerging skylights		Sk.5	Replacement of windowed portions with glass panes complying with current prescriptions			X
		Sk.6	Substitution/Thermal insulation of opaque components in shed skylights structure	X	X	

6.6 Economic evaluation of the retrofit solutions considered in the research

In order to evaluate the economic impact and feasibility of the retrofit actions mentioned in the retrofit protocol outlined in the previous section, a detailed analysis was performed to compare various redevelopment interventions for the external envelope and the conditioning system. The study was specifically tailored on the peculiarities of the P_rc_b typology, making reference to the same case study introduced in section 5.2.3.1. This choice was meant to focus on the most widespread typology retrieved at regional scale. This part of the research aims at the identification of the most cost-effective measure, based on a Life Cycle Cost analysis and analysing the payback period of each scenario. Figure 6.1 illustrates the methodology used in this part of the research.

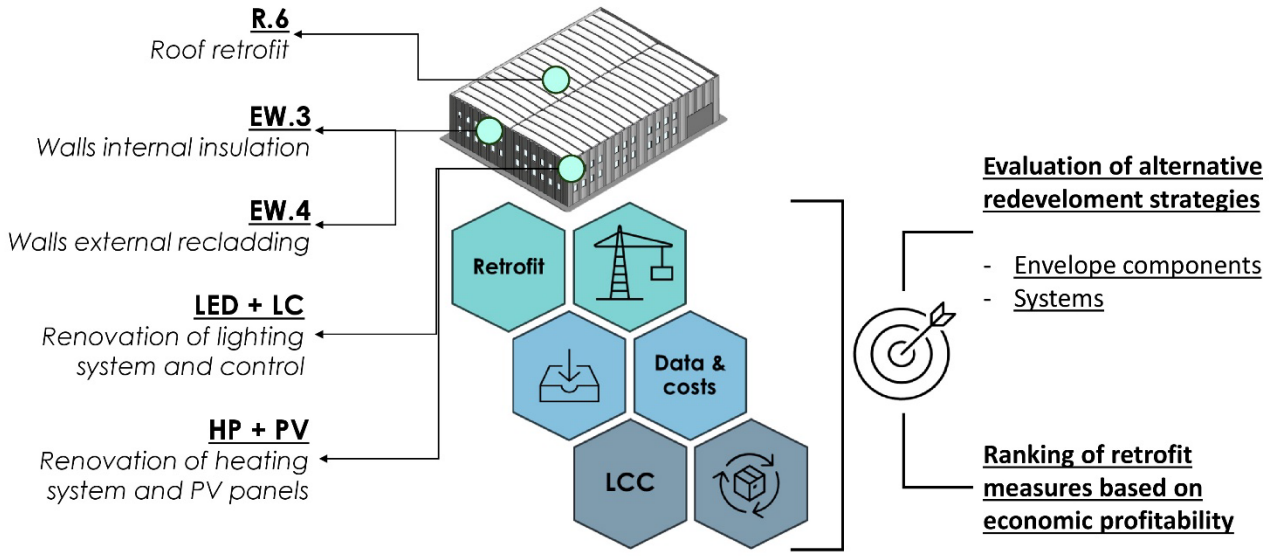


Figure 6.1 Research workflow adopted for LCC evaluations. *Source: elaboration of the author.*

The retrofit measures evaluated in this case, were selected to address both envelope and system installations. In particular, EW.3, EW.4, R.6 interventions from the protocol addressing this building type were included in this analysis as they emerged as the most likely to be used with limited interruptions of working activities. For EW.3 and EW.4, the dismantling and replacement of windows currently in place was also foreseen. Along with them, acting on the lighting and heating system was also considered. For the former, the substitution of current fluorescent lamps with LED ones and the installation of a lighting control system was analysed. An air-source-heat pump coupled with PV panels on the roof was hypnotized to replace the current outdated heating system. The main characteristic of the retrofit solutions evaluated are reported in Table 6.6.

Table 6.6 Details about the retrofit solutions evaluated. *Source: elaboration of the author.*

Id.	Measure	Technological solution	Properties of the element in retrofit conditions
EW.3	Retrofit of the external walls without demolishing the existing ones	Installation of internal insulated counter-walls (Thermal insulation: rock wool)	U = 0.272 W/m²K Surface mass = 145 kg/m²
EW.4	Retrofit the external walls without demolishing the existing ones	External recladding with sandwich panels (Thermal insulation: polyurethane)	U = 0.247 W/m²K Surface mass = 118 kg/m²
R.6	Demolition of the external fibre cement panels with asbestos and substitution of the existing roof	External sandwich panels (Thermal insulation: polyurethane)	U = 0.209 W/m2K Surface mass = 15 kg/m²
HP + PV	Installation of a reversible air-to-air heat pump (100 Kw) and flexible photovoltaic panels (230 modules - 0.165 kWp/item)		
LED + LC	Installation of LED lamps with (Radiant fraction = 15%, Visible fraction = 15%)		

Each retrofit scenario was modelled in the DesignBuilder environment to produce energy simulations and derive the annual energy operational costs.

The cost for each element to be included in the LCC calculation was derived from the following sources:

- Recognised Italian regional price lists [1][2];
- DEI price list (2022) [3][4];-
- Producer's website.

The cost of energy for the calculation of the operational cost was established according to ARERA and it is equal to 0.123 €/kWh for electricity and 0.355 €/Sm^3 for natural gas. As for maintenance cost, when not considered in the mentioned price lists, a percentage of the initial investment cost was assumed as annual expenditure. The prices used in the analysis are collected in Table 6.7

Table 6.7 Price list used in the study. *Source: elaboration of the author.*

Retrofit measure	Component	Initial investment cost	Dismantling cost	Disposal cost	Maintenance	Expected lifetime	Quantity
EW.3	Plasterboard panel	56.80 €/m²	9.32 €/m²	17.5 €/m²	-	20 years	2518 m²
	Rock wool	38.34 €/ m²	1.91 €/m²	710.73 €/m²	-	20 years	1259 m²
	Finishing	8.56 €/ m²	9.32 €/m²	Included in plasterboard panel cost	-	20 years	1259 m²
	Substructure	1.37 €/m	Included in plasterboard panel		-	20 years	2058 m
	Windows	700 €/m²	21.59 €/m²	17.5 €/m²	3.5 €/m²year	20 years	114 m²
EW.4	Sandwich panels	85.29 €/m²	10.77 €/m²	17.5 €/m²	-	20 years	900 m²
	Substructure	1.37 €/m	Included in sandwich panels cost		-	20 years	711 m
	Windows	700 €/m²	21.59 €/m²	17.5 €/m²	3.5 €/m²year	20 years	114 m²
R.6	Sandwich panels	95.17 €/m²	10.77 €/m²	17.5 €/m²	-	20 years	1136 m²
	Polycarbonate Skylights	200 €/m²	16.36 €/m²	389.42 €/Ton	3.5 €/m²year	20 years	28 m² (2.7 kg/ m²)
	Demolition of existing polycarbonate skylights	-	16.36 €/m²	389.42 €/Ton	-	20 years	28 m² (2.7 kg/ m²)
	Demolition of asbestos panels	-	16.43 €/m²	733.17 €/Ton	-		11.17 m³ (0.01 m thick)
HP + PV	HP (100 kW) + 230 modules of semi-flexible PV (0.165 kWp/item)	25000 €/unit + 800 €/unit	20%(Ci) + 60.98 €/kWp	100 €/Ton	129 €/item*year + 120.7 €/item*year	15 years / 25 years	1-unit HP + 130 PV items
	Inverter	1278.386 €/unit	20%(Ci)	0.90 €/kg	2% (Ci)	10 years	20 -unit (21 kg/unit)
	Demolition of the existing condensing boiler	-	110.32 €	100 €/Tn	-		1-unit
LED + LC	43-unit LED + 6-unit lighting management control	246.93 €/unit + 50 €/unit	20%(Ci)	0.30 €/kg	2% (Ci)	10 years	21-unit LED + 6-unit light sensors (4.34 kg)
	Demolition of Fluorescent lamps	-	49.38 €/item	0.90 €/kg	-		60-unit

In addition, to account for all the costs related to construction works, other expenses were considered and quantified in the LCC analysis. Labour cost was evaluated for both qualified and specialized workers, 36.30 €/p-hour and 39.06 €/p-hour respectively. All the necessary lifting and height-access equipment and machinery were also estimated as it follows. For cranes and platforms, a cost of 7.6 €/hour and 5.53 €/hour was considered, while scaffolding and lifting towers were assumed to cost 21.68 €/m^2 and 35.18 €/m^2 based on average values derived from the cited price lists.

The LCC analysis was conducted assuming a remaining 20-year operational lifetime for the manufacturing building and following the guidelines of ISO 15686:2017 [5]. All of the components with a shorter lifespan were hence supposed to be substituted in this time shift and replacement costs were added in the overall balance. As for the global cost, it was determined in accordance with UNI EN 15459:2018 [6] using the following equation:

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) * R_d(i) \right) - V_{f,\tau}(j) \right]$$

- $C_G(\tau)$: global cost (starting year)
- C_I : initial investment cost;
- $C_{a,i}(j)$: annual cost of component *j* during year *i*, obtained considering:
    - C_O operational cost,
    - C_m maintenance cost;
    - C_r replacement cost;
    - C_{dm} dismantling cost;
    - C_{dp} disposal cost;
- $R_d(i)$: discount factor for year *I*:
- $V_{f,\tau}(j)$: residual value of the component *j* at the end of the lifetime (20 years).

In particular, the discount factor $R_d(i)$ was calculated according to the formula:

$$R_d(p) = (\frac{1}{1+\frac{r}{100}})^p$$

Where p stand for the year of the calculation and the real discount rate (r) was assumed equal to 3%.

The necessary calculations were performed by defining a semi-automatized calculation sheet in Excel environment, which allowed to effortlessly deal with the different ranges of units, quantities and related costs for each solution and component of the stratigraphy or system equipment. The calculation tool, qualitatively illustrated in Figure 6.2, was autonomously drafted as part of the research effort and can be easily implemented for different applications.

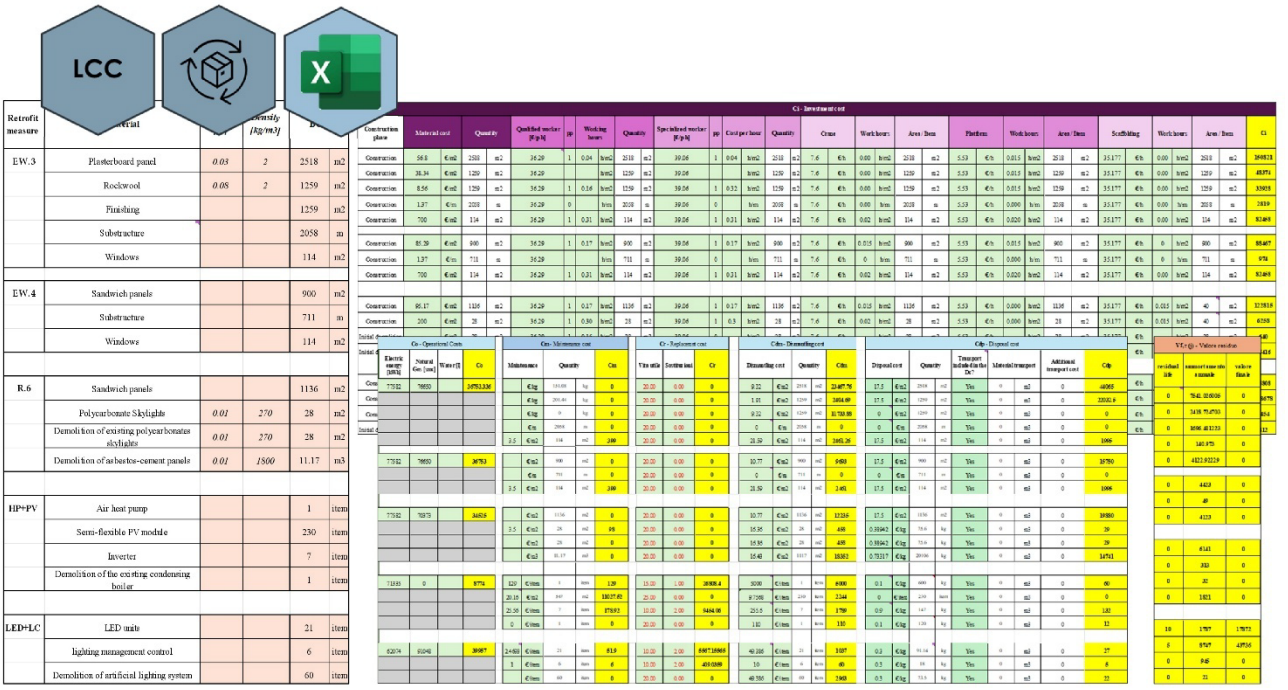
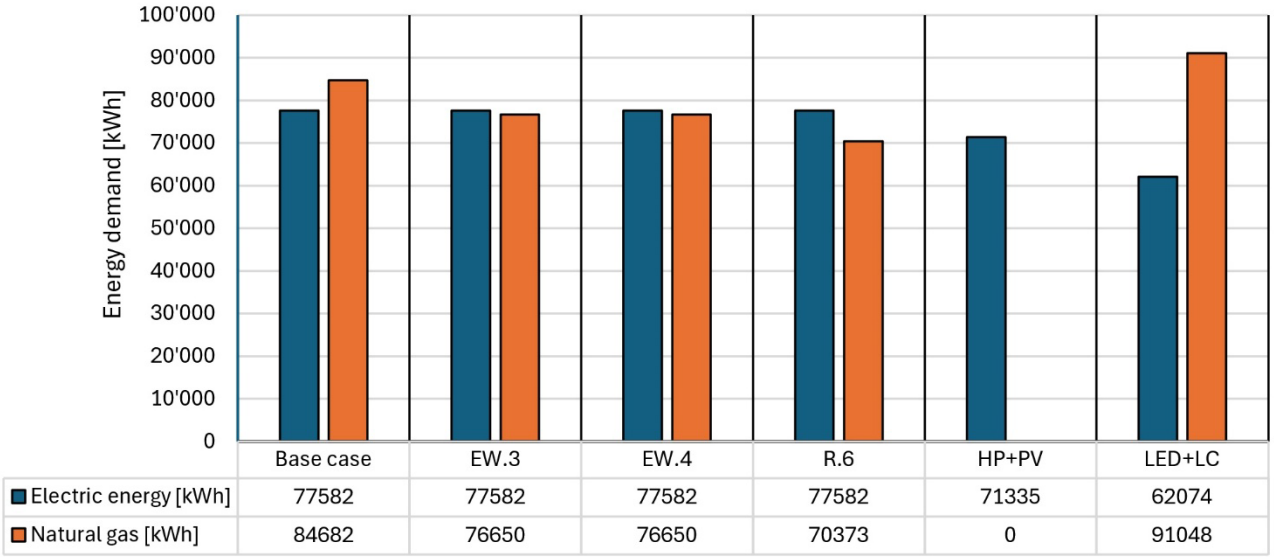


Figure 6.2 Excel calculation worksheet for LCC analysis. *Source: elaboration of the author.*

To quantify the energy savings ensured by each intervention strategy, the case study building was modelled in DesignBuilder to produce energy simulations for both the existing conditions and the retrofit states. Notably, even if the energy simulations were performed with a simplified approach, roof redevelopment proved to be more effective than enhancing the thermal resistance of external walls and gas heating energy savings amount to 17% and about 10%, respectively. No savings in terms of electric energy can be registered in these cases, while acting on the system installations proved to be highly beneficial in that sense. Following the installation of PV modules and heat pump for space heating, the total electric energy consumption decreases by about 9% with respect to current conditions, where it is simply used for lighting and machinery. Conversely, while resulting in a consistent reduction of electricity consumption (-20%), LED installation leads to an increased energy

demand for heating, due to the lower radiant fraction of the new lamps. Figure 6.3 illustrates these findings in both graphical representation and table form.



	Base case	EW.3	EW.4	R.6	HP+PV	LED+LC
Electric energy [kWh]	77582	77582	77582	77582	71335	62074
Natural gas [kWh]	84682	76650	76650	70373	0	91048

Figure 6.3 Energy simulation results. *Source: elaboration of the author.*

Coming to the evaluation of the global cost of the different configurations, the main results of the analysis are reported in Table 6.8 and illustrated in graph form in Figure 6.4 and 6.5. Along with the total global cost, the contribution of each phase is highlighted to allow for in-depth considerations. Notably, the different retrofit solutions are characterized by remarkable differences in terms of both global overall cost and its composition. Envelope-related interventions are characterized by significative global costs, higher than the ones of measures targeting systems installation.

Table 6.8 Results of Global cost calculation. In the headings: Ci stands for initial investment cost, Co stands for Operational costs, Cm for maintenance costs, Cr for replacement costs, Cdm for dismantling costs, Cdp for disposal costs, Vf for residual final value, Cg for global cost. *Source: elaboration of the author.*

	Ci [€]	**Co [€]**	**Cm [€]**	**Cr [€]**	**Cdm [€]**	**Cdp [€]**	**Vf [€]**	**Cg [€]**
EW.3	318'401	546'797	5'936	-	22'184	37'701	-	931'020
EW.4	171'899	546'797	5'936	-	6'730	9'825	-	741'187
R.6	166'130	513'645	1'458	-	7'028	11'023	-	699'284
HP+PV	255'353	130'538	168'643	17'207	3'209	39	61'608	513'381
LED+LC	9'507	594'461	861	7'225	1'346	35	-	613'436

For the building envelope, improvements to the roof's stratigraphy are recommended over those targeting the external walls from an economic standpoint too. In fact, R.6 scenario is characterized by the lowest global cost, due to the lower initial investment and it guarantees a more significant reduction of the operational costs thanks to the higher energy efficiency ensured. In the initial expenses, the disposal of asbestos panels were also included. Among the wall retrofit options, the installation of an internal false wall (E.W3) proves to be the least cost-effective measure in terms of total lifecycle cost. In contrast, the alternative external wall improvement (EW.4). It offers both economic and aesthetic advantages. Its external installation enhances the visual appeal of the industrial facility while reducing finishing costs, thanks to the prefabricated nature of the solution. Moreover, due the simpler technology used, it significantly reduces the effort necessary during the dismantling and disposal stages at the end of life. When considering external wall redevelopment, the replacement of windows represents one of the most significant cost factor, contributing approximately €700/m² to the overall budget.

Acting on systems allows to reduce the overall global cost of the retrofit intervention. Regarding the redevelopment measure incorporating renewable energy sources (heat pump and photovoltaic system - HP+PV), the initial cost is higher than the LED-based intervention due to the substantial investment required for the PV system, amounting to about 220'000 €. Furthermore, this configuration boasts the highest residual value, given that the PV panels have a lifespan of 25 years. Despite this, the reduced operational cost ensured by the savings connected to the annual energy demand makes this retrofit scenario particularly convenient in terms of global costs. Conversely, the retrofit solution involving the replacement of existing fluorescent lamps with LED lighting and sensors emerges as particularly profitable because of the limited resources required in the initial stages. In fact, this solution is characterized by the lowest initial investment cost compared to all the other configurations. Despite requiring at least one replacement of LED lighting and sensors over the building's lifetime (after approximately 10 years), these additional costs are outstood by the savings in electric energy.

Some general considerations can be derived from the global cost calculations carried out. At first, it is important to emphasize that operational costs (Co) represent one of the most significant contributors to the total cost for industrial facilities. However, this trend differs in the HP+PV scenario due to the integration of an air-to-air heat pump, which eliminates natural gas consumption costs.

In terms of maintenance costs (Cm), the PV modules require an annual maintenance to ensure the proper functionality and avoid decays in their efficiency, whereas the LED+LC intervention incurs almost no maintenance costs. Meanwhile, maintenance requirements for external envelope improvements are limited to window components or exceptional damages. Additionally, dismantling and disposal costs have a minimal impact on the total global cost.

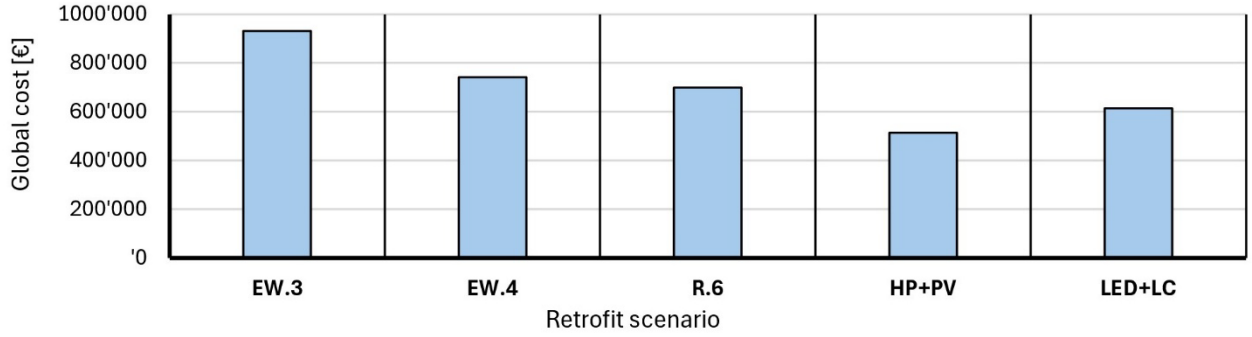


Figure 6.4 Global cost associated to each Retrofit scenario following the LCC calculation. *Source: elaboration of the author.*

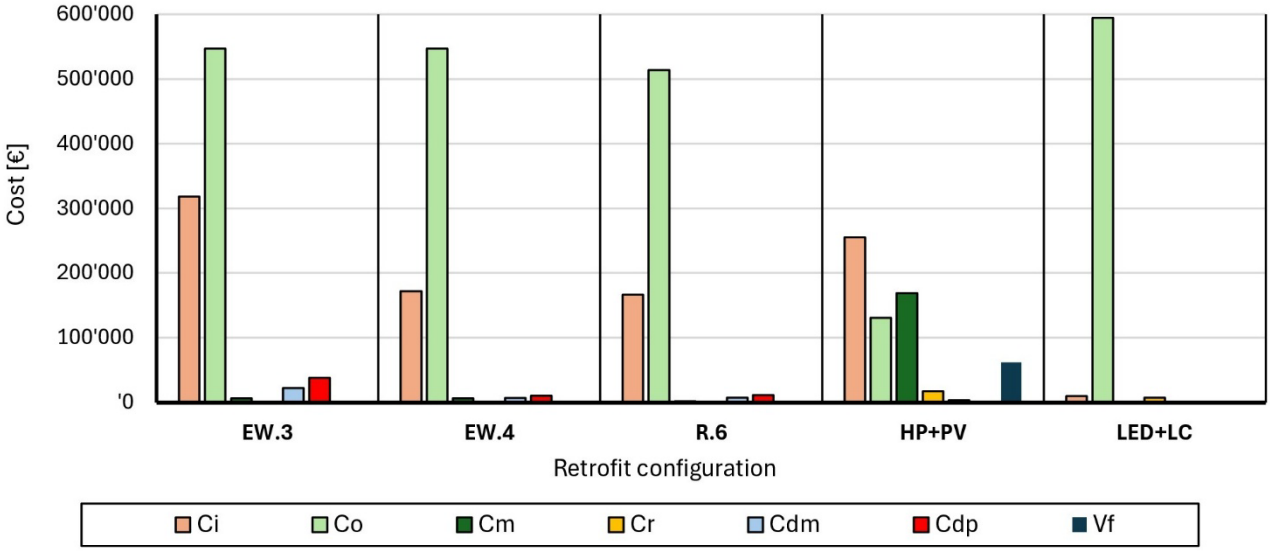


Figure 6.5 Share of the different expenditure categories in each retrofit scenario. *Source: elaboration of the author.*

The comparative analysis was deepened to evaluate the expected payback period for the different retrofit options, taking into account the initial investment, the replacement costs over time and the energy savings ensured on annual basis. The results are illustrated in Figure 6.6.

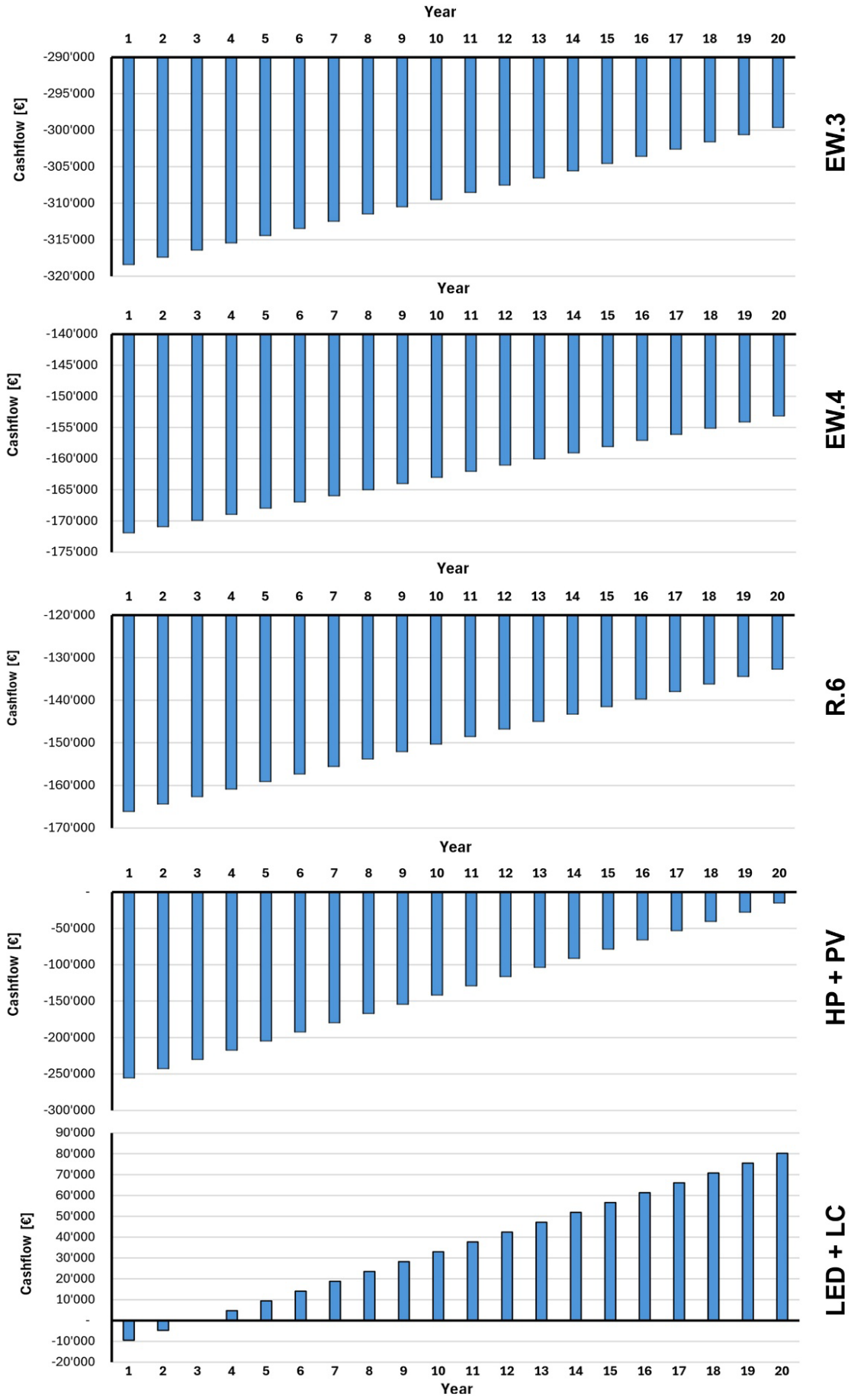


Figure 6.6 Payback period for the considered retrofit scenarios. *Source: elaboration of the author*.

As evident from the graphs, LED+LC is the only solution characterized by an early, almost immediate, break-even point which is reached after 2 years from installation. This result is justified by the extremely reduced initial investment required and the considerable savings in terms of energy demand for lighting purposes. The installation of heat pump and PV modules, despite the considerable installation costs, has a payback period of about 22 years due to the relevant energy savings and the recurs to on-site energy production. Notably, this analysis does not account for the potential financial benefits derived from surplus energy generated by the onsite PV system. In the solutions leading to building envelope redevelopment the initial investment outstands the reduction of annual operational costs, leading to considerable payback periods.

To sum up the main findings obtained, the following conclusions can be noted. Based on the life-cycle cost (LCC) analysis conducted on an industrial building retrofit, the study let to identify the most cost-effective intervention strategies. Renovating the lighting system emerges as the optimal solution due to its low initial investment and a short payback period of two years. In contrast, upgrading the heating system with heat pumps and photovoltaic modules (HP+PV) results in higher upfront costs and a lengthy 20-year payback period. The findings highlight that combining lighting and heating upgrades would provide the best cost-effectiveness. Coming to external envelope solutions, roof insulation is preferable over wall insulation due to reduced installation complexity and the enhanced energy performance. The internal insulation through the installation of a gypsum-fibre counter wall, poses the greatest technical and construction challenges, leading to higher initial investment costs. However, energy savings alone may not justify the considerable initial costs of extensive interventions. The study underscores the necessity of balancing initial investment and operational savings to ensure financial feasibility and maximize cost-effectiveness.

Additionally, the research highlights that financial incentives and institutional support should play a pivotal role in promoting the adoption of retrofit solutions, particularly for interventions with substantial initial costs. Government policies, subsidies, and regulatory frameworks can help mitigate the current financial barriers, making energy-efficient retrofitting more accessible and attractive to stakeholders. Without such support, businesses may be reluctant to pursue significant upgrades, despite their potential for long-term energy and cost savings.

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7 CONCLUSIONS

7.1 Summary and conclusions

The research aimed at defining a guideline to be adopted in the design of redevelopment interventions on the existing industrial building stock, with reference to precast concrete facilities given their widespread diffusion. In the perspective of integrated redevelopment of buildings currently affected by several deficiencies, different retrofit measures addressing energy, environment, architecture, and technology aspects were proposed and their impact evaluated.

The existing industrial building stock is particularly vulnerable given the old age of construction of the structures currently in use, the outdated construction technologies adopted, the energy intensive systems installed, and the poor aesthetical appeal of the productive facilities. Because of the loose regulation framework in force at the time of construction, the majority of these facilities are nowadays not in line with current prescriptions in terms of energy and environmental performance required for buildings at both National and European level.

An extensive and exhaustive survey of the existing industrial building stock typical of Tuscany was performed in the initial stages of the research, focusing on two different macro-areas within the regional borders. At his stage, a series of both virtual and on-field inspections were carried out to collect both qualitative and quantitative data at building level. At the same time, direct interactions with owners of the buildings or companies currently using them were held to derive information about the operative conditions, energy consumptions, and requirements to be fulfilled in case of retrofit interventions.

The post-processing of the data collected, allowed to highlight the main distinguishing features of these peculiar class of buildings and to point out recurrent typological variants, based on both structural and architectural aspects. This preliminary step was crucial for the development of the research, providing a solid knowledge base to deepen the subsequent analysis.

Based on the peculiarities of each variant, tailored retrofit measures were hence outlined: interventions at both urban and building levels were included in the analysis, to ameliorate not only the energy performance of single facilities but also the environmental conditions and architectural quality in industrial districts. Given the current deficiencies of the envelope components particular

attention was paid to the definition of their enhancement, considering strategies customizable and scalable according to design requirements and constraints. External walls, windows, roof and skylights were analysed individually to better adapt the retrofit solutions to the features of the single typological variants. Systems installations were also analysed: given the outdated solutions currently adopted for winter heating and the considerable internal volumes to be conditioned, the associated energy consumption are extremely relevant in the energy balance of these facilities.

The energy saving potential of each measure was evaluated by considering a series of representative case study and performing multidisciplinary simulations. Environmental simulations were carried out at a district scale while building energy models were produced to analyse the energy performance at building level. Other aspects such as thermal and visual comfort were also investigated, foreseeing the adoption of smart solutions to enhance the indoor conditions. In this regard, mitigation of possible summer overheating was analysed, as well as the influence of skylights distribution and the associated lighting energy saving achievable.

The retrofit scenarios outlined and validated were finally collected and organized in a comprehensive redevelopment protocol, declined according to the typological variants retrieved on the territory. While it remains essential to conduct case-specific assessments for each individual building, the methodology adopted has enabled the generalization of the research findings, making them scalable and replicable across a large number of facilities. This generalization offers a dual advantage: on one hand, it allows for the application of highly adaptable design solutions in diverse contexts; on the other, it promotes the widespread implementation of optimized practices for building retrofits, thereby contributing to a systemic improvement of the existing building stock.

In conclusion, the key points of the research can be synthesized as follows:

- An extensive territorial analysis was carried out to assess the main features of the existing industrial buildings stock in Tuscany. More than 2000 long span facilities have been retraced and examined, with particular focus on the ones hosting productive activities that represent about 60% of the total. A detailed assessment was hence produced to outline the prevalent geometrical features, the mainly adopted technological solutions and the recurrent features.

- The majority of industrial buildings in both Casentino and Mugello were built before the first half of the 80’s. Precast concrete construction systems emerged as the reference solution for

this kind of facilities, especially in the Casentino area due the presence of local precast producer companies. On the other hand, Mugello clearly exhibits construction solutions widely adopted in Northern Italy and a consistent share of cast in place buildings.

- 6 different typological variants were defined according to the structural layouts and components and roofing solutions, addressed as key distinguishing features for buildings classifications. A clear evolutionary trend was highlighted from both dimensional and technological point of view. Typologies fostering steel framed roofing structures are referrable to dated facilities, progressively replaced by precast concrete solutions allowing to cover wider areas.

- Starting from the typological variants retraced, issues and criticalities were investigated at both urban and building level:

    - In older industrial districts, the dense construction density causes numerous challenges such as inadequate manoeuvring and a lack of open spaces for shared functions like parking and storage. The architectural and aesthetic quality of these environments is often low, with excessive paved and built surfaces exacerbating UHI effects. The absence of greenery and insufficient draining surfaces increase the risk of flooding, while air quality suffers from industrial processes and heavy vehicles traffic, affecting the environmental quality.

    - The visual-aesthetic quality of many buildings is compromised by poor architectural design of the external walls, frequently realized with precast panels. Energy performance is inadequate for modern standards, due to insufficient thermal insulation, thermal bridges, and concerns about air and water leakages. From a structural standpoint, the heavy mass of precast cladding panels can negatively affect the building's response, with potential failures in connections and rocking effects during earthquakes. Additionally, windowed portions often have single non insulated pane, poor frames, and low airtightness, further reducing energy efficiency and comfort levels in indoor environments.

    - Similar deficiencies affect roofing components. From an energy perspective, roofs often suffer from inadequate thermal insulation, compromised airtightness, and

thermal bridges caused by precast roofing beams. Moreover, the use of fibre-cement panels that may contain asbestos can induce further health and environmental risks from. Seismically, the heavy mass of precast components at the top of buildings represents a detrimental factor for structural response under horizontal actions. Skylights in older buildings, commonly made of polycarbonate panes, offer poor energy performance, and insufficient airtightness.

- Systems and installations include the widespread use of outdated unit heaters, which are energy intensive, inefficient and lack control mechanisms. Heat recovery systems are generally absent, while cooling needs are often neglected. Fluorescent lighting is still prevalent, with LED systems still rarely adopted. Automation via sensors for system control is missing, leading to inefficient operations. Energy supply remains heavily reliant on fossil fuels and grid electricity, and nearly 90% of the facilities investigated have no renewable energy production systems from solar source in place.

- On these premises, retrofit measures were drafted and their potential impacts estimated:
  - Cool pavements are highly effective at lowering outdoor air temperatures, reducing district-wide temperatures by 0.45°C, though they may increase building surface temperatures due to higher reflectivity. Trees and green walls help mitigate this by shading façades and reducing mean radiant temperatures by up to 9°C locally. Green roofs lower air temperatures by up to 1.5°C and improve energy performance by cooling roofing surfaces. While tree planting primarily benefits local microclimates, both trees and green roofs enhance air quality by capturing pollutants and particulate matter.
  - Actions on existing buildings were examined referring to real existing case study buildings and producing dedicated energy models using DesignBuilder, under current and retrofit conditions. Roofs, identified as major heat loss contributors, should be prioritized for retrofit interventions, guaranteeing up to 18% energy savings in winter. Combined interventions on roof and walls could reduce energy demand by 30-40%, with improved airtightness further enhancing savings. Infiltration rates were also proved to significantly impact the building's energy performance, emphasizing the importance of accurate modelling. The expected results can vary for different building types and geometries. Up to 35% reduction in primary energy usage can be achieved acting on existing walls and significantly tackling air tightness issues by complete

redevelopment of windows and large industrial doors. Despite these improvements, the building's energy class was proved to slightly ameliorate, suggesting that to achieve the highest energy efficiency levels, further interventions on systems and installations are needed.

- Retrofitting lighting systems and integrating skylights can significantly reduce energy consumption and improve visual comfort. For example, skylight configurations with up to 24% coverage can enhance natural light, achieving an Average Daylight Factor of 4.6% and an illuminance of 350 lux. However, skylights can increase heating demand, while upgrading to LED lighting can cut electricity use by 50%.

- To prevent summer overheating without compromising visual comfort, a multi-objective optimization study was performed. Different solar shading solutions have been explored to balance indoor temperature and natural lighting. The recommended shading for external windows involves horizontal or nearly horizontal louvres to be installed on the facades with a vertical spacing of 0.2 to 0.4 meters; this intervention can reduce indoor temperature by 0.46°C.

- Similarly, a AHP approach was adopted when evaluating possible retrofit scenarios for heating systems. This allowed to account for contrasting aspects and conflicting parameters affecting companies' decision-making process. The initial investment is the most influential factor in selecting energy systems, with practical considerations such as installation procedures and operational compatibility also playing crucial roles. For enterprises in Tuscany, a gas boiler combined with localized hot-water fan heaters is recommended due to its flexibility, low initial cost, and straightforward installation. However, the sensitivity analysis highlights the benefits of incorporating heat pumps and photovoltaic (PV) systems despite their higher initial costs, as they significantly enhance environmental sustainability.

- The profitability of PV installation was evaluated from an energy, environmental and economical point of view. Despite the considerable benefits achieved in terms of CO2 emissions' reduction, the economic feasibility and productivity may not be guaranteed in case of large PV system implementation and for ESS installation. At this regard, the need for specifically intended subsides and incentives was remarked. Focusing on the

ESS solutions, seasonal storage may result more appropriate given the high amount of energy involved and the peculiar occupancy schedule of industrial facilities, in which energy production by PV and consumption profiles are qualitatively coinciding.

  - The study identifies was deepened to identify the most cost-effective retrofit strategies through life-cycle cost analysis. Lighting system renovation is optimal due to its low investment and quick two-year payback, while heating upgrades (HP+PV) require higher upfront costs and a 20-year payback. Roof insulation is preferable to wall insulation for ease of installation and performance. However, as balancing investment and savings is crucial for feasibility, financial incentives and policies are essential to overcoming cost barriers and encouraging energy-efficient retrofits for business companies.

- A comprehensive redevelopment protocol was produced, capable of adequately address the issues and criticalities connected to the different typological variants but scalable and adjustable according to case-specific needs and boundaries.

Although this study is focused on a specific Italian region, its methodological approach provides a framework that can be extended and adapted to a broader range of contexts. The use of the generalized analytical method proposed ensures that the conclusions drawn are not restricted to the local case but can find further applications in regions with comparable characteristics. A key aspect of this approach is the identification and systematic application of repeated constructive technological solutions, which allow for the recognition of recurring design principles and widespread issues. By relying on these patterns, it becomes possible to formulate strategies that transcend regional constraints, making the findings more universally applicable.

The peculiarities of the industrial building stock let to foresee the replicability of the results of this research also to different geographical areas. In Italy, as in many other European countries, the industrial building stock is largely composed of prefabricated reinforced concrete structures. The variety of construction systems is relatively limited, and despite some differences in the specific components used, these buildings share common construction principles, similar structural behaviour, and the same regulatory framework, as most were built within the same time period. As a result, the critical issues affecting them can be generalized on a broader scale. The extensive analysis conducted in this research, covering a large number of buildings, has made it possible to examine a wide range

of construction solutions, providing a comprehensive overview of the built environment at both regional and national levels. This is further reinforced by comparisons with findings from previous studies in the literature. In this regard, both the results obtained and the proposed improvement strategies have the potential for widespread application in other regional contexts. By systematically analysing representative case studies and integrating best practices, the research provides a replicable model that can be adjusted based on specific environmental, technical, and regulatory factors.

The flexibility of the methodology used is furthermore crucial for ensuring that it can be adopted also in varying conditions, allowing its extension to different geographical areas and structural typologies. The principles established in this research are not inherently tied to a single type of construction or intervention but can be extended to different building typologies, with distinct material properties, architectural features, or functional requirements. The adaptability of the approach makes it applicable to a diverse range of facilities, even if adequate evaluations would be needed to introduce the necessary changes. Future research should focus on refining these adaptations, validating the methodology across a wider array of case studies, and identifying potential limitations that may arise when applying it in different contexts.

Ultimately, while this study is grounded in a specific regional context, its broader implications highlight the value of a systematic and replicable approach to technical analysis. In this perspective, the research can lay the groundwork for future developments that can enhance the efficiency, sustainability, and resilience of construction practices on a larger scale.

7.2 Future developments

The research presented can be further developed and refined to deepen some aspects, overcome possible limitations and provide a more comprehensive framework. Some proposals and outlooks for future developments are hence illustrated.

On field inspections and survey campaigns to evaluate indoor conditions can enhance the reliability of energy modelling and simulations, currently affected by some uncertainties. The latter are mainly related to the accurate quantification of air infiltration rates, highly influential for the final results.

Internal gains induced by production equipment currently represent another factor of uncertainty to be addressed. In this case a comprehensive survey of heat emissions produced by machinery related to different industrial sector can help to overcome this limitation in the study.

The focus of the analysis can be furthermore extended to encompass different regions or geographical areas, in order to acquire a more consistent amount of data and possibly point out other typological variants currently not included in the research because not sufficiently widespread in the area investigated. Similarly, various climate zones should be also foreseen to carry out additional energy simulation and validate passive strategies to improve the energy performance, to define other retrofit measures or to discard some of the ones proposed in the research because not adequate or replicable in different contexts.

Research about systems and energy production can be extended, foreseeing the exploitation of renewables resources such as wind energy and geothermal one with the integration of different type of systems.

Further studies should also explore the integration of advanced computational tools, data-driven approaches, and innovative techniques to enhance the predictive capabilities of the methodology. By incorporating digital modelling, parametric design, and performance-based simulations, it is possible to optimize decision-making processes and further improve the scalability of the framework.

Additional evaluation from both economy and environmental standpoint can be included through dedicated Life Cycle Assessments and Life Cycle Costs assessments. These could provide further indications to prioritize, rank, and select the most appropriate and favourable retrofit initiatives to be adopted.