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DIPARTIMENTO DI INGEGNERIA INDUSTRIALE E
DELL'INFORMAZIONE E DI ECONOMIA DIIE

Dottorato di Ricerca in **Ingegneria Industriale e dell'Informazione e di Economia**
Curriculum **Ingegneria meccanica, energetica e gestionale**
XXXVIII ciclo

Titolo della tesi
Energy Efficiency in Buildings with a Multiscale Approach

SSD ING-IND/11

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a.a. 2024/2025

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ABSTRACT

Energy efficiency is a cornerstone of the transition to a low-carbon future, representing a fast and cost-effective strategy to reduce CO₂ emissions while enhancing energy security. The building sector, accounting for over one-third of global energy consumption, plays a critical role in achieving the “Net Zero Emissions by 2050” target. Improving the energy performance of buildings requires integrated strategies that combine innovative construction techniques, high-performance materials, efficient design solutions, and accurate assessment methods.

This doctoral research investigates the topic of building energy efficiency through a multiscale approach, encompassing different levels of analysis progressing from the scale of the individual building component to that of the architectural element, and finally to the building in its entirety. At the component scale, the study explores the design and production of three-dimensional printed building blocks with optimized thermal properties, leveraging additive manufacturing to overcome geometric limitations of current construction processes and enhance thermal performance of the building component. At the architectural element scale, two analysis methods for assessing wall thermal transmittance, namely Heat Flux Meter and Infrared Thermography, are tested and compared, highlighting their applicability, advantages, and limitations. At the building scale, the research examines the role of Building Information Modeling in supporting energy-conscious design, enabling interoperability with energy simulation tools, the development of digital twins for monitoring and optimization, and the integration of renewable energy systems such as photovoltaics.

The study combines theoretical analysis and experimental validation, ensuring rigorous and empirically robust results. The multiscale framework allows for a holistic understanding of thermal performance, considering both micro-level component behavior and macro-level building dynamics. Results demonstrate the potential of additive manufacturing and advanced measurement techniques in improving energy efficiency and provide insights into the practical integration of Building Information Modeling-based workflows in the design process.

Overall, this research contributes to advancing sustainable construction technologies, offering strategies to reduce energy demand and CO₂ emissions, while supporting the digital transformation of the building industry. The findings provide guidance for future research, technology implementation, and policy development in the pursuit of high-performance, energy-efficient buildings.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to all those who have made this doctoral program possible.

First of all, I thank Professor Dario Ambrosini for his guidance, constant availability, and invaluable scientific advice that have guided and enriched my work. His experience and rigor have been a model of research excellence for me.

My heartfelt thanks also go to Professor Tullio de Rubeis for his daily support and the expertise he has demonstrated in overseeing the experimental and theoretical developments of my research. His availability has been essential in addressing the challenges of this work.

I also thank Professor Domenica Paoletti, a constant presence throughout my doctoral program. Her suggestions, insights, and daily encouragement have profoundly enriched my work and my scientific growth, making every day in the lab a stimulating and motivating experience.

Finally, special recognition goes to Giovanni Pasqualoni, laboratory technician, for his constant assistance and practical expertise, which enabled the experimental activities and the proper use of the instruments necessary for my work.

I conclude by thanking everyone who, over the past three years, has made my doctoral program a stimulating and enriching experience, both scientifically and personally.

NOMENCLATURE

ACRONYMS

3DP	Three-Dimensional Printing	HTTPS	Hypertext Transfer Protocol Secure
ABS	Acrylonitrile Butadiene Styrene	IDM	Information Delivery Manual
AECO	Architecture, Engineering, Construction and Operation	IEA	International Energy Agency
AI	Artificial Intelligence	IFC	Industry Foundation Class
AM	Additive Manufacturing	IoT	Internet Of Things
API	Application Programming Interface	IRA	Inflation Reduction Act
ASTM	American Society for Testing and Materials	IRT	Infrared Thermography
BAPV	Building-Applied Photovoltaics	ISO	International Organization for Standardization
BEM	Building Energy Modeling	LBNL	Lawrence Berkeley National Laboratory
BIM	Building Information Modeling	LEED	Leadership in Energy and Environmental Design
BIPV	Building-Integrated Photovoltaics	LPWANs	Low Power Wide Area Networks
BOS	Balance Of System	LWC	Lightweight Concrete
CC	Contour Crafting	LWFC	Lightweight Foamed Concrete
CETEMPS	Center of Excellence Telesensing of Environment and Model Prediction of Severe events	MBE	Mean Bias Error
CFD	Computational Fluid Dynamics	MDM	Material Detection Module
CFRCHSs	Continuous Fiber-Reinforced Composite Honeycomb Structure	MEPCM	Macroencapsulated Phase Change Materials
CLT	Cross Laminated Timber	MFA	Multi-Factor Authentication
CP	Concrete Printing	MVDs	Model View Definitions
CSA	Calcium Sulfoaluminate	NCC	National Construction Code
CS-LCCs	Core-framework Lattice Cementitious Composite	NDT	Non-Destructive Techniques
CV	Coefficient of Variation	NFC	Nearfield Communication
DC	Direct Current	NZE	Net Zero Emissions
DCW	Direct Cryo Writing	NZEB	Nearly Zero Energy Building
DIW	Direct Ink Writing	PAM	Pertubuhan Akitek Malaysia
DT	Digital Twin	PERC	Passivated Emitter and Rear Cell
EA	Energy Absorption	PETG	Polyethylene Terephthalate Glycol
ECBC	Energy Conservation Building Code	PLA	Polylactic Acid
E-PLA	Enhanced-PLA	PME-DRIVE	PM Electric Drive Revolution in Innovative Vehicle Enhancement
E-THM	Enhanced-Thermometric Method	PV	Photovoltaic
EU	European Union	PVGIS	Photovoltaic Geographical Information System
EVA	Ethylene-Vinyl Acetate	RBAC	Role-Based Access Control
FDM	Fused Deposition Modeling	RC	Robocasting
FEA	Finite Element Analysis	RMC	Reactive Magnesium oxide Concrete
FFF	Fused Filament Fabrication	RMSE	Root Mean Square Error
gbXML	Green Building XML	SEA	Specific Energy Absorption
GDPR	General Data Protection Regulation	SHDF	Social Housing Decarbonisation Fund
GHB	Guarded Hot Box	SLS	Selective Laser Sintering
GHG	Greenhouse Gas	SMP	Shape Memory Polymer
GIS	Geographic Information System	SSL	Secure Sockets Layer
GPP	Geopolymer Paste	TGA	Thermogravimetric Analysis
HCC	Half Cut Cells	THM	Thermometric Method
HFM	Heat Flow Meter	UK	United Kingdom
HPC	High-Performance Concrete	US	United States
HVAC	Heating, Ventilation and Air Conditioning	WSN	Wireless Sensors Nodes

LATIN ROMAN

A	Area, m ²	Ra	Rayleigh number
c	Specific heat, J kg ⁻² K ⁻¹	RH	Relative humidity, %
h	Surface heat transfer coefficient, W m ⁻² K ⁻¹	s	Thickness, m
L	Latent heat, J kg ⁻¹	T	Temperature, K or °C
Nu	Nusselt number	U	Thermal transmittance, W m ⁻² K ⁻¹
P	Power, W	v	Air speed, m/s
Pr	Prandtl number	V	Volume, m ³
Q̇	Thermal energy consumption, kWh	w	Uncertainty in measurement
q	Heat flux, W m ⁻²	g	Gravitational acceleration, m/s ²
R	Thermal resistance, m ² K W ⁻¹		

GREEK SYMBOLS

α	Thermal diffusivity, m ² s ⁻¹	$\mathcal{A}$	Conductance, W/m ² K
β	coefficient of volume expansion, K ⁻¹	ν	kinematic viscosity, m ² /s
Δ	Difference	ϕ	Surface porosity, %
ε	emissivity	ρ	Density, kg/m ³
η	Efficiency	σ	Stefan–Boltzmann constant, W/m ² K ⁴
λ	Thermal Conductivity, W m ⁻¹ K ⁻¹	ω	Thermal effusivity, Ws ^{1/2} m ⁻² K ⁻¹

SUBSCRIPTS

air	Air	max	Maximum
ave	Average	min	Minimum
c	Convective	n	N-th
cond	Conductive	p	Pressure
e	External	r	Radiative
eff	Effective	s	Surface
i	Internal	s	Superficial
j	J-th	tot	Total
m	Medium		

1. INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Energy efficiency is often called the "first fuel" in the clean energy transition, as it represents one of the fastest and most cost-effective strategies for mitigating CO₂ emissions. In addition to reducing energy costs, it helps strengthen energy security. On the path to the "Net Zero Emissions by 2050" (NZE) scenario, energy efficiency is the main lever for containing energy demand, in synergy with other key measures such as electrification, behavioral changes, digitalization, and more efficient use of materials [1].

Over the past year, energy efficiency policies have been reinforced worldwide. Since the onset of the current energy crisis, countries accounting for more than 70% of global energy use have adopted new or enhanced efficiency measures. For example, in May 2024, the European Union (EU) adopted the revised Energy Performance of Buildings Directive (EPBD); in the same year, the United States (US) updated standards for passenger cars, while China issued its 2024–2025 Energy Conservation and Carbon Reduction Action Plan. Finally, in September 2024, India launched the PM Electric Drive Revolution in Innovative Vehicle Enhancement (PM E-DRIVE) scheme to promote the rollout of electric vehicles [1].

The building sector, which accounts for approximately 37% of global energy consumption and nearly 40% of energy-related emissions, plays a central role in this transition [2].

Across countries, minimum performance standards and building energy codes are becoming more comprehensive and stringent, while the adoption of efficient and renewable building technologies is accelerating. However, the sector must implement changes more rapidly to align with the NZE by 2050 Scenario [2].

In accordance with the latest monitoring data provided by the International Energy Agency (IEA) [2], in 2022, direct emissions from building operations showed a slight year-on-year decline, reversing the previous trend from 2015 to 2021, when they had grown by nearly 1% annually. Meanwhile, indirect emissions increased by about 1.4% in 2022, reflecting greater reliance on electricity.

Regional trends varied. In the EU, emissions decreased, supported by a mild winter, whereas in the US, extreme temperatures drove an increase in buildings emissions.

Beyond operational emissions, buildings construction added another 2.5 Gt CO₂ in 2022, including emissions from producing and processing cement, steel, and aluminium. Combined, operational and construction-related emissions from buildings account for over one-third of global energy-related emissions (Figure 1), highlighting the need for mitigation and adaptation measures across the entire buildings value chain [2].

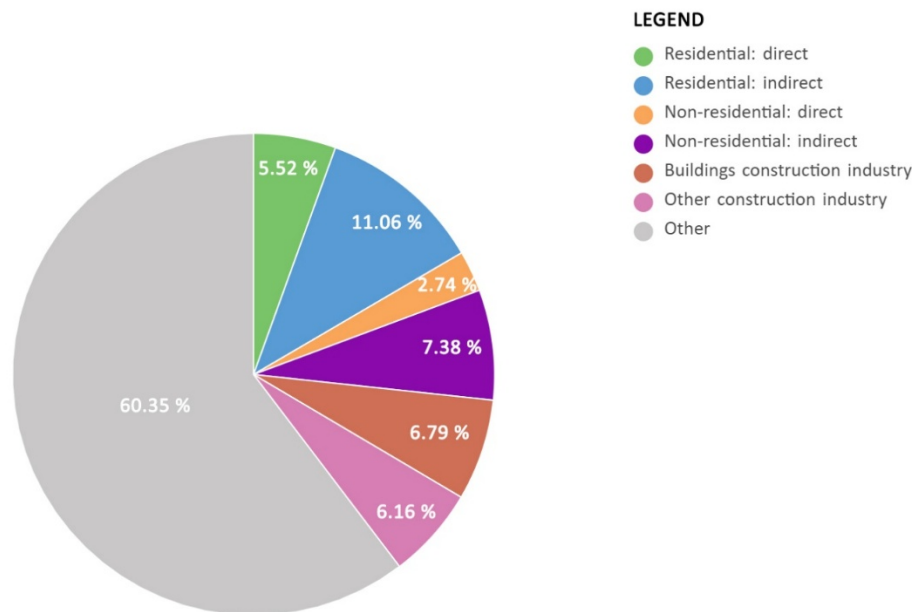


Figure 1. Global CO₂ emissions from buildings, including embodied emissions from new construction, 2022. Adapted from [2].

Operational energy use in buildings accounts for around 30% of global final energy consumption. When the energy used to produce construction materials such as cement, steel, and aluminium is included, this share rises to 34%.

In 2022, space cooling recorded the largest increase in demand among all building end uses for the second consecutive year, rising by more than 3% compared with 2021. In contrast, space heating energy consumption fell by 4%, largely due to milder winter conditions in several regions, including Europe.

Over the past decade, energy demand in buildings has grown by just over 1% annually on average. In 2022, it increased by nearly 1% relative to 2021. Electricity accounted for about 35% of total building energy use in 2022—up from 30% in 2010. Although there has been a gradual shift away from fossil fuels toward electricity and renewables, fossil fuel use in buildings has still grown at an average annual rate of 0.5% since 2010. Figure 2 shows the final energy consumption of buildings relative to other sectors in 2022.

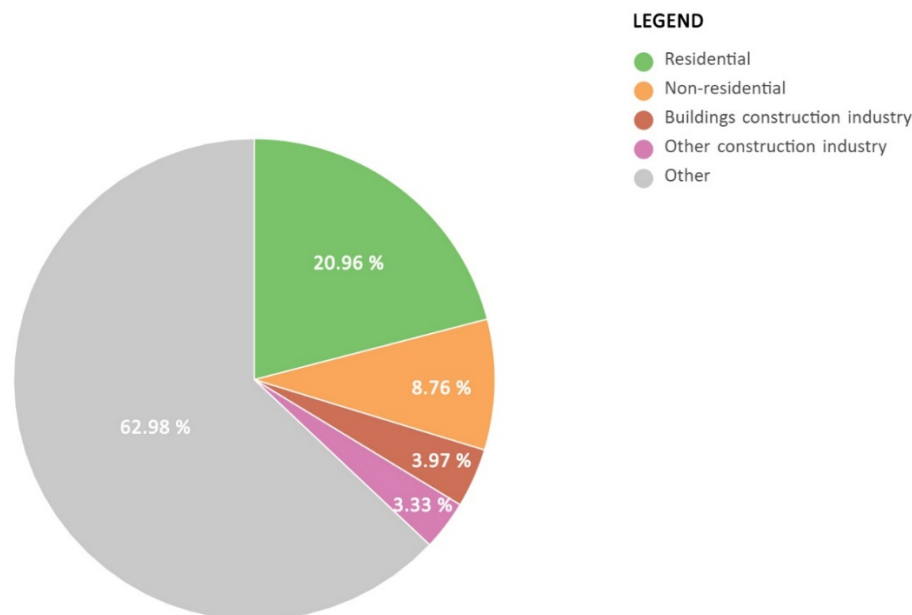


Figure 2. Final energy consumption of buildings relative to other sectors, 2022. Adapted from [1].

Under the NZE Scenario, compared to data recorded in 2022, emissions are required to decline by an average of 9% per year until 2030—effectively more than halving over the decade—while building energy consumption is projected to decrease by approximately 25% (Figure 3) [2].

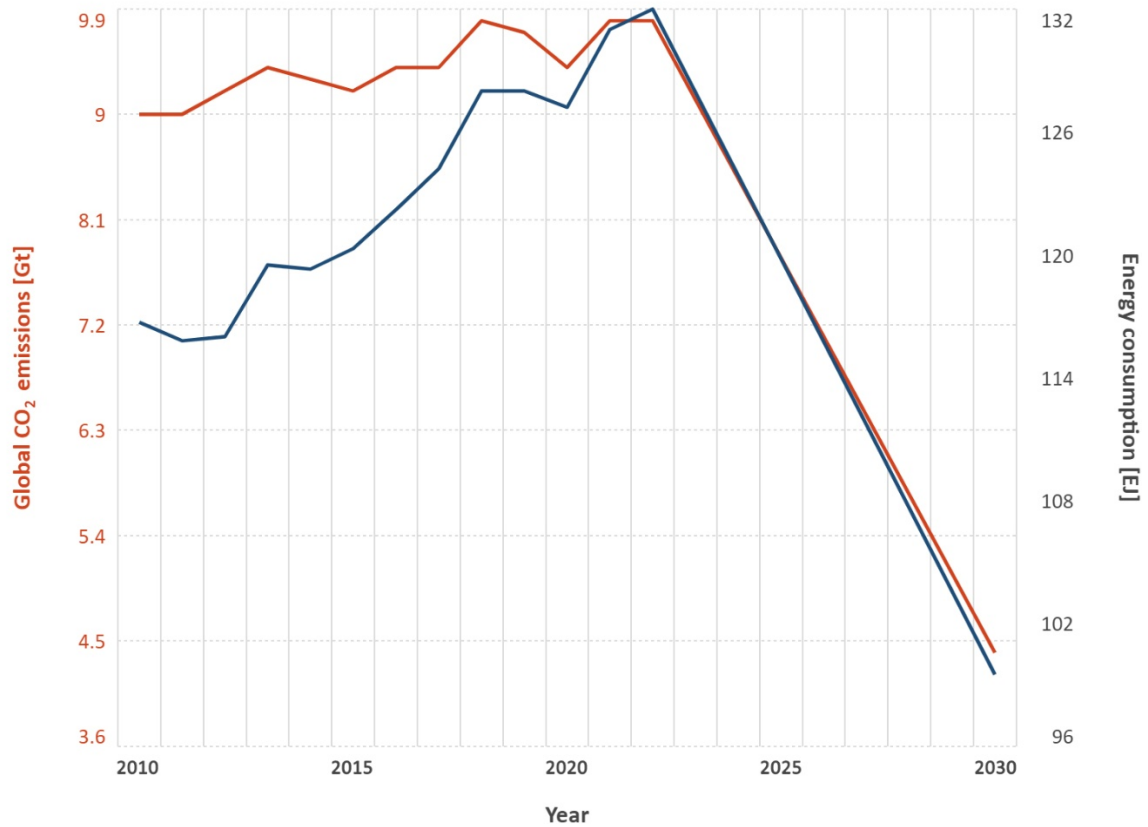


Figure 3. Net Zero Scenario, 2010-2030. In red, Global CO₂ emissions from the operation of buildings. In blue, Energy consumption in buildings by fuel. Adapted from [1].

In recent years, several countries have strengthened their regulations to promote net-zero or zero-carbon-ready buildings. In the US, the Inflation Reduction Act (IRA) of 2022 [3] introduced tax credits for home energy assessments, insulation, and the installation of heat pumps, solar panels, water heaters, and battery storage systems, thereby encouraging the construction and sale of more energy-efficient homes. In the United Kingdom (UK), the Energy Security Strategy [4] launched in 2022 aims to enhance the energy efficiency of homes, while the Social Housing Decarbonisation Fund (SHDF) [5] was established to reduce reliance on gas heating in residential buildings. Turkey strengthened its building regulations in 2023, requiring all new buildings to be nearly zero-energy, with improved insulation standards and at least 5% of total energy demand met by renewable sources [2]. India introduced the Energy Conservation Building Code (ECBC) [6] in 2022, which sets energy performance standards for commercial and residential buildings, mandating the integration of renewable energy. In Japan, energy efficiency and insulation requirements were added in 2023 to the Flat 35 mortgage scheme, which now offers lower interest rates for zero-energy homes [2]. Korea launched the Energy Cashback pilot program in 2022, providing financial incentives for households that successfully reduce their energy consumption [2]. In Australia, the National Construction Code (NCC) [7] was updated in 2022, strengthening energy efficiency standards for new homes and apartments for the first time in a decade. The revised EPBD [8] is the main legislative instrument aiming to promote the improvement of the energy performance of buildings within the EU. It entered into force on 28 May 2024 and will need to be transposed into national laws by 29 May 2026.

The complexity of the buildings is increasing more and more to meet regulatory requirements that are even more stringent. However, construction methods, design practices, and building lifecycle management methods have evolved only to a limited extent, and energy considerations are not yet fully integrated into the design process [9].

The global energy scenario we face may seem alarming, but at the same time, it could pave the way for sustainable energy planning to be conducted in the construction sector [9]. In this context, scientific research plays a key role in developing energy-efficient and sustainable technologies, providing reliable data and protocols, and guiding effective energy policies, accelerating the reduction of consumption and emissions in the building sector.

1.2 RESEARCH OBJECTIVES AND SCOPE

Achieving energy efficiency in buildings requires an integrated approach, including the adoption of innovative construction methods, the use of high-performance materials, the selection of efficient design solutions, and the use of reliable and accurate energy analysis techniques.

In the context of energy optimization, the building envelope certainly represents a central theme. Serving as the “skin” of the building, it is in direct contact with both the external and internal environments, regulating the energy exchanges between them. The greater the envelope’s capacity to minimize heat transfer, the higher its contribution to the building’s overall energy efficiency. A well-designed, low-thermal-loss envelope ensures a significant reduction in energy consumption, leading to lower energy costs and minimized CO₂ emissions. Consequently, the selection of appropriate insulating materials is fundamental. Moreover, in recent years, research attention has also increasingly focused on the impact of the envelope’s geometric configuration on its thermal performance, highlighting how shape and design can further enhance energy efficiency [9]. The search for useful geometric solutions to minimize heat loss through the envelope is widely debated in the literature [9- 16]. However, contemporary construction technologies are mostly limited to the creation of simplistic shapes, rarely optimized for thermal efficiency [17]. Therefore, there is a need for innovative production techniques capable of revolutionizing the building construction process, bringing technological and energy benefits [18]. Technologies such as three-dimensional printing (3DP), also known as Additive Manufacturing (AM), could be a disruptive innovation for the construction industry [19]. The unique features of 3DP—including the use of recycled materials, shorter supply chains with lower greenhouse gas (GHG) emissions, reduced post-processing requirements, and cost-efficient production of complex products—make it a potential technology of the future [20- 25]. By overcoming geometric and dimensional constraints, 3DP can bridge the gap between mass production and customization, achieving results that conventional manufacturing methods cannot [26, 27]. Furthermore, its capacity to create complex shapes offers the potential to significantly enhance the thermal and mechanical performance of buildings [28]. For these reasons, despite still being in development, 3DP is considered a key technology that could reduce the energy and environmental footprint of buildings [29] while also accelerating the digital transformation of the construction industry.

Just as it is important to design high-performance building envelopes, it is equally essential to have precise and in-depth knowledge of their thermal properties, that is, the characteristics that determine their energy behavior. Currently, several non-destructive standard methods are available to determine these properties, ranging from traditional and widely used techniques such as the Heat Flow Meter (HFM) method [9, 17, 30- 32], to less commonly applied approaches like Infrared Thermography (IRT) [33- 38] and the Thermometric Method (THM) [39], as well as more innovative developments such as the Enhanced Thermometric Method (E-THM) [39- 42]. Among them, HFM stands out for its degree of accuracy [32], linked to the standardization of the method, while IRT for its speed and low invasiveness [33, 34].

In the contemporary building design landscape, the search for cutting-edge solutions, conceived with extreme attention to detail and oriented towards the building's overall efficiency—in terms of energy, architecture, structure, and the environment—inevitably leads to increased design and construction complexity [43]. Innovative technologies are needed to support the entire building design process, seamlessly integrating all

design aspects and including energy efficiency considerations from the preliminary stage of a project. The challenge of designing a high-energy performance building requires the creation of a shared working environment where the architectural and energy spheres can communicate easily and exchange information expeditiously [44]. In this context, Building Information Modeling (BIM) could be the key to revolutionizing the entire construction industry, ensuring the delivery of complete, coherent, and well-structured projects. By means of detailed three-dimensional modeling, BIM provides a highly accurate representation of building components, allowing professionals to better manage all aspects of a project. BIM is a useful support during the entire lifecycle of a building, starting from the design phase, up to the demolition/renovation phase [45-47].

In light of the above, this doctoral thesis falls within the scope of energy efficiency in buildings, addressing multiple issues on multiple scales.

Specifically, the proposed research aims to:

1. contribute to the search for energy-efficient design solutions with the support of innovative construction techniques;
2. test two different non-destructive techniques (NDTs) to evaluate the thermal performance of building elements, their applicability, advantages and disadvantages, and identifying the most suitable areas of application for each;
3. explore innovative technologies capable of better managing the complexity of building systems and design processes, enabling the integration of energy aspects already in the early design phases.

1.3 METHODOLOGICAL APPROACH

In the present research, an integrated methodological approach was adopted, combining both theoretical and experimental dimensions in a complementary manner. The theoretical elaboration made it possible to construct a coherent conceptual framework and to formulate well-grounded hypotheses, thereby guiding the definition of the research questions and the structuring of interpretative models. In parallel, the experimental investigation enabled these hypotheses to be subjected to empirical verification, providing concrete evidence that not only confirmed but, in certain instances, also refined and reformulated the initial assumptions. The synergy between the two approaches proved to be crucial, as it ensured both theoretical rigor and empirical robustness, thereby strengthening the overall validity of the analysis and enhancing its scientific significance.

1.4 MULTISCALE APPROACH: CONCEPT AND RATIONALE

The research was conducted through a multiscale approach, encompassing different levels of analysis progressing from the scale of the individual building component to that of the architectural element, and finally to the building in its entirety. This perspective allowed for a comprehensive investigation that did not remain confined to the isolated performance of individual elements, but instead considered their interactions and cumulative effects within the overall architectural system. By moving across scales, it was possible to identify both micro-level phenomena—linked to the behavior of specific components—and macro-level dynamics concerning the integrated functioning of the entire building. Such an approach ensured a more holistic understanding of the subject under study, strengthening the robustness of the findings and their applicability to real-world contexts.

1.5 THESIS STRUCTURE

The thesis is organized into seven main sections, divided as follows.

Section 2 provides a literature review of the topics covered in the thesis, highlighting knowledge gaps and research opportunities, which form the basis for the work conducted.

Section 3 describes the methodology adopted, based on a multiscale approach, and the methods and tools used to apply it. The experimental protocols, data analysis techniques, and simulation tools are presented, clarifying how each scale contributes to the overall thermal performance assessment.

Sections 4, 5, and 6 form the core of the thesis and are dedicated to the analysis at the scale of the building component, the architectural element, and the building as a whole, respectively. Chapter 4 deepens the design and construction of 3D building blocks optimized for thermal performance, with a detailed experimental analysis and discussion of the results. Chapter 5 focuses on assessing the thermal transmittance of walls using two methodologies, namely HFM and IRT, evaluating their areas of application.

Chapter 6 explores the use of BIM for energy design, analyzing the interoperability with simulation tools, the role of software for the design of photovoltaic systems, and the creation of digital twins for monitoring and optimization.

Section 7 integrates the results obtained from the analyses conducted at different scales, demonstrating the interactions between components, architectural elements, and the building, assessing practical implications and technology transfer, and discussing the relevance of the findings for industry and the market, as well as outlining future prospects for multi-scale building design.

Finally, Section 8 summarizes the main research findings, highlights the thesis's scientific contribution, discusses the study's limitations, and suggests possible directions for further research.

The described structure allows for the construction of a coherent path that starts from a critical review of the literature, passes through experimental and simulation analysis at multiple scales, and culminates in an integrated discussion oriented towards practical application.

A summary of the main contents is included at the end of each chapter. These summaries serve to clarify the conceptual issues that have emerged, facilitate the reader's orientation within the overall argument, and highlight the logical progression of the work, particularly given the breadth and complexity of the discussion.

SUMMARY

1.1 Background and motivation

Energy efficiency is widely recognized as a key and cost-effective strategy for reducing CO₂ emissions and enhancing energy security, forming a cornerstone of the path toward “Net Zero Emissions by 2050.”

The building sector, which accounts for approximately 37% of global energy consumption and nearly 40% of energy-related emissions, plays a central role in this transition. In recent years, several countries have strengthened their regulations to promote net-zero or zero-carbon-ready buildings. The complexity of the buildings is increasing more and more to meet regulatory requirements that are even more cogent. However, construction methods, design practices, and building lifecycle management methods have evolved only to a limited extent, and energy considerations are not yet fully integrated into the design process. The global energy scenario we face may seem alarming, but at the same time, it could pave the way for sustainable energy planning to be conducted in the construction sector. In this context, scientific research plays a key role in developing energy-efficient and sustainable technologies, providing reliable data and protocols, and guiding effective energy policies, accelerating the reduction of consumption and emissions in the building sector.

1.2 Research objectives and scope

This research focuses on enhancing energy efficiency in buildings through an integrated approach that combines innovative construction techniques, high-performance materials, and advanced design strategies.

A central focus is the building envelope, where both material choice and geometric design significantly affect thermal performance and energy consumption. Emerging technologies such as 3D printing (3DP) offer the potential to create complex, optimized shapes that improve thermal and structural efficiency.

In addition to designing high-performance building envelopes, it is crucial to accurately understand their thermal properties, as these strongly influence energy behavior and design decisions. Selecting the appropriate measurement methods—ranging from more traditional and common techniques like Heat Flow Meter (HFM), to less used (IRT, THM) or more innovative (E-THM)—is essential, since each method has specific strengths and limitations that determine its suitability for different situations.

Designing high-energy-performance buildings requires full integration of all components and systems, ensuring efficient and harmonious operation. Innovative technologies, particularly Building Information Modeling (BIM), play a key role by supporting energy efficiency from the earliest design stages and throughout the building’s lifecycle, from construction to demolition or renovation.

In light of the above, this doctoral thesis falls within the scope of energy efficiency in buildings, addressing multiple issues on multiple scales. Specifically, the proposed research aims to:

1. contribute to the search for energy-efficient design solutions with the support of innovative construction techniques;
2. test different non-destructive techniques (NDT) to evaluate the thermal performance of building elements, highlighting their advantages and disadvantages and identifying the most suitable areas of application for each;
3. explore innovative technologies capable of better managing the complexity of building systems and design processes, enabling the integration of energy aspects already in the early design phases.

1.3 Methodological approach

In the present research, an integrated methodological approach was adopted, combining both theoretical and experimental dimensions in a complementary manner.

1.4 Multiscale approach: concept and rationale

The research was conducted through a multiscale approach, encompassing different levels of analysis progressing from the scale of the individual building component to that of the architectural element, and finally to the building in its entirety. This perspective allowed for a comprehensive investigation that did not remain confined to the isolated performance of individual elements, but instead considered their interactions and cumulative effects within the overall architectural system.

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Section 7 integrates the results obtained from the analyses conducted at different scales, demonstrating the interactions between components, architectural elements, and the building, assessing practical implications and technology transfer, and discussing the relevance of the findings for industry and the market, as well as outlining future prospects for multi-scale building design.

Section 8 summarizes the main research findings, highlights the thesis's scientific contribution, discusses the study's limitations, and suggests possible directions for further research.

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2. STATE OF THE ART

This section provides a literature review of the topics covered in the thesis. Specifically, it begins by analyzing the potential of 3D printing (3DP) for the thermal optimization of building components, then moves on to a review of current non-destructive techniques (NDTs) for assessing the thermal performance of walls, and concludes with an analysis of the use of Building Information Modeling (BIM) for building energy design.

2.1 BUILDING COMPONENTS AND THERMAL PERFORMANCE: THE POTENTIAL OF ADDITIVE MANUFACTURING IN CONSTRUCTION

Production processes contribute significantly to harmful environmental impacts. As noted by Shuaib et al. [1], efforts to improve these processes have been ongoing since the early 1990s. Nevertheless, the construction industry is still regarded as a low-tech sector [2–4], largely because its methods have remained heavily dependent on manual labor for decades [5, 6]. Consequently, adopting new production techniques is essential to minimize environmental impacts [7] and promote technological advancement within the sector.

3DP, also referred to as Additive Manufacturing (AM), represents a potentially disruptive innovation in the construction industry [8]. This technology enables highly automated manufacturing processes [9] by sequentially depositing materials based on a digital model [10, 11]. Unlike traditional manufacturing, which relies on subtractive or formative methods, 3DP is built on an additive fabrication approach [12–14]. According to ISO/ASTM 52900, it is defined as a “process of joining materials together to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” [15].

While many manufacturing sectors have already adopted 3DP to enhance their production processes, its application in construction remains relatively new. The unique advantages of 3DP—such as the use of waste materials, reduced supply chain complexity and greenhouse gas (GHG) emissions, shorter post-processing time, and lower costs for fabricating complex geometries—position it as a promising technology for the future [16–21]. Moreover, 3DP offers the ability to reconcile mass production with customization, overcoming geometric and dimensional constraints that limit conventional methods [22, 23]. Its capacity to create intricate shapes can also contribute to significant improvements in buildings’ thermal and mechanical performance [24].

Therefore, even though 3DP is still in the development stage, it holds great potential to enhance the energy and environmental performance of buildings [25] and to act as a key driver in the digital transformation of the construction industry.

2.1.1 3DP: overview and application in the construction sector

The evolution of 3DP began in the 1980s with the invention of the first 3D printer by Charles W. Hull [26]. This event marked the advent of rapid prototyping—an approach that was fast, precise, and capable of creating consistent, repeatable products [27]. In 1986, Hull founded 3D Systems, which launched the world’s first commercially available 3D printer in the United States the following year. Soon after, several 3DP technologies emerged [28], reducing costs, improving accessibility, and enhancing user-friendliness, leading to the widespread adoption of 3D printing across various industries.

3DP processes can be categorized in several ways. For instance, the American Society for Testing and Materials (ASTM), in collaboration with the International Organization for Standardization (ISO), classifies 3DP into seven primary process types: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination, and Vat Photopolymerization [29]. For more detailed discussions on specific printing processes, refer to studies [31–35].

In general, 3DP workflows consist of three main stages: input, production, and output. In the initial stage, the focus is on the materials [36], which must be compatible with the selected printing process and exhibit suitable properties for fabrication [35]. The ultimate objective is to transform the chosen material into a finished three-dimensional product.

Recent advancements [37, 38] have led to large-scale applications [39], notably 3D concrete printing, which enables rapid construction of complex forms without formwork [40–42], enhancing architectural flexibility and cost efficiency [43]. Consequently, numerous laboratory studies have been conducted to evaluate the performance of cementitious materials produced through additive manufacturing [44–46].

Despite its promising potential, 3DP in construction remains at a developmental stage [47, 48]. One of its key benefits—high construction speed—makes it especially relevant for addressing housing shortages in many regions [49, 50]. The most commonly used 3DP technique in the construction industry, initially applied on a small scale and now expanding to larger applications, is material extrusion using cementitious mixtures [51]. Currently, three main large-scale 3DP methods are employed in construction: Contour Crafting (CC), Concrete Printing (CP), and D-Shape. CC and CP suit large structural components [52, 53], while D-Shape achieves finer detail and precision [54]. For more detailed analyses of these methods, refer to works [42, 52, 54–56].

Although the global progress in developing these printing systems demonstrates their technical feasibility, the absence of standardized building codes and regulatory frameworks currently limits their widespread adoption. Establishing standardized regulations could accelerate safe and reliable adoption [57–59].

To date, several 3D-printed buildings have already been constructed, reflecting significant interest in exploring the potential of this technology within the construction sector. Notable examples include the “Canal House” in the Netherlands [27], the “WinSun Company buildings” in China [27, 60], the “Office of the Future” in the United Arab Emirates [61, 62], and the “Apis Cor Printed House” in Russia [61, 63, 64].

2.1.2 3DP for the thermal optimization of the building envelope

The energy performance of buildings is mainly determined by heat losses through the envelope, which are significantly influenced by its structure and the materials from which it is made. In this context, considering that 3DP gives the possibility of realizing varied geometric shapes with high accuracy, it would be interesting to explore this technology to create internal envelope geometries with air cavities that can control heat transfer, even allowing the use of waste materials as cavity fillers (wood processing waste, recovered sheep wool, etc.).

Some preliminary studies have explored the use of 3DP to optimize the thermal performance of building envelopes, some focusing on topology, others on materials. However, experiments in this area are still fragmented.

The studies conducted on topology [65–81] demonstrated that 3DP enables advanced control of the thermal performance of building elements through the targeted design of their internal geometry and cavities (Figure 1). In both polymer and cementitious systems, topological optimization allows for substantially reduced thermal transmittance, sometimes exceeding the performance of traditional solutions even with the same or reduced thickness.

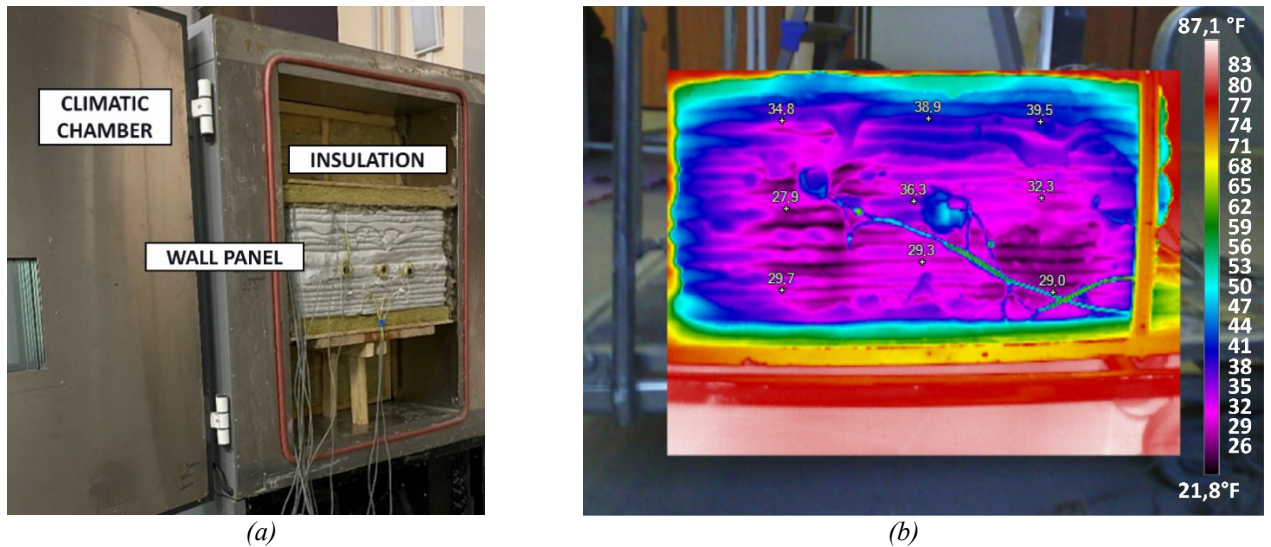


Figure 1. Experimental analyses on the 3D-printed wall. (a) Test configuration in the climatic chamber. (b) Thermal imaging of 3D-printed wall. Adapted from [71].

Studies focused on materials are aimed at the implementation of insulating materials in the 3D printing process, trying to find a balance between thermal performance and mechanical properties [82– 84]. In general, there has been a strong research interest in 3D printed concrete [85– 92]. In detail, several studies [93– 107] have examined how to improve its insulating capabilities through mixture optimization and the use of waste materials.

Overall, 3DP remains an emerging and underexplored field in terms of energy efficiency [108–120], yet the increasing number of innovative approaches suggests significant improvements are likely [78].

Table 1 summarizes the main information on the literature in this field, highlighting the thermal parameters investigated and the results obtained by applying the two optimization strategies.

Table 1. Summary of the research studies cited.

Reference	Research object	Printing Material	3DP process used	Optimization strategy used		Thermal analyzes approach	Thermal parameter s investigated	Thermal paramete rs values
				topology	material			
Sarakinioti et al. [65]	Adaptive facade panel	Polylactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG)	Fused Deposition Modeling (FDM)	✓		HFM in Hot-Box	λ (W/mK)	$0.09 < \lambda < 0.1$ W/mK
Dey et al. [66]	3D-printed slabs with cavities	Concrete	CP	✓		HFM in Hot-box, Infrared Thermography (IRT)	T_{si} (°C)	$T_{si1} = 48^{\circ}\text{C}$, $T_{si2} = 49^{\circ}\text{C}$
Kaszynka et al. [67]	3D printed wall, concrete wall, brick wall	Concrete	CP	✓		Hot plate apparatus	R (m ² K/W); U (W/m ² K)	$R_1 = 5.04$ m ² K/W, $R_2 = 5.74$ m ² K/W,

							$R_3 = 5.45$ $\text{m}^2\text{K/W};$
							$U_1 = 0.2$ $\text{W/m}^2\text{K},$ $U_2 = 0.17$ $\text{W/m}^2\text{K},$ $U_3 = 0.18$ $\text{W/m}^2\text{K}$
Grabowska and Kasperski [68]	Printed multilayer insulation with quadrangle, hexagonal, and triangular closures	PA-12	Selective Laser Sintering (SLS)	✓	Poensgen apparatus	λ (W/mK)	$0.06 \leq \lambda \leq 2.5$ W/mK
Mihalache et al. [69]	3D printed plates	PLA	FDM	✓	IRT, Finite Element Analysis (FEA)	T (°C)	$36 \leq T_{si} \leq 55$ °C, $32 \leq T_{se} \leq 50$ °C
Alkhalidi et al. [70]	3D printed walls	Concrete, Enhanced PLA (E-PLA)	Binder jetting, Material Detection Module (MDM)	✓	Ansys simulation	U (W/m ² K)	$0.15 \leq U \leq 0.55$ W/m ² K
Nemova et al. [71]	3D printed enclosing structures	Concrete	CP	✓	Climatic chamber, IRT, Ansys simulation	U (W/m ² K)	U = 1.18 W/m ² K
Marais et al. [72]	3D printed walls with cavities	Lightweight Foamed Concrete (LWFC), High-Performance Concrete (HPC)	CP	✓	HFM in Hot-box, FEA	λ (W/mK)	$\lambda_1 = 0.37$ W/mK, $\lambda_2 = 1.1$ W/mK
Cuevas et al. [73]	3D printed walls	Concrete	CP	✓	FEA	U (W/m ² K)	$0.59 \leq U_1 \leq 0.83$ W/m ² K, $0.2 \leq U_2 \leq 0.58$ W/m ² K
Suntharalingam et al. [74]	3D printed walls	Concrete, E-PLA	CP	✓	FEA	U (W/m ² K)	$0.34 \leq U \leq 3.16$ W/m ² K
de Rubeis et al. [75]	3D-printed blocks	PLA	FDM	✓	HFM in Hot-box, IRT, FEA	U (W/m ² K)	$U_1 = 1.43$ W/m ² K, $U_2 = 1.25$ W/m ² K, $U_3 = 1.22$ W/m ² K

de Rubeis et al. [76]	3D-printed block	PLA	FDM	✓	HFM in Hot-box, IRT	U (W/m ² K)	U ₁ = 1.22 W/m ² K, U ₂ = 0.65 W/m ² K, U ₃ = 0.53 W/m ² K, U ₄ = 0.66 W/m ² K
de Rubeis et al. [77]	3D-printed block	PLA	FDM	✓	HFM in Hot-box, IRT	U (W/m ² K)	U _{1a} = 1.22 W/m ² K, U _{1b} = 1.13 W/m ² K, U ₂ = 1.18 W/m ² K, U ₃ = 1.08 W/m ² K
de Rubeis [78]	3D printed block	PLA	FDM	✓	HFM in Hot-box, IRT	U (W/m ² K)	U ₁ = 2.19 W/m ² K, U ₂ = 1.24 W/m ² K, U ₃ = 0.69 W/m ² K
de Rubeis et al. [79]	3D printed block	PLA	FDM	✓	HFM in Hot-box, IRT	U (W/m ² K)	U ₁ = 1.22 W/m ² K, U ₂ = 1.13 W/m ² K
El-Mahdy et al. [80]	3D printed block	Salt, sand, Ethylene-Vinyl Acetate (EVA)	Robocasting (RC)/ Direct ink writing (DIW)	✓	Mathematical calculation	U (W/m ² K)	U = 0.94 W/m ² K
He et al. [81]	3D printed wall	Concrete	CP	✓	Energy modeling analysis	q _m (W/m ²)	q _m = 3.94 W/m ²
Mahadevan et al. [93]	3D printed building, conventional building	Concrete	CP	✓	Energy modeling analysis	U (W/m ² K)	U ₁ = 3.69 W/m ² K, U ₂ = 2.97 W/m ² K, U ₃ = 2.28 W/m ² K
Cuevas et al. [94]	3D printed concrete samples	Lightweight concrete (LWC)	CP	✓	Hot Disk	λ (W/mK); c (MJ/m ³ K)	0.35 ≤ λ ≤ 0.74 W/mK; 0.35 ≤ C ≤ 0.94 MJ/m ³ K
Malek et al. [95]	3D printed brick samples	PETG	Fused filament fabrication (FFF)	✓	ISOMET analyzer	λ (W/mK); α (μm ² /s); c (MJ/m ³ K)	0.87 ± 0.05 ≤ λ ≤ 0.99 W/mK; 0.61 ≤ α ≤ 0.69 μm ² /s; 1.31 ≤ C ≤ 1.64 MJ/m ³ K

Ebrahimi et al. [96]	3D printed building	Concrete with Reactive magnesium oxide concrete (RMC), Concrete with Calcium sulfoaluminate (CSA)	CP	✓	Energy modeling analysis	(TSE, El, DC, DH)	9171.29 ≤ TSE ≤ 10390.47 kWh; 5398.13 ≤ El ≤ 5419.5 kWh; 3036.42 ≤ DC ≤ 4192.14 kWh; 609.58 ≤ DH ≤ 915.24 kWh
Kam et al. [97]	3D printed objects	Wood	DIW, Direct cryo writing (DCW), Binder Jetting	✓	TC Thermal Conductivity Analyzer	λ (W/mK)	$\lambda_1 = 0.09$ W/mK, $\lambda_2 = 0.05$ W/mK
Zeng et al. [98]	3D printed Continuous fiber-reinforced composite honeycomb structure (CFRCHSs)	Shape memory polymer (SMP)	FFF	✓	In-plane compression tests	Energy absorption (EA) (kJ); Specific energy absorption (SEA) (kJ/kg)	$0.27 \leq EA \leq 1.10$ kJ; $2.2 \leq SEA \leq 14.00$ kJ/kg
Maier et al. [99]	3D-printed polymer lattice embedded in the cement-based matrices	Acrylonitrile butadiene styrene (ABS)	not specified	✓	HFM in Hot-box, Differential scanning calorimetry (DSC)	C (J/g°C)	C = 57.55 J/g°C
Rahemipour et al. [100]	Macroencapsulated phase change materials (MEPCM) integrated into a 3D printable Geopolymer paste (GPP)	GPP	not specified	✓	KD2 analyzer, DSC, Thermogravimetric analysis (TGA), Humidity chamber, IRT	L (J/kg); T_m (°C); λ (W/mK)	$6.40 \leq \Delta H \leq 24.74$ J/g; $18.30 \leq T_m \leq 27.27$ °C; $0.38 \leq \lambda \leq 0.84$ W/mK
Song et al. [101]	3D Core-framework lattice cementitious composite	Polymer	Stereolithography (SLA)	✓	Finite element analysis (FEA)	λ (W/mK)	$0.21 \leq \lambda \leq 0.33$ W/mK

	(CS-LCCs)						
Chung et al. [102]	3D printed insulating materials	ABS	FDM	✓	FEA, Hot Disk	λ (W/mK)	$0.12 \leq \lambda \leq 0.18$ W/mK
Bahar et al. [103]	3D printed insulating materials	Wood, PLA	FFF	✓	Hot wire probe, hot plane probe, hot ring probe, DSC, TGA	λ (W/mK); ω ($Ws^{0.5}/m^2K$); α (m^2/s)	$31.50 \leq \lambda \leq 36.00$ W/mK; $61.00 \leq \omega \leq 70.50$ $Ws^{0.5}/m^2K$; $4.08 \cdot 10^{-7} \leq \alpha \leq 4.23 \cdot 10^{-7}$ m^2/s
Di Luigi et al. [104]	Wheat-straw-based composite materials	CF, silica aerogel	DIW	✓	DSC, TGA	λ (W/mK)	$\lambda = 0.04$ W/mK
Lee et al. [105]	3D printed cellulose aerogel insulation composites	Cellulose, silica aerogel	FDM	✓	HFM, IRT	λ (W/mK)	$\lambda = 34.68$ W/mK
Zhou et al. [106]	3DP graphene-based aerogels	Graphene-based aerogels	FDM	✓	MATLAB	ϕ (%)	$\phi < 5\%$
Shemelya et al. [107]	Polymer matrix composites	ABS, Polymer composites	FDM	✓	CubeSat, Hot Disk	λ (W/mK)	$0.14 \leq \lambda \leq 0.37$ W/mK

As can be seen from Table 1, the most investigated thermal parameters are the thermal conductivity λ and the thermal transmittance U . In detail, the lowest recorded thermal conductivity, 0.04 W/mK, was achieved using wheat straw-based composite materials. Instead, the minimum thermal transmittance value, 0.15 W/m²K was obtained for a 3D printed wall.

2.1.3 3DP for the sustainability of the construction sector

3DP introduces technological innovations across manufacturing processes, promoting industrial digitization, enhancing production speed, improving product quality, and increasing overall performance, with potential positive effects on sustainability at every stage of production [121]. Certain additive processes have demonstrated up to a 70% reduction in environmental impact compared to conventional manufacturing [122–124]. In the construction sector, 3DP has opened up new sustainable possibilities [125], contributing to reducing waste by 30–60% [61] and potentially lowering CO₂ emissions by up to 75% while decreasing construction waste by 86% [126, 127]. Despite these advantages, assessing the energy consumption and environmental impact of 3DP remains challenging due to the lack of standardized methodologies [128–131]. Future research should focus on optimizing design, material selection, and environmental assessment to fully exploit 3DP's sustainable potential [132–135]. 3DP also supports circular economy strategies through the use of recycled and sustainable materials [136–147]. 3DP enables customization, supply chain simplification, reduced manpower, and safer construction practices by automating hazardous tasks [8, 51, 144, 148].

Moreover, the technology can extend product life and improve durability, contributing to social and economic sustainability [148, 149]. To maximize these benefits, coordinated efforts among designers, manufacturers, and environmental experts are essential to understand the full environmental, social, and economic impacts of 3DP [150–152]. As the industry grows rapidly, sustainability assessment and systematic studies of environmental advantages will become increasingly critical, particularly in construction applications [36, 153–159].

2.2 THERMAL TRANSMITTANCE OF WALLS AS AN INDICATOR OF THERMAL PERFORMANCE: TOWARDS INNOVATIVE MEASUREMENT METHODS

A comprehensive understanding of the thermal characteristics of the building envelope is a fundamental prerequisite for conducting a rigorous energy assessment. The accuracy and reliability of such an evaluation are inherently dependent on the selection of appropriate analytical methods, which must be both precise and robust in capturing the envelope's performance under varying conditions. It is only through the judicious implementation of these methodologies that meaningful and reliable results can be obtained, thereby providing a robust foundation for informed decisions regarding energy efficiency improvements.

NDTs play a crucial role in the analysis of the thermal transmittance (U-value) of the building envelope, as they allow in-situ examinations without causing damage to the structure. Among non-destructive techniques, the Heat Flow Meter (HFM) method remains the most widely adopted. Less commonly employed are Infrared Thermography (IRT) and the Thermometric Method (THM), while the most recent advancement in the field is represented by the Enhanced-Thermometric Method (E-THM) [160].

Below, a general overview of the above-mentioned techniques is provided, with reference to the cited works for further information.

2.2.1 Heat Flow Meter (HFM) method

The HFM method is the most widely used since it is standardized and regulated by EN ISO 9869 [161]. It allows transmittance evaluation starting from direct measurement of the heat flow passing through the wall and of the air temperatures in the internal and external environment [162]. The main advantage of this method is certainly the accuracy of the results; however, great attention must be paid not only to the experimental setup and instrumentation used, but also to the state of the sample and the surrounding conditions.

To ensure reliable measurements, the standard [161] establishes specific requirements, including:

- quasi-steady state during the measurement period;
- difference of at least 10°C between the internal and external temperatures;
- minimum measurement duration of 72 hours;
- positioning of the flow plates on surfaces away from thermal bridges;
- positioning of the temperature probes close to the plate, in good contact with the surface;
- absence of direct sunlight, rain, or strong wind.

Ahmad et al. [163] investigated how the orientation of a wall can significantly influence the results of a measurement campaign. Their analyses showed that the same type of wall, when facing east, exhibited a U-value 37.3% higher than that of the same wall facing north. This difference is attributed to the longer exposure of the east-facing wall to solar radiation compared with the north-facing wall.

Similarly, Desogus et al. [164] evaluated the impact of the thermal gradient on measurements, demonstrating that as the difference between internal and external temperatures increases, the error in the results is

significantly reduced. However, de Rubeis et al. [165] demonstrated that, by ensuring steady-state conditions for the analysis, it is possible to obtain reliable values even with a low temperature gradient. In their study, stationarity was guaranteed thanks to the use of the Guarded Hot Box (GHB) apparatus.

With reference to the instrumentation, many studies have highlighted how the positioning of the sensors, the adherence to the support and the sensitivity of the probes can influence the result. In particular, the heat flux plate must be 1,50 m from the floor [166, 167]. The internal and external temperature probes must be installed 30-40 cm from the vertical surface of the wall to avoid convective phenomena [168, 169]. Evangelisti et al. [170] investigated the positioning of the heat flux plate, in summer and winter, highlighting its relevance for the reliability of the result. The plates positioned at high heights between 1,80 m and 2,20 m do not obey the conditions imposed by EN ISO 9869 [161] and also produce differences with respect to the transmittance value calculated with the theoretical method of over 20%, an unacceptable range. In addition to the margin of error induced by the positioning of the heat flux plate, it is important to ensure the effectiveness of the pasting of the probe to the wall. Gaspar et al. [171] noted that the application of a PVC film as a protective wall can actually lead to deviations in the transmittance results due to poor thermal contact between the probe and the wall, providing values that are 19 to 27% lower than the experiment without the film. In this case, extending the measurement time does not overcome the problem. Meng et al. [172] determined the combined influence of thermocouple and heat flow meter positions on U-value measurement accuracy. The study was conducted using a three-dimensional wall heat transfer model, including the effects of thermal bridges in mortar joints, and validated by thermoelectric analogy theory. The results showed that when the probes are glued to the thermal bridges, the measurement error can reach up to 6% for thermocouples and up to 26% for heat flow meters. As can be seen, one of the main limitations of the HFM is caused by the measurement uncertainty related to imprecise installations of the flow probes.

Finally, a significant disadvantage that characterizes the HFM is the long test period required [173], which, according to the EN ISO 9869 [161] standard, must be at least 72 hours. The standard suggests stopping the test when the obtained conductance value deviates by less than 5% from the value obtained in the previous 24 hours. However, very often, measurement campaigns are extended to 7 days to compensate for any unforeseen weather conditions and ensure the accuracy of the results [174]. The long duration of the experimental campaigns makes the method not usable in all circumstances.

2.2.2 Infrared Thermography (IRT)

Compared to traditional in-situ measurement techniques, IRT offers a fast and minimally invasive alternative [175, 176]. Unlike the HFM method, which primarily measures heat transfer by conduction [75- 79], IRT captures the radiative energy received by the target surface [177]. Albatici and Tonelli [176] evaluated the thermal performance of three exterior wall types to assess the practical applicability of the IRT method. Through simultaneous IRT and HFM measurements, they found that the deviation of IRT results was comparable to that of the internationally standardized HFM method, confirming IRT's reliability for field applications.

In recent years, several approaches have been developed to determine thermal transmittance using IRT, with specific formulations depending on whether measurements are taken from the interior or exterior of the building [178]. Exterior measurement models can be broadly categorized into two main approaches: one proposed by Albatici and Tonelli [176], and another by Dall'O' et al. [179]. Both rely on the same convective heat transfer correlation. Nardi et al. [180] validated these methods under controlled conditions using a Guarded Hot Box and obtained comparable results for both.

Nonetheless, numerous studies [181- 184] have highlighted that IRT results are strongly affected by boundary conditions, which remain a major limitation to its accuracy. For instance, Tejedor et al. [181] demonstrated that external air temperature has a significant influence on calculations and that IRT performs better on massive, multi-leaf walls with higher thermal conductivity. Simões et al. [182] emphasized the necessity of steady-state conditions to ensure accurate U-value estimations. Similarly, Nardi et al. [183] underlined the

importance of maintaining a high temperature difference between indoor and outdoor environments, as well as stable weather conditions. Tzifa et al. [184] further noted that short-term IRT measurements can exhibit relative uncertainties up to 20% under real environmental conditions.

As with HFM, the IRT method is also sensitive to boundary conditions, which can significantly influence its accuracy. However, literature consistently shows that HFM techniques generally yield more precise and repeatable results, with mean relative errors of about 3.3% compared to theoretical values [185]. In contrast, IRT—although faster and more flexible—can exhibit substantial variability when boundary conditions are not adequate, with deviations ranging from 6% to 43% relative to HFM results [186]. These findings are further supported by Nardi et al. [187], who reported that U-values derived from IRT differed from those obtained via HFM by between 1.69% and 37.28%.

2.2.3 Thermometric Method (THM) / Enhanced Thermometric Method (E-THM)

Among the various measurement methods, the THM is the least common and least investigated, yet it shows promise due to its simplicity, and lower cost than the more widely used HFM method [162]. Evangelisti et al. [162] provided an overview of the two methods, showing the theory behind their application and detailing the tools required for the experimental setups. The fundamental difference between the HFM and the THM is that the HFM method measures heat flow directly using a specific flow probe, while the THM measures heat flow indirectly by recording surface and air temperatures via probes and considering a fixed surface heat transfer coefficient (h) as established by ISO 6946 standard [188]. The main advantage of the THM method is the absence of a heat flux sensor, which avoids errors deriving from it [162]. A literature study showed that the inaccuracy of the heat flux sensor can reach up to 30% [189]. Moreover, measurement errors can arise from poor contact between the heat flux sensor and the wall surface [189] and the sensor's installation height [170]. However, adopting a fixed value for the heat transfer coefficient entirely disregards the influence of boundary conditions on it. As demonstrated by the study by de Rubeis et al. [190], factors such as the orientation of the wall [163], external environmental conditions [191, 192], the presence of heating or air conditioning systems inside the building [193], and the thermal gradient between the internal and external environments [164] significantly affect the measurements.

For this reason, building upon the Thermometric Method (THM), Evangelisti et al. [194] developed a low-cost, tailor-made measurement system within the research project “Thermometric Method Enhancement for building wall Thermal Resistance evaluation” (THE-METHER). This novel system implements the Enhanced Thermometric Method (E-THM), designed to estimate heat flux indirectly through a completely contactless approach. The setup allows for fully non-contact temperature measurements, enabling the assessment of building façade thermal performance without any physical interaction with the surface. This feature is particularly advantageous for historic buildings, where conventional techniques often rely on adhesives or mechanical supports that may conflict with conservation principles. The E-THM evolves from the classical THM, which estimates heat flux indirectly from temperature data. The term “enhanced” does not refer to an entirely new methodology but rather highlights a series of methodological improvements. In particular, the E-THM simultaneously considers both convective and radiative heat transfer, applying dimensionless numbers to rigorously determine the prevailing heat transfer regime [195].

2.3 FROM DIGITAL MODEL TO EFFICIENT BUILDING: THE ROLE OF BIM IN ENERGY-CONSCIOUS DESIGN

In a context in which the construction industry represents one of the sectors most responsible for global carbon emissions and energy consumption [196], improving the management of a building's energy and environmental performance across its entire life cycle is essential. Current building design practices need to be reconsidered to incorporate innovative technologies that address energy efficiency from the earliest stages of a project.

In the past two decades, BIM has established itself as a tool with the potential to revolutionize the construction industry [197]. The potential of BIM lies in its ability to accurately and comprehensively recreate a building's architectural features in digital form [198]. According to the National Building Information Model Standard Project Committee in the United States, “BIM is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition” [199]. Through detailed 3D modeling, it provides a highly accurate representation of the building's components, enabling different users to fully understand all aspects of the project [200 -206]. BIM provides valuable support throughout a building's entire lifecycle, from the design phase to demolition or renovation [197, 207, 208], as illustrated in Figure 2.

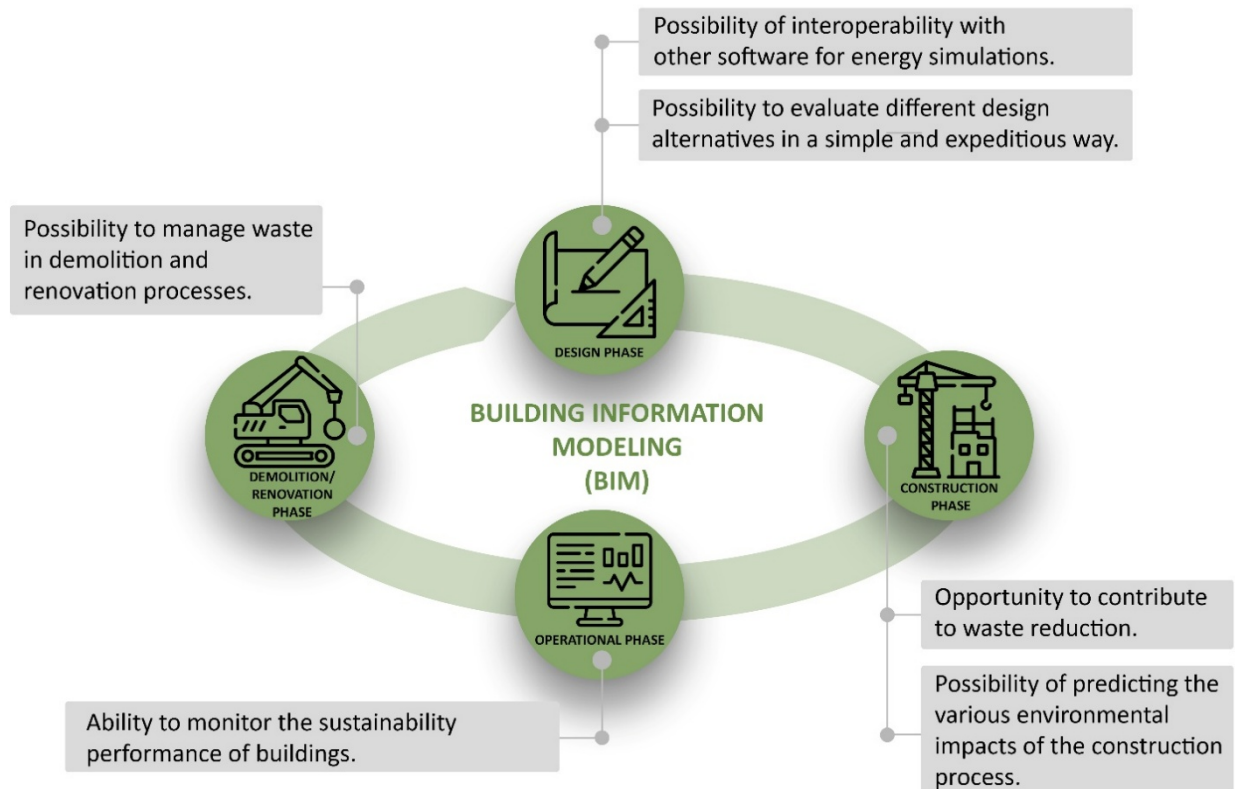


Figure 2. BIM support during the various phases of the construction process.

The design phase of a building is critical for making informed and environmentally responsible decisions [209–213]. A BIM-based model enables construction stakeholders to collaborate effectively, ensuring that sustainability measures are seamlessly integrated throughout the design process [197, 209, 214]. BIM's ability to exchange data with other software allows professionals from various disciplines to work on the same project, addressing different aspects while fostering a cohesive and multidisciplinary dialogue. Its interoperability also allows energy considerations to be incorporated during the conceptual phase, enabling the evaluation of design alternatives that enhance indoor comfort and energy efficiency during the building's operational phase [215, 216]. Accurate predictions of a building's energy performance are essential for minimizing its environmental impact [217–222].

Additionally, the 3D model created during the design phase helps estimate the precise quantities of construction materials, contributing to waste reduction [223, 224].

During the operational phase, BIM can also support monitoring and controlling indoor thermal comfort [225].

Finally, BIM proves valuable in managing waste during demolition and renovation [226].

2.3.1 BIM–BEM Interoperability

Interoperability refers to the capability of different software systems to exchange and utilize information effectively [247]. Smooth communication between modeling tools is essential for fostering a collaborative design environment [247]. In recent years, interoperability between BIM and BEM tools has gained growing attention. The BIM-based BEM approach uses architectural design data as input to create an energy model, enabling designers to make informed decisions after evaluating multiple design alternatives [248]. This methodology aims to generate the building's energy model directly from its architectural model, thereby saving modeling time and improving the integration of energy and architectural aspects. However, the full potential of BIM is often limited by data loss—both geometric and thermal—that occurs during the export process [244, 249]. In some cases, this loss results in inaccurate geometric surfaces [250], while in others, it involves missing information about thermal properties or HVAC systems [251]. Such inconsistencies can lead to errors in simulation results [245]. Due to these unresolved issues in data exchange, interoperability between BIM and BEM remains underutilized by professionals [252]. For complex buildings, substantial manual adjustments are often required after transferring the model, making the BIM-to-BEM workflow cumbersome and impractical when deadlines are tight. Nonetheless, this topic continues to attract significant research interest, with efforts focused on developing new methods to improve integration between the two systems [247]. Advancements in this field are crucial to achieving effective coordination between a building's passive elements (e.g., envelope) and active systems (e.g., Heating, Ventilation and Air Conditioning-HVAC). In this regard, it is vital to develop tools that can manage various design aspects dynamically, accommodating changes throughout the design process. Currently, four main BIM–BEM interoperability strategies have been identified [247, 253]:

1. Real-time connection.
2. Standardized exchange formats and middleware correction tools.
3. Adherence to Model View Definitions (MVDs).
4. Proprietary tool chains.

A literature search conducted revealed that the most used interoperability strategy is that of standardized exchange formats and middleware corrective tools, with 60% of publications, followed by the proprietary tool-chain (23%), and real-time connection (11%). The least common strategy was found to be adherence to MVD (6%), as shown in Figure 3.

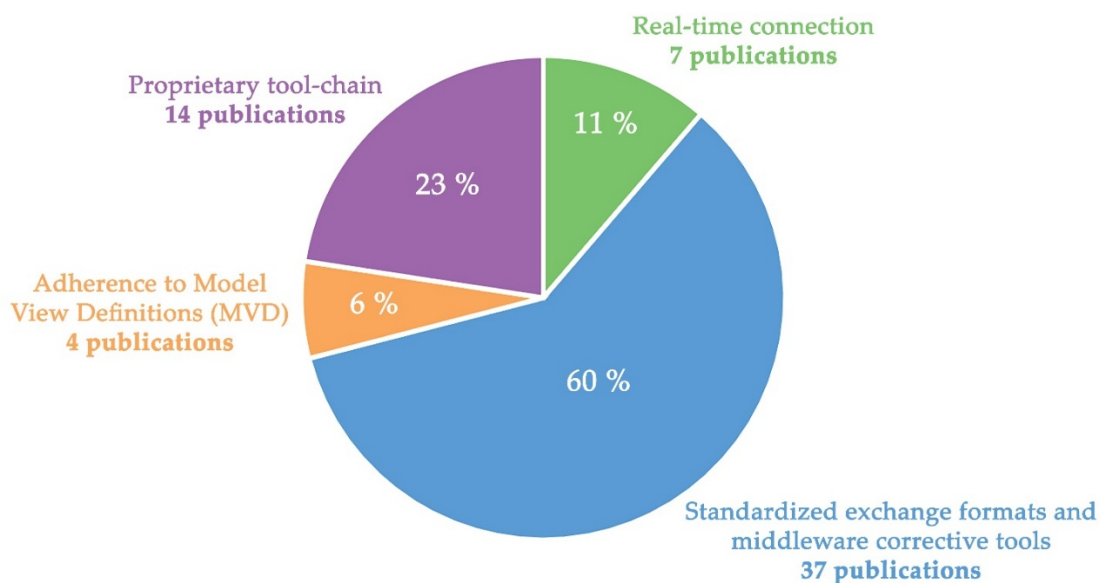


Figure 3. Percentage spread of interoperability strategies in the papers analyzed in this review.

The following provides an overview of BIM–BEM interoperability strategies, outlining their respective strengths and limitations.

1. Strategy 1- Real-time connection

In the latest versions of BIM software, it is now possible to install energy simulation plugins that enable the creation of an energy analytical model directly from the architectural model [247]. This eliminates the need to export or import data between different software programs, thereby reducing modeling errors [253]. Moreover, any design modifications are instantly reflected in the energy analysis results [253]. Among tools adopting this “Real-time connection” interoperability strategy, Autodesk Insight 360, which can be integrated as a plugin in Revit, is the most widely used for energy analysis [217, 218, 227, 254–257] (Figure 4).

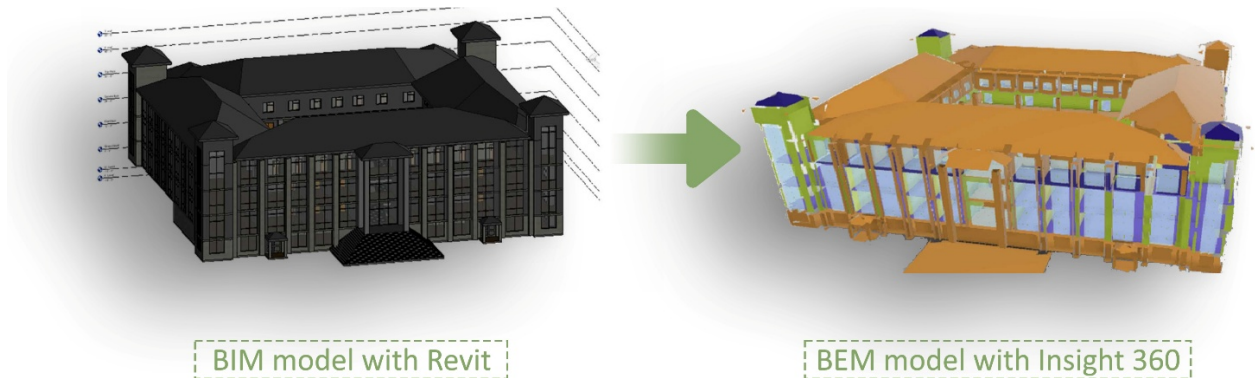


Figure 4. Creating the energy model using Autodesk Insight 360. Adapted from [227].

However, currently, these BIM plugins can only deliver general, building-level energy analyses and are not yet capable of providing detailed assessments of individual thermal zones or specific building components. Therefore, they are more suitable for preliminary rather than advanced energy evaluations. Additionally, many of the available features in these applications remain limited and lack customization options [255].

2. Strategy 2 - Standardized Exchange Formats and Middleware Corrective Tools

Currently, the Industry Foundation Class (IFC) and Green Building XML (gbXML) formats are the two most commonly used standardized data exchange formats for transferring information between different software platforms [258, 259].

Several studies have explored BIM–BEM interoperability, showing that while gbXML and IFC formats enable data exchange between modeling and energy simulation tools, challenges remain—such as geometric inconsistencies, HVAC data inaccuracies, and software performance issues with large models [251, 260–262]. Some research works have compared IFC and gbXML formats, examining their technical challenges, applications, and limitations [214, 221, 250, 258, 263, 264]. While IFC can represent virtually any geometric shape, gbXML is limited to rectangular geometries [265]. However, gbXML supports the transfer of environmental data and thermal zone information from BIM, which IFC does not [258, 266]. Porsani et al. [250] found that while gbXML was generally easier to export than IFC, complex building geometries led to geometry loss and unreliable energy simulations with both formats, with different energy results observed even for simpler models (Figure 5).

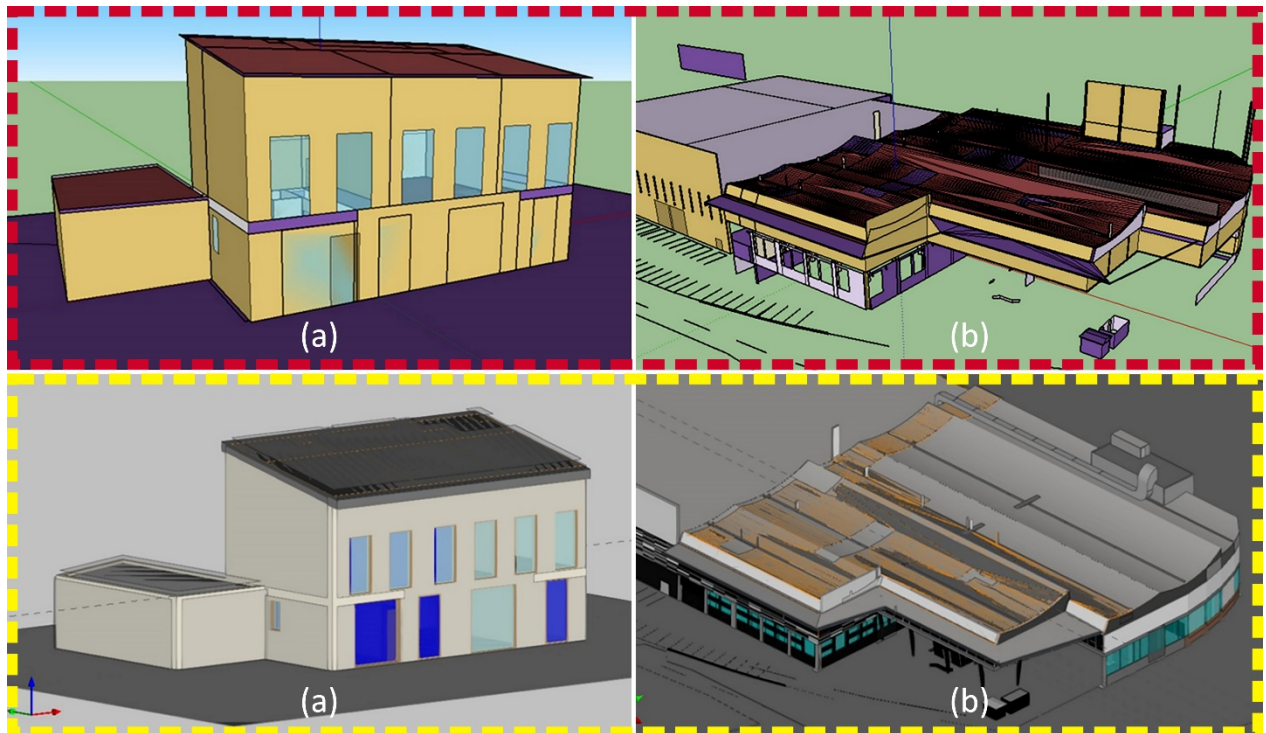


Figure 5. Comparison between the standardized exchange formats. In red are the models exported in gbXML; in yellow are the models exported in IFC. (a) Residence (simple geometry well recognized). (b) Industrial warehouse (complex geometry, with information loss). Adapted from [250].

A major limitation in the current data exchange process using standardized formats—both IFC and gbXML—is the loss of information that occurs when models are imported into analytical software [99].

To address this issue, middleware tools have been developed to enhance IFC and gbXML files by adding missing or incomplete information [247, 253]. A review of the literature identified several studies focused on the development of middleware solutions aimed at improving interoperability and data transfer between BIM and BEM platforms [267–292] (Figure 6).

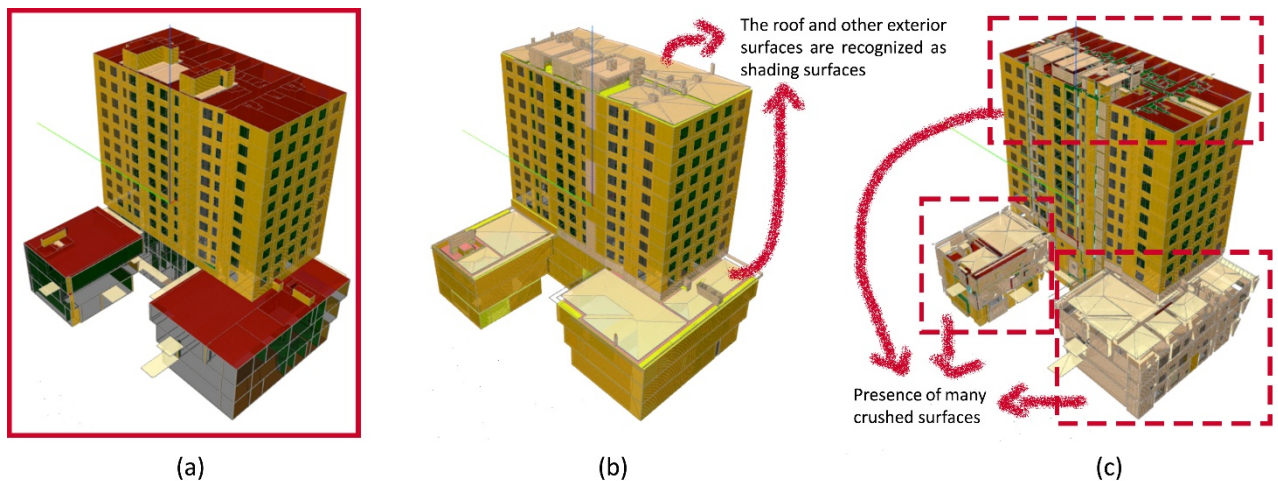


Figure 6. Comparison of three different gbXML exports. (a) Using the workflow developed in the work [272]. (b) Using “Room Volumes” in Revit. (c) Using “Energy Model” in Revit. Adapted from [272].

Although middleware tools remain one of the most commonly used interoperability solutions, they have significant disadvantages. Among these, a major one is the reliance on data sources external to the BIM environment, which can introduce errors or duplicate information. Furthermore, middleware tools are often designed for specific simulation software and particular scenarios, limiting their applicability to different case

studies [247]. For the above reasons, it is often necessary to proceed with a manual simplification of the BIM model (Figure 7).

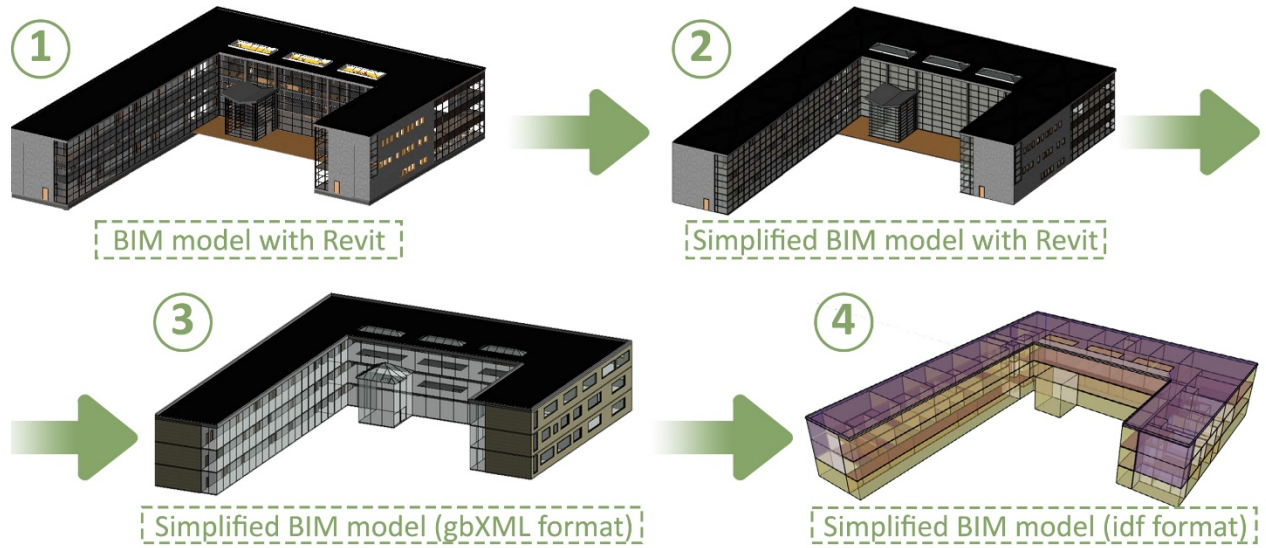


Figure 7. Process of simplifying the BIM model. Adapted from [275].

3. Strategy 3 - Adherence to Model View Definitions (MVD)

Many existing workflows based on the IFC format deviate from the primary objectives of energy simulation tools. In reality, BEMs do not require all the detailed information contained within IFC files. To address this issue, Model View Definitions (MVDs) were developed as subsets of the IFC schema [293]. MVDs specify which data sets are relevant and can be exported to BEM software [293- 297], following the Information Delivery Manual (IDM) methodology (Figure 8). This approach offers high flexibility since it is not tied to any proprietary software [247].

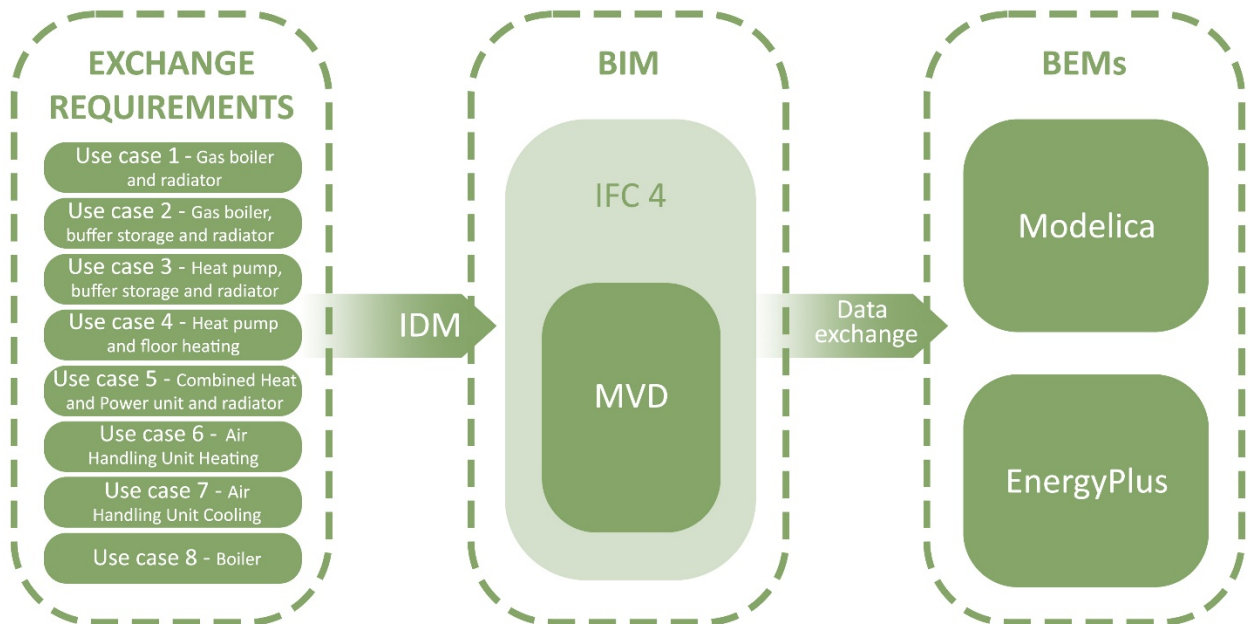


Figure 8. The methodology used for the development of the MVD, extracting the information necessary for the BEM software from eight use cases. Adapted from [294].

Despite the promise of MVD-based interoperability strategies, challenges remain due to the incomplete compatibility between BIM platforms and the IFC4 standard, as well as the need for customized MVDs tailored to specific applications [247].

4. Strategy 4 - Proprietary Tool-Chain

This interoperability strategy relies on proprietary software—typically the BIM Application Programming Interface (API)—to facilitate data transfer between BIM and Building Energy Modeling (BEM) tools. By using the software’s API, data loss is minimized because the exchange process remains fully compatible with the BIM environment [298- 311] (Figure 9).

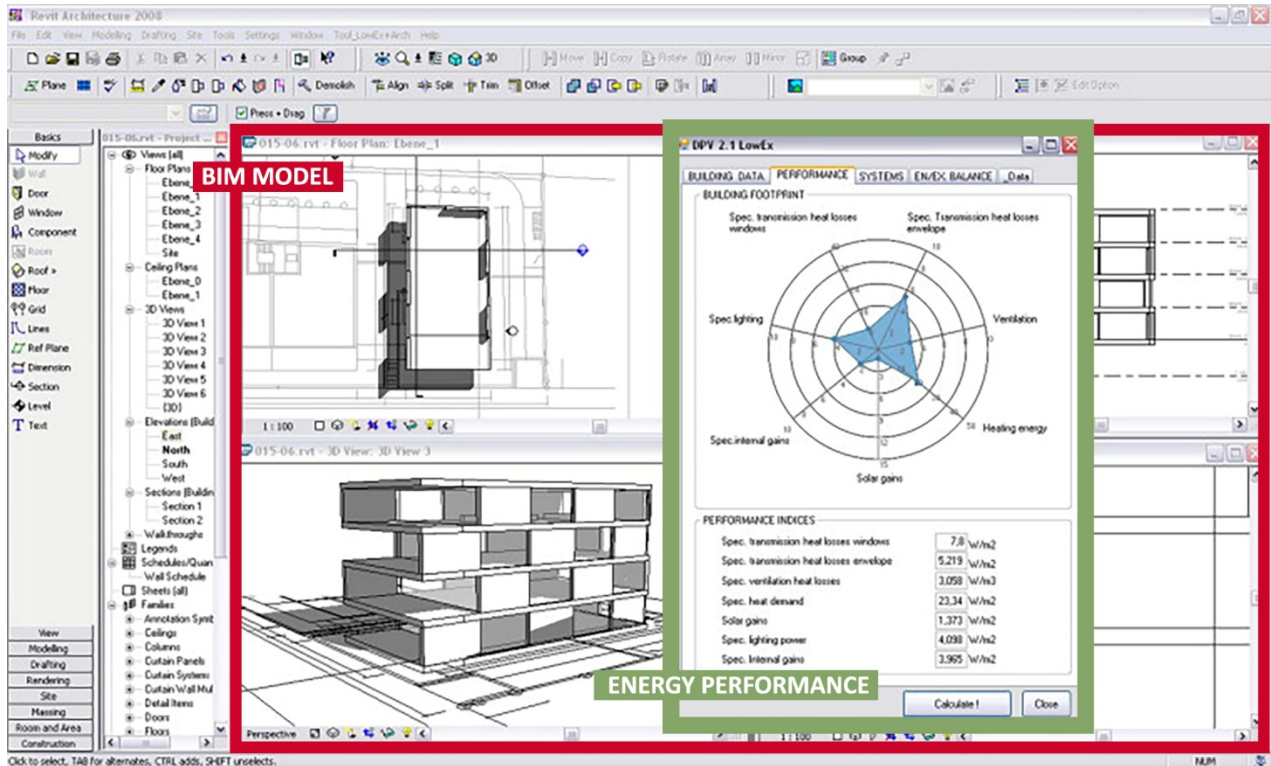


Figure 9. Comparison between architectural design and energy results. Adapted from [309].

In general, the proprietary toolchain approach offers several advantages—minimal data loss during model transfer, immediate access to energy simulation results, and real-time evaluation of design alternatives. However, its main limitation lies in its dependency on vendor-specific software, which restricts interoperability and scalability across different platforms.

2.3.2 BIM for photovoltaic system design

BIM has recently emerged as a tool capable of providing significant support in energy-related design, as it allows for the simple and rapid evaluation of various design alternatives, facilitating the choice of the most appropriate one. One of the contexts in which this technology is increasingly gaining ground is the design of photovoltaic (PV) systems.

The design of a PV system involves numerous interrelated factors that are difficult to analyze accurately through manual design methods. Traditional approaches typically rely on theoretical equations to assess energy demand, estimate solar resources, size system components, and analyze tilt, orientation, shading, and basic performance. However, manual design is not only cumbersome but also limited in several ways [312, 313]:

- Calculations often lack accuracy due to the use of static analyses that ignore temporal data variations;
- Loss estimations (e.g., from mismatches or wiring) are oversimplified;

- Complex roof geometries and surrounding contexts cannot be easily visualized;
- The process is time-intensive;
- It is difficult to rapidly test and compare multiple design scenarios;
- Calculation errors are more likely to occur.

Today, various software tools exist to assist in PV system design. Each tool typically focuses on specific functions and must be integrated with others to achieve a comprehensive, implementation-ready project. However, these tools often fail to communicate effectively, resulting in fragmented and disconnected design workflows. Moreover, most PV simulation tools do not directly support the integration of PV systems within buildings, leading to design inconsistencies [314, 315]. The lack of interoperability between PV simulation and building design software further fragments the process into separate, non-communicating phases [315, 316]. This compartmentalized approach creates model incompatibilities, complicates synchronization across project stages, and hampers collaboration among professionals [317]. As a result, resolving conflicts between models often requires specialized expertise, increasing project costs and complexity [318].

BIM facilitates highly accurate and realistic performance simulations [319] and is increasingly used for PV system design and building integration [320]. It supports multi-scenario analyses, including solar studies [227] and performance assessments. The ability to compare different design strategies is crucial for PV systems, whose efficiency depends on factors such as module characteristics, costs, climate data, and solar radiation. The quantity, angle, and stability of solar irradiance determine the system's potential energy output. Variables such as geographic location, panel orientation and tilt, shading, and local weather conditions (cloud cover, dust, temperature) all influence solar availability. Therefore, accurate solar radiation analysis during design is vital for optimizing layout and maximizing energy yield [321, 322], and BIM offers significant support in this regard. Integrating BIM and PV technologies promotes sustainable project development across multiple applications, including building-integrated photovoltaics (BIPV) [323–326], building-applied photovoltaics (BAPV) [327], and PV systems in both historical buildings [328] and skyscrapers [329]. Nonetheless, despite the growing adoption of BIM in the energy sector, research in this field remains nascent. The absence of standardized procedures for PV integration within BIM workflows [330] continues to hinder consistent and widespread implementation.

The literature search conducted on the application of BIM for PV plant projects [324–336] revealed that: (i) a fully defined workflow based entirely within a BIM environment is still lacking [324, 325, 327, 329, 334, 337–339]; (ii) certain aspects of photovoltaic (PV) system design are treated with less precision than others, resulting in an imbalance across the various design stages [326, 328, 331, 333, 3335, 336]; and (iii) design software is often used in isolation, hindering the unification of the overall design process [332].

2.3.3 BIM-based Digital Twin for monitoring and optimization

As BIM and related technologies continue to advance, there is an increasing interest in real-time building monitoring and control to enhance comfort, security, and overall quality of life. This is achieved through the management of real-time data collected from installed sensors. From a technical standpoint, several modern monitoring solutions are now available that are low-cost, minimally invasive, and easy to install. However, traditional monitoring systems often face significant limitations in the data visualization and processing phase, which is typically cumbersome, unintuitive, and difficult to scale [340].

Moreover, the lack of seamless information exchange between physical and digital systems hampers the rapid identification of critical issues, thereby reducing the efficiency and intuitiveness of real-time monitoring—particularly in multi-environmental contexts. Developing more intuitive interfaces that clearly illustrate the relationships between indoor comfort parameters and the building's structure could actively engage users in energy management, fostering their participation in the optimization process.

In this context, BIM offers a promising solution to many of the shortcomings of current monitoring approaches while supporting closer integration between architectural and energy systems. Through three-dimensional informative modeling of both new and existing buildings, BIM provides an exceptionally accurate virtual representation of all building components, serving as a reliable basis for decision-making throughout the entire life cycle of the facility [199, 341–344]. However, managing dynamic real-time data were not part of BIM's original design, resulting in a lack of such capabilities in BIM software [345].

In response to these limitations, the concept of the digital twin (DT) has emerged as a promising solution and is gaining significant attention [346]. A digital twin is defined as “the virtual representation of a physical entity, living or non-living, of a person or even a complex system connected to a physical part and with which it can exchange data and information, both in synchronous mode (in time real), than asynchronous (in subsequent times)” [347]. While BIM primarily provides a static, data-rich model, a digital twin extends this framework by incorporating live data and analytics during the operational phase. This enables real-time monitoring, predictive maintenance, and scenario-based simulations.

The integration of BIM and digital twin technologies results in a powerful synergy for asset management. By combining static models with live operational data, digital twins enable a deeper understanding of building performance under varying conditions. Given its potential, DT technology could play a pivotal role in enhancing both the communication and processing of sensor-derived data, offering numerous advantages in the energy sector. Firstly, its user-friendly interface fosters more effective interaction between the building, its systems, and occupants. This, in turn, increases user awareness and engagement—key factors for the responsible management of indoor environments. Actively involving end users in the monitoring process can encourage behavioral improvements in energy consumption habits [348]. Moreover, the adoption of DT technology provides substantial benefits for both immediate and long-term energy interventions. Facility managers can continuously and simultaneously monitor data from multiple sensors distributed throughout the building, enabling the rapid detection of anomalies and precise localization of issues—even remotely. This capability supports proactive maintenance strategies, facilitating timely interventions when required [349]. In addition, integrating DT systems with automated control mechanisms allows for the regulation of environmental parameters within predefined thresholds, ensuring optimal indoor conditions. For planned energy upgrades, historical monitoring data can be utilized to calibrate the building's thermal model, resulting in more accurate and reliable energy analyses that can serve as a foundation for optimization projects. Finally, in extended monitoring scenarios involving numerous spaces, the instantaneous and automated data processing offered by an integrated BIM–DT platform minimizes the risk of human error in data interpretation, further enhancing the accuracy and efficiency of energy management processes.

To date, numerous researchers have explored this approach. Marzouk et al. [225] integrated wireless sensors with a BIM model of a subway system to monitor its thermal conditions. Lin and Cheung [350] proposed a visually enhanced solution for environmental monitoring and management. Wang et al. [351] facilitated real-time environmental monitoring by semantically enriching BIM models with sensor data for facility management applications. Spudys et al. [352] employed digital twin (DT) technology to conduct an energy assessment of a case study building. Similarly, Opoku et al. [353] combined sensor networks with BIM to continuously monitor thermal comfort, lighting, and air quality within a library. Qian et al. [354] proposed an intelligent indoor air quality management system based on digital twin platforms, while in a subsequent study, the same authors [355] applied DT technology to comprehensively analyze the thermal environments of interior and semi-open spaces in traditional Chinese courtyard dwellings.

Despite the growing academic interest in digital twin technology, its practical implementation in the professional sector remains limited, constrained by a lack of standardized methodologies that hinder its widespread adoption.

2.4 OUTCOMES: KNOWLEDGE GAPS AND RESEARCH OPPORTUNITIES

3DP within the construction sector has underscored its potential to significantly reduce the energy footprint of buildings. By leveraging complex geometries and advanced materials, 3DP has demonstrated the ability to optimize the thermal performance of walls, yielding substantial benefits for overall building energy efficiency.

A comprehensive review of the literature identifies two primary strategies for enhancing the thermal properties of building envelopes through 3DP: (i) topology optimization and (ii) material optimization. Most studies employing the first strategy have focused on the internal geometric configuration of walls, while the second strategy has predominantly explored modifications to the composition of printing materials, with more than half of these experiments achieving promising results. The analyzed studies indicate that 3DP can reduce wall thermal transmittance by up to 70% and produce insulating materials with thermal conductivity values below 0.04 W/mK. Figure 10 illustrates a comparison of the optimization strategies adopted in these works, highlighting their impact on the thermal performance of building envelopes.

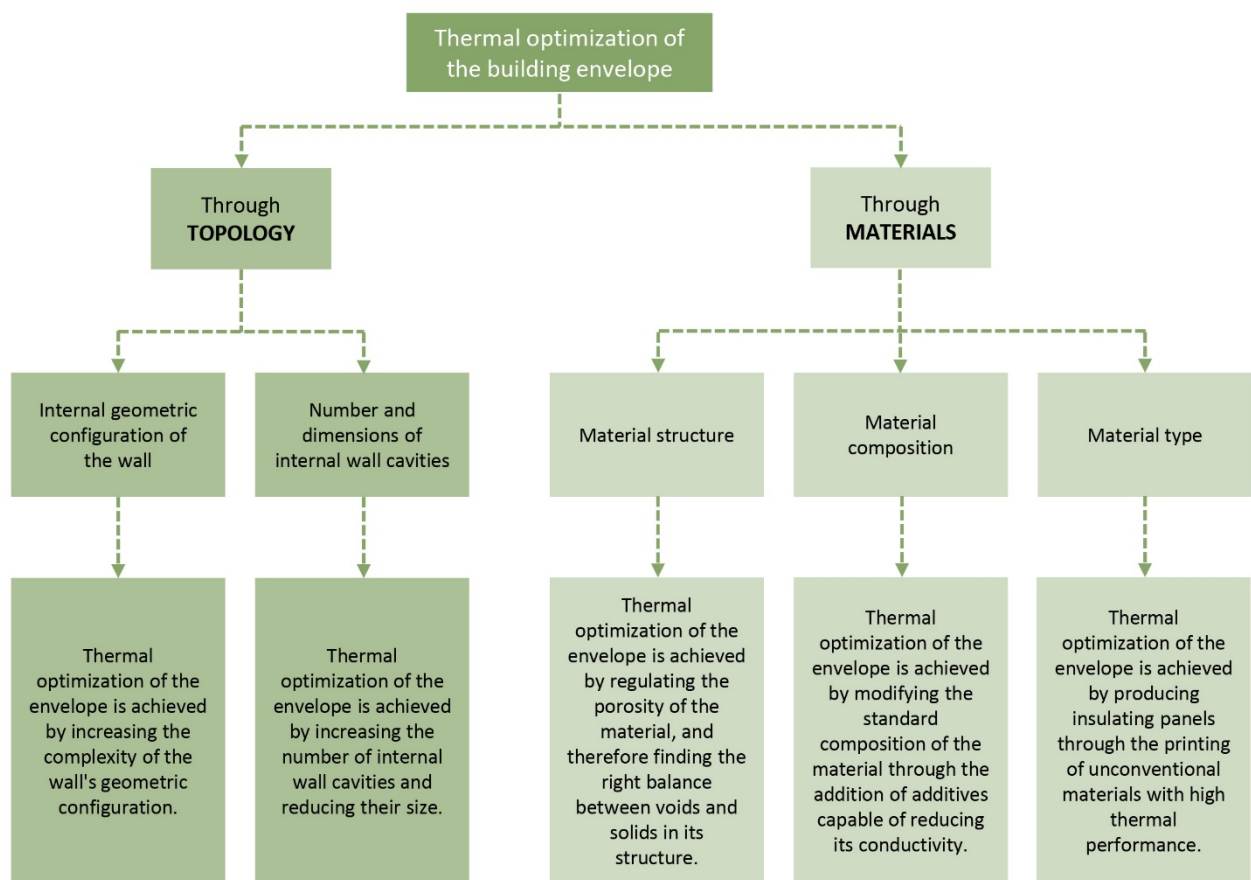


Fig. 10. Summary of research results.

Despite these encouraging outcomes, research in this field remains at an early stage. Therefore, further efforts are needed to conduct comprehensive investigations into building thermal optimization through 3DP. Future lines of research may focus on finding thermally efficient geometries, using waste materials to reduce the thermal conductivity of building components, and adopting environmentally friendly printing materials.

NDTs play a crucial role in achieving a comprehensive understanding of the thermal behavior of the building envelope, as they enable in-situ investigations without causing any damage to the structure. To date, there are various non-destructive techniques, some more traditional and common (HFM), others less used (IRT, THM) or more innovative (E-THM). Several studies have tested the use of the aforementioned techniques, identifying

the potential and limitations of each of them. Table 2 summarizes the main advantages and disadvantages of the methods, based on the literature search carried out.

Table 2. Main advantages and disadvantages of NDTs for calculating the thermal transmittance of walls.

Approach	Advantages	Disadvantages
HFM	• Standardization of the method • Accuracy of results, if experimental requirements are met • Direct measurement of heat flux	• Influence of boundary conditions • Uncertainty due to imprecise flow probe installations • Long duration of the experimental campaign
IRT	• Speed of the experimental campaign • Low invasiveness • No flow probe-related errors	• Influence of boundary conditions • Lack of standardization of the method • Greater uncertainty in measurements
THM	• Low invasiveness • Low cost • No flow probe-related errors	• Using a fixed value for the heat transfer coefficient h
E-THM	• Low invasiveness • Low cost • No flow probe-related errors	• Influence of boundary conditions • Lack of standardization of the method • Method still under development

Each of the methods mentioned above currently has advantages and disadvantages. Therefore, it's important to be fully aware of the limitations of the different approaches to ensure the accuracy and reliability of the data obtained.

The design of a high-energy-performance building requires the achievement of full integration among all its components and systems so that each element performs its function effectively while harmoniously interacting with the others. Meeting this challenge requires the adoption of innovative technologies capable of addressing energy efficiency from the earliest design stages and of better managing the entire design process, integrating all the aspects that characterize a project.

In this context, in recent years, BIM has emerged as a transformative tool with the potential to significantly influence the green footprint of buildings, as it is able to provide support throughout their entire lifecycle, from the design phase to demolition or renovation.

BIM's capacity to exchange data and information with other software enables multiple professionals to collaborate on the same project, addressing different aspects while fostering a harmonious and multidisciplinary dialogue. Its potential for interoperability allows energy considerations to be incorporated from the conceptual design phase, facilitating the evaluation of design alternatives that can enhance both indoor comfort and energy efficiency during the building's operational life.

To date, interoperability between BIM and energy modeling software is addressed using four main strategies, schematized in Figure 11.

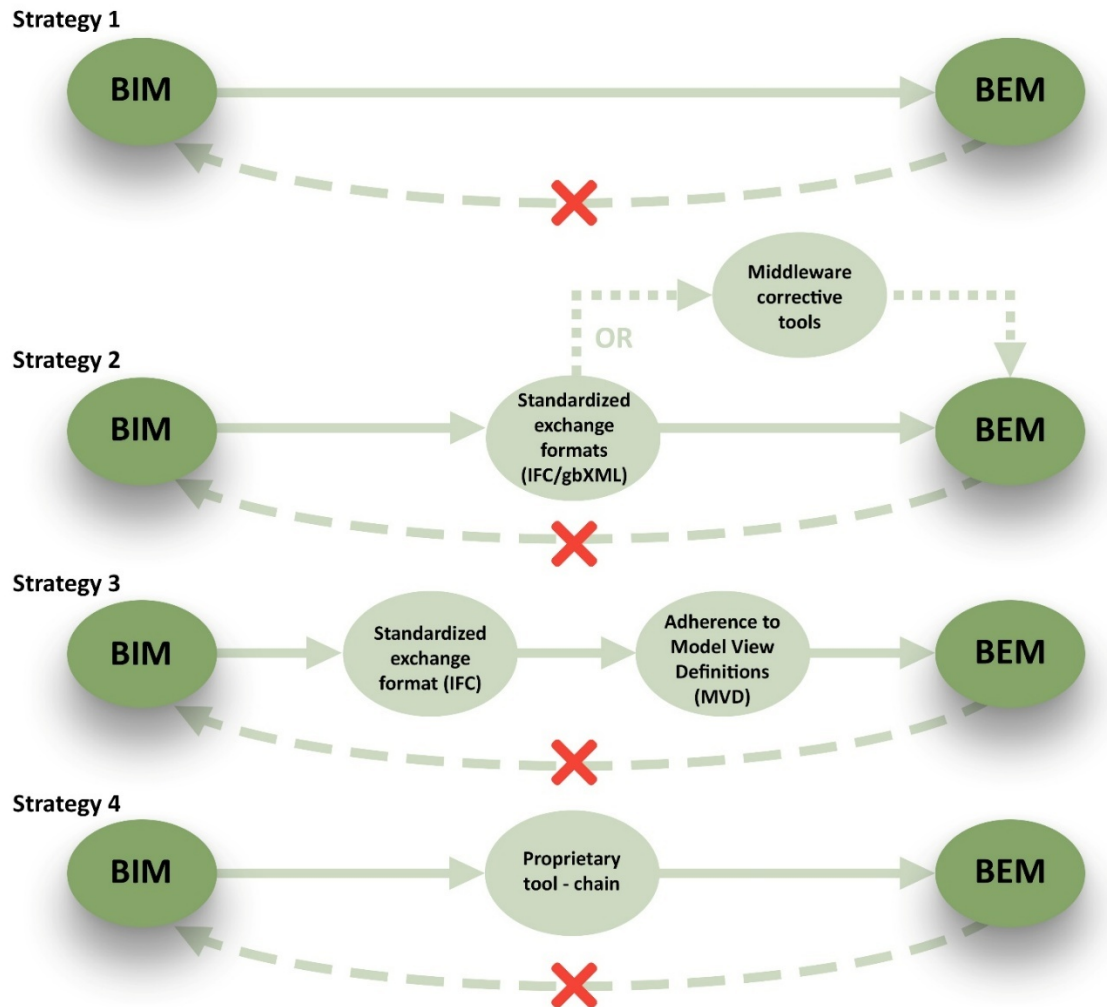


Figure 11. Comparison of different BIM–BEM interoperability strategies.

The potential and limitations of each strategy are summarized in Figure 12.

PARAMETERS STRATEGIES	CORRECT DATA EXPORT	DIRECT TRANSFER BETWEEN BIM AND BEM	POSSIBILITY TO CARRY OUT DETAILED ENERGY ANALYSES	REAL TIME CONNECTION OF BIM AND BEM MODELS	APPLICABILITY TO ALL CASE STUDIES / VERSATILITY	INDEPENDENCE FROM PROPRIETARY SOFTWARE	POSSIBILITY OF CUSTOMIZATION OF OPERATIONS
I. REAL-TIME CONNECTION	😊	😊	😞	😊	😊	😊	😞
II. STANDARDIZED EXCHANGE FORMATS AND MIDDLEWARE CORRECTIVE TOOLS	😞	😐	😊	😞	😐	😊	😊
III. ADHERENCE TO MODEL VIEW DEFINITION (MVD)	😊	😐	😊	😞	😊	😊	😊
IV. PROPRIETARY TOOL-CHAIN	😊	😊	😊	😐	😊	😞	😊

LEGEND

😊 ALWAYS 😐 NOT ALWAYS 😞 NEVER

Figure 12. Comparison between interoperability strategies pros and cons.

As observed, communication between the software poses challenges that, although frequently identified in the literature, are often not addressed in practice. Furthermore, in the literature, there is a tendency to study the different approaches to energy modeling individually, without comparing them with each other.

In addition to the problems related to interoperability between BIM and other energy analysis software, there is also a lack of unified protocols that facilitate the use of BIM-based workflows for design and monitoring in the energy sector.

The standardization of BIM-driven procedures is essential to facilitate the use of the tool in the professional field and to encourage the digitalization of the construction sector.

SUMMARY

2.1 Building components and thermal performance: the potential of additive manufacturing in construction

Industrial production has a significant environmental impact, and in the construction sector—traditionally low-tech and reliant on manual labor—adopting innovative technologies is crucial to reduce these effects.

3D Printing (3DP), or Additive Manufacturing (AM), represents a potentially transformative solution: it enables highly automated processes, reduces waste, emissions, and costs, and allows the creation of complex, customized geometries that can improve both the thermal and mechanical performance of buildings.

Originating in the 1980s with Hull's invention of stereolithography, 3DP now includes several techniques (e.g., Material Extrusion, Powder Bed Fusion, Vat Photopolymerization) and is increasingly applied in construction, particularly through 3D concrete printing methods such as Contour Crafting, Concrete Printing, and D-Shape.

Despite still being in development, 3DP holds great promise for enhancing building energy efficiency and sustainability—cutting material waste and CO₂ emissions, promoting digitalization, and advancing a circular and environmentally conscious construction industry.

By using complex geometries and advanced materials, 3DP has demonstrated that it can significantly improve the thermal performance of building components. Research identifies two main optimization strategies: i) optimization through topology, and ii) optimization through material. The first strategy works on the internal geometric configuration of the walls and on the number and size of the internal cavities, the second on the structure, composition, and type of material.

CHALLENGES

Research in this field remains at an early stage. Therefore, further efforts are needed to conduct comprehensive investigations into building thermal optimization through 3DP.

RESEARCH OPPORTUNITIES

Future lines of research may focus on finding thermally efficient geometries, using waste materials to reduce the thermal conductivity of building components, and adopting environmentally friendly printing materials.

2.2 Thermal transmittance of walls as an indicator of thermal performance: towards innovative measurement methods

A thorough understanding of a building envelope's thermal behavior is essential for accurate energy assessments, which rely on precise and reliable analytical methods. Non-destructive techniques (NDTs) are crucial for determining thermal transmittance (U-value) without damaging structures. Below are the main approaches that emerged from a literature search.

- The Heat Flow Meter (HFM) method is accurate and standardized, directly measuring heat flux, but it is time-consuming and highly sensitive to boundary conditions and probe placement.
- The Infrared Thermography (IRT) method is fast, non-invasive, and avoids probe flow-related errors, though it lacks standardization and its accuracy depends strongly on environmental conditions.
- The Thermometric Method (THM) method is quick, inexpensive, non-invasive, and avoids probe flow-related errors, but its reliance on a fixed heat transfer coefficient (h) limits precision. For this reason, building upon the THM, the Enhanced-Thermometric Method (E-THM) method shares its advantages, with added improvements regarding the calculation of h , but it is still under development, lacks standardization, and remains sensitive to boundary conditions.

CHALLENGES

Each NDT currently used has advantages and disadvantages.

RESEARCH OPPORTUNITIES

It's essential to be fully aware of the limitations of the different approaches to ensure the accuracy and reliability of the data obtained.

2.3 From digital model to efficient building: the role of BIM in energy-conscious design

Designing a high-energy-performance building requires full integration of all its systems and components from the earliest design stages. In this context, Building Information Modeling (BIM) has become a transformative tool with the potential to significantly influence the green footprint of buildings, as it is able to provide support throughout their entire lifecycle, from the design phase to demolition or renovation.

BIM's ability to exchange data with other software fosters effective collaboration among professionals, enabling multidisciplinary integration throughout the design process. Its potential for interoperability allows energy analyses to be incorporated from the conceptual phase, supporting the evaluation of design alternatives that improve indoor comfort and overall energy efficiency. To date, there are four main BIM-BEM interoperability strategies: (1) real-time connection; (2) standardized exchange formats and middleware corrective tools; (3) adherence to model view definitions (MDV); (4) proprietary tool-chain. These strategies were found to be characterized by different degrees of complexity, time required for information exchange, proprietary or opensource software, ability to reduce information loss, and detailed energy results.

Recently, BIM has proven to be a valuable tool for energy-related design, enabling quick and efficient assessment of multiple design alternatives and helping identify the most suitable solution. Its application is increasingly prominent in the design of photovoltaic (PV) systems.

In the context of the operational management of a building, the integration of BIM and digital twin (DT) technologies results in a powerful synergy for asset management. By combining static models with live operational data, digital twins enable a deeper understanding of building performance under varying conditions. Given its potential, DT technology could play a pivotal role in enhancing both the communication and processing of sensor-derived data, offering numerous advantages in the energy sector and overcoming the limitations of current monitoring systems.

CHALLENGES

Communication between BIM and energy analysis software faces persistent challenges that, while widely recognized in the literature, are rarely addressed in practice. Research often examines energy modeling approaches individually rather than through comparative studies, limiting a full understanding of their relative performance. Moreover, there is a notable lack of unified protocols to guide the use of BIM-based workflows for both design and monitoring in the energy sector.

RESEARCH OPPORTUNITIES

Future research should aim to address the persistent challenges in interoperability between BIM and energy modeling software, focusing on developing practical methods that ensure seamless data exchange while minimizing errors.

Furthermore, standardizing BIM-driven workflows is essential to create unified procedures for energy design, simulation, and monitoring, ensuring reliability, repeatability, and practical usability in professional settings.

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3. MATERIALS AND METHODS

3.1 OVERVIEW OF THE MULTISCALE APPROACH

This research was developed through a multiscale approach, encompassing several interconnected levels of investigation that progressed from the individual building component to the architectural element, and ultimately to the building as a whole. This hierarchical perspective enabled a comprehensive and integrative examination of the subject, which moved beyond the isolated assessment of single components to consider their mutual interactions, interdependencies, and cumulative influences within the overall architectural system.

By systematically shifting across scales, the study was able to capture both micro-level phenomena—associated with the specific performance and behavior of individual materials or components—and macro-level dynamics, which pertain to the integrated operation, efficiency, and spatial coherence of the entire building. This cross-scalar approach thus facilitated a more holistic understanding of architectural performance, bridging detailed technical insights with broader systemic interpretations.

3.2 METHOD AND TOOLS FOR APPLYING THE APPROACH

The research work developed gradually from the micro-scale of the building component to the macro-scale of the entire building. Figure 1 provides a general overview of the work phases involved in each level of analysis, which will be explored in greater detail in the following subsections.

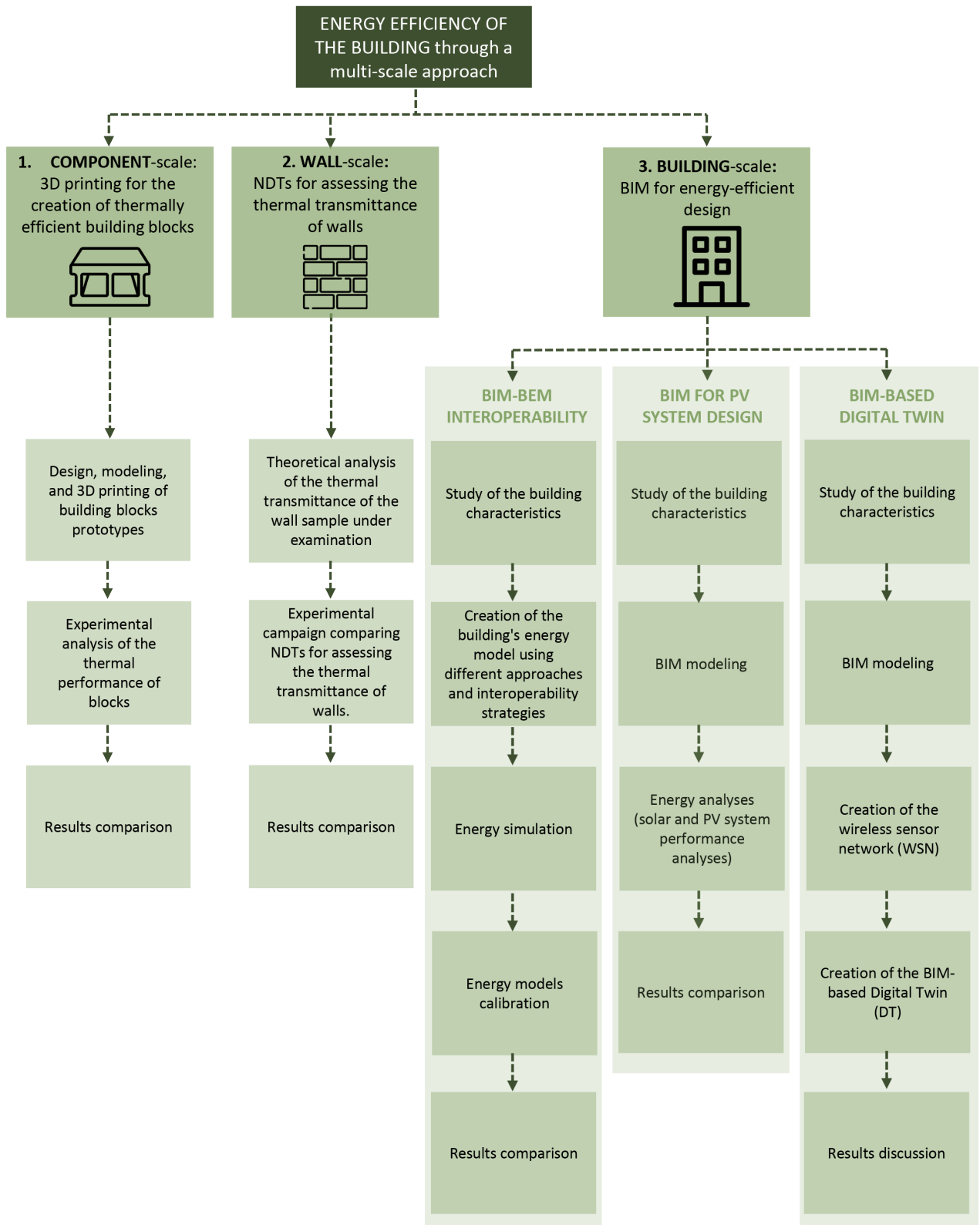


Figure 1. Methodology flowchart representing the various work phases for each analysis scale.

3.2.1 Component-scale

The objective of the research on the component-scale was essentially twofold: (i) exploring the 3D printing technology and its potential, pushing towards the creation of increasingly complex forms, and (ii) analyzing the thermal performance of the 3D-printed blocks as their geometric configuration, orientation, and filling with waste materials vary.

To pursue these goals, the applied methodology, which is described in Figure 2, was divided into two macro-phases.

- **Phase 1 - Design, modeling, and creation of the blocks:**

- The 3D models were designed with AutoCAD Inventor®, a three-dimensional modeling software (Autodesk Inc., San Rafael, CA, USA); then, the G-Codes were generated using the slicer software Creality Slicer 4.2 (Creality 3D Technology Co., Shenzhen, China) to assign all of the printing properties.
- Thus, the designed blocks were realized using the Creality CR-3040 PRO 3D printer, (Shenzhen Creality 3D Technology Co., Ltd., Shenzhen, China), after having chosen Polylactic Acid as the printing material. PLA was chosen because it is an ecological, biodegradable, and economical material with exceptional properties, and it can be easily printed with the FDM technique [1, 2]. The printing temperature of the PLA used is 200–225 °C, and the filament diameter is 1.75 mm.

- **Phase 2 - Thermal performance analysis of the blocks:**

- An experimental analysis was conducted with the heat flux meter (HFM) method and infrared thermography (IRT) using the Hot Box designed and built by the “G. Parolini Laboratory of Applied and Technical Physics” of the University of L’Aquila. The effects on heat transfer of the geometric configuration of the cells, the orientation of the blocks, and the filling of the cells with waste insulation materials were studied in detail.

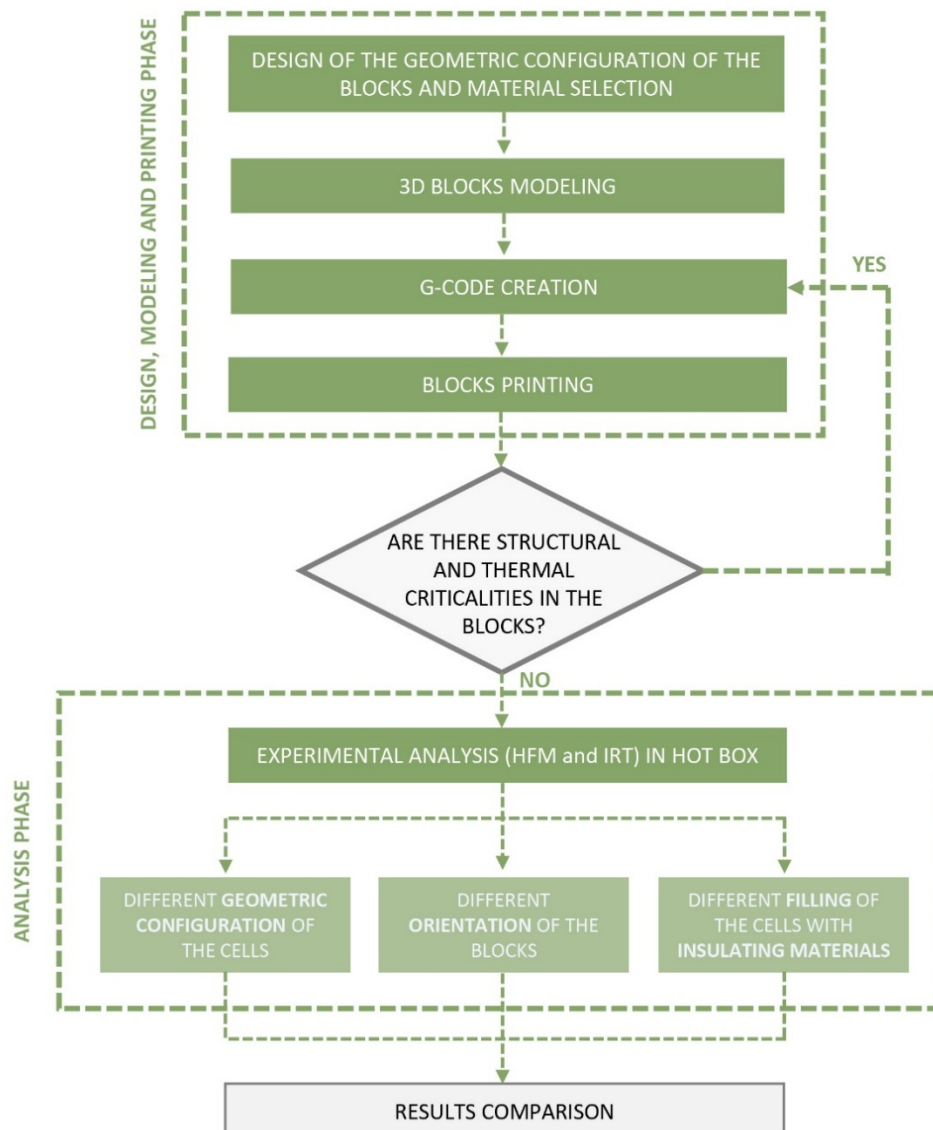


Figure 2. Working methodology applied to component-scale.

3.2.2 Wall-scale

Building on past studies by the “G. Parolini Laboratory” on the comparison between HFM and IRT in Guarded Hot Box (GHB) [3], the aim of this research is to conduct new experimental campaigns using more recent instruments with different technical characteristics. To do this, the methodology illustrated in Figure 3 was used, which includes two main phases:

- **Phase 1- Theoretical analysis:** Evaluation of the design U-value.
- **Phase 2 - Experimental campaign:** Experimental analysis in GHB for simultaneous NDTs evaluation.

In particular, the following NDTs were analyzed:

- Heat flow meter (HFM)
- Infrared Thermography (IRT)

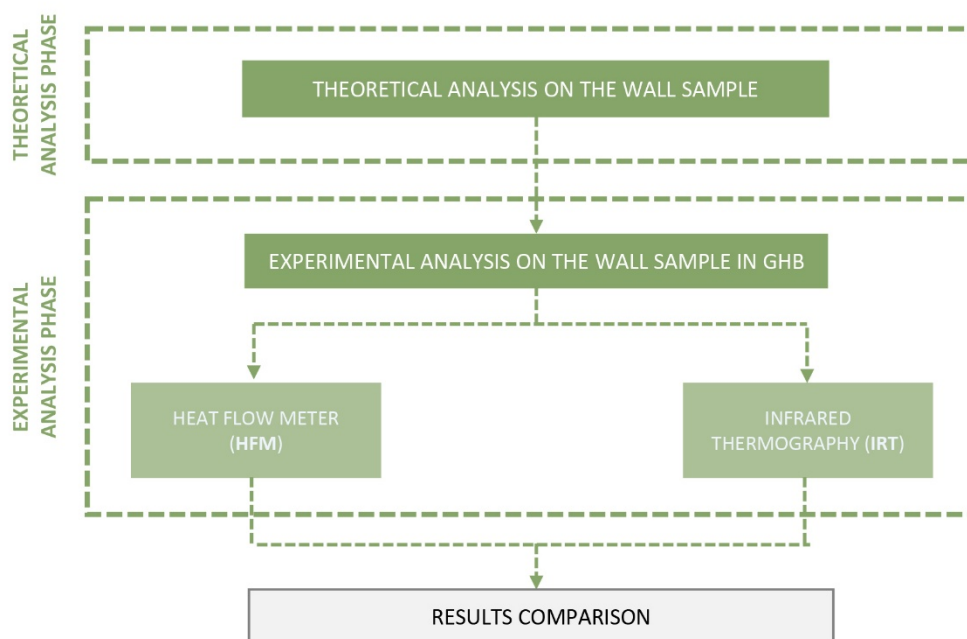


Figure 3. Working methodology applied to wall-scale.

3.2.3 Building-scale

The primary goal of the building-scale research was to explore the role of BIM in energy-conscious design, testing its potential in energy modeling (BIM-BEM interoperability), in PV system design and Digital Twin creation.

In light of this, first of all, the BIM-to-BEM approach was tested through the application of two interoperability strategies. The validity of the BIM-to-BEM approach was verified by comparing it with the traditional approach, which involves the creation of the energy model directly in the BEM environment. Basically, four main phases of work can be identified:

- **Phase 1 - Case study analysis:** Choice of the case study building and analysis of its design characteristics. Specifically, the following were examined.
 - context in which the building is located.
 - layout and intended use of the internal spaces of the floor in question.
 - thermal characteristics of the building envelope (opaque and transparent closures).
 - characteristics of the Heating, Ventilation and Air Conditioning (HVAC) system.

- **Phase 2 - Energy model creation:** Creation of the energy model following two different approaches, the BIM-to-BEM approach and the traditional approach.
 1. BIM-to-BEM approach (A1)

After creating the architectural model on Autodesk Revit BIM software, the BIM-to-BEM approach was tested by applying two ability strategies.

 - *Strategy 1 (S1):* Creation of the energy model directly on the BIM software using the Revit plug-in, Insight 360, giving rise to a real-time connection between BIM and BEM models.
 - *Strategy 2 (S2):* Export of the architectural model using the standardized gbXML format and subsequent creation of the energy model on DesignBuilder BEM software, addressing potential errors and gaps arising from the export process.
 2. Traditional approach (A2)

The use of the traditional approach involved the creation of the building's energy model from scratch, directly in the BEM environment (i.e., Energy Plus and DesignBuilder).
- **Phase 3 - Energy analysis:** EnergyPlus simulation through two graphical interfaces (Insight 360 for A1/S1 and DesignBuilder for A1/S2 and A2), with the aim of obtaining the annual thermal consumption of the building in question.
- **Phase 4 - Model calibration:** Statistical analysis of experimental thermal energy data from heating system, with the purpose of calibrating the simulated consumption on the basis of the real ones, obtained from a monitoring period. The calibration was conducted in accordance with the ASHRAE M&V guidelines, using the hourly calibration.

At the end of the energy analysis, the results obtained were discussed and compared in order to evaluate the effective applicability of the BIM-to-BEM approach. The methodology used to achieve the set objective is outlined in Figure 4 through a flowchart.

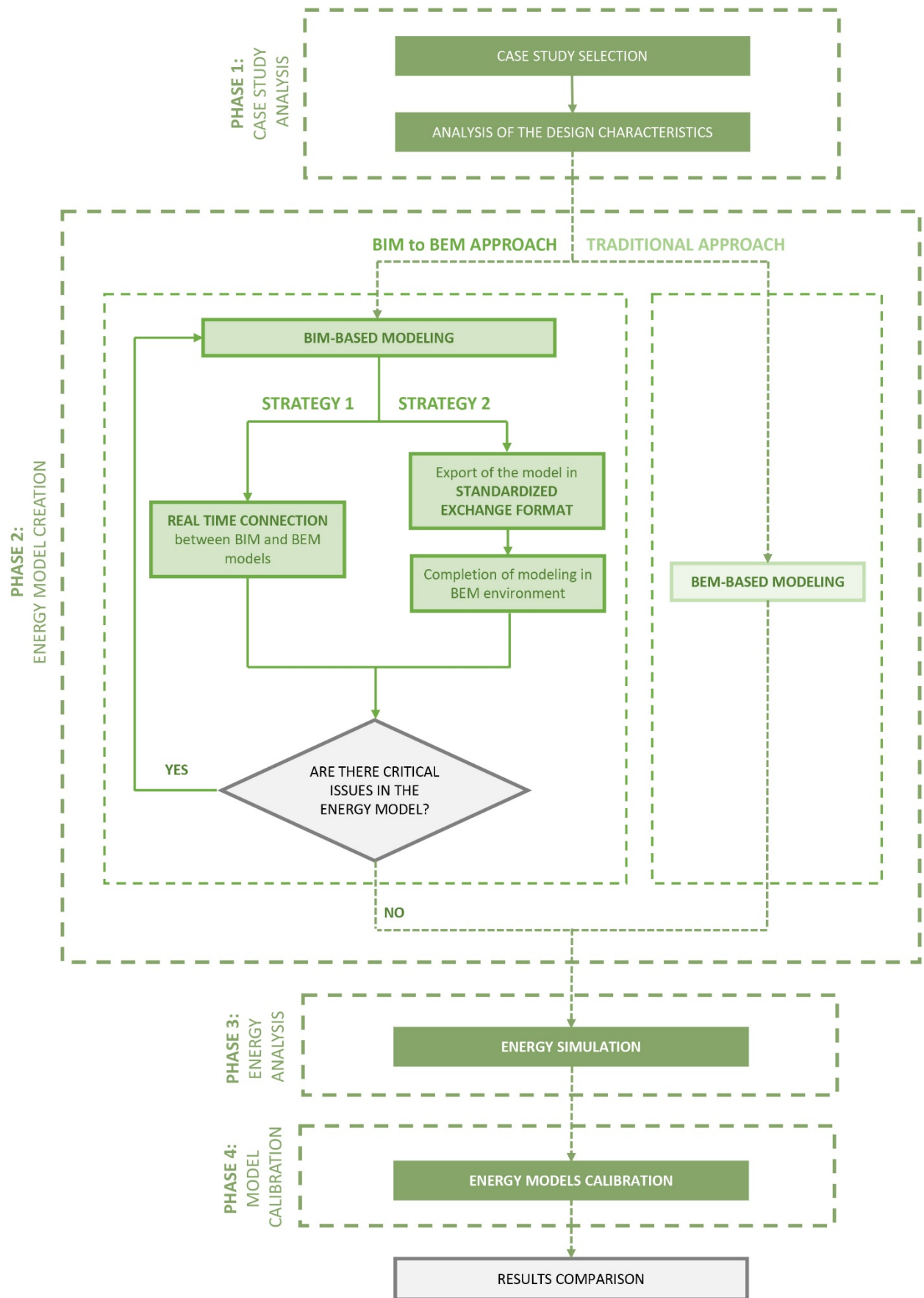


Figure 4. Working methodology applied to building-scale, in reference to the topic BIM-BEM interoperability.

Regarding the use of BIM for PV system design, a completely BIM-based workflow was conceived, with the aim of developing a standardized and replicable procedure capable of guiding the professional through all project phases, starting from the most embryonic to the most detailed.

The workflow consists of six phases:

- **Phase 1 - Study of the building characteristics:** Analysis of the building's design features and the environmental context in which it is located.
- **Phase 2 - BIM modeling:** Detailed 3D modeling and geolocation of the building on Autodesk Revit.
- **Phase 3 - Solar analyses:** Study of the PV potential of roofs, taking into account their exposure and shading caused by any surrounding obstacles or particular morphological characteristics of the building, with the aim of identifying the most suitable areas (A_n) for the installation of the system.
- **Phase 4 - “Solution-matrices” (S_n) creation:** Creation of solution matrices capable of systematically representing the characteristics of different photovoltaic system solutions conceived based on various parameters such as the orientation (θ_n) of the panels, their inclination with respect to the horizontal plane (β_n), their power (P_n), the technology that characterizes them (T_n), the number of modules installed (N_n) and the distance between them (D_n).
- **Phase 5 - PV system performance analysis:** Energy simulation of the different S_n designed.
- **Phase 6 - Cost-performance analysis:** Cost-performance assessment of each matrix to identify the most convenient solution for the case in question.

Figure 5 provides a schematic of the proposed workflow.

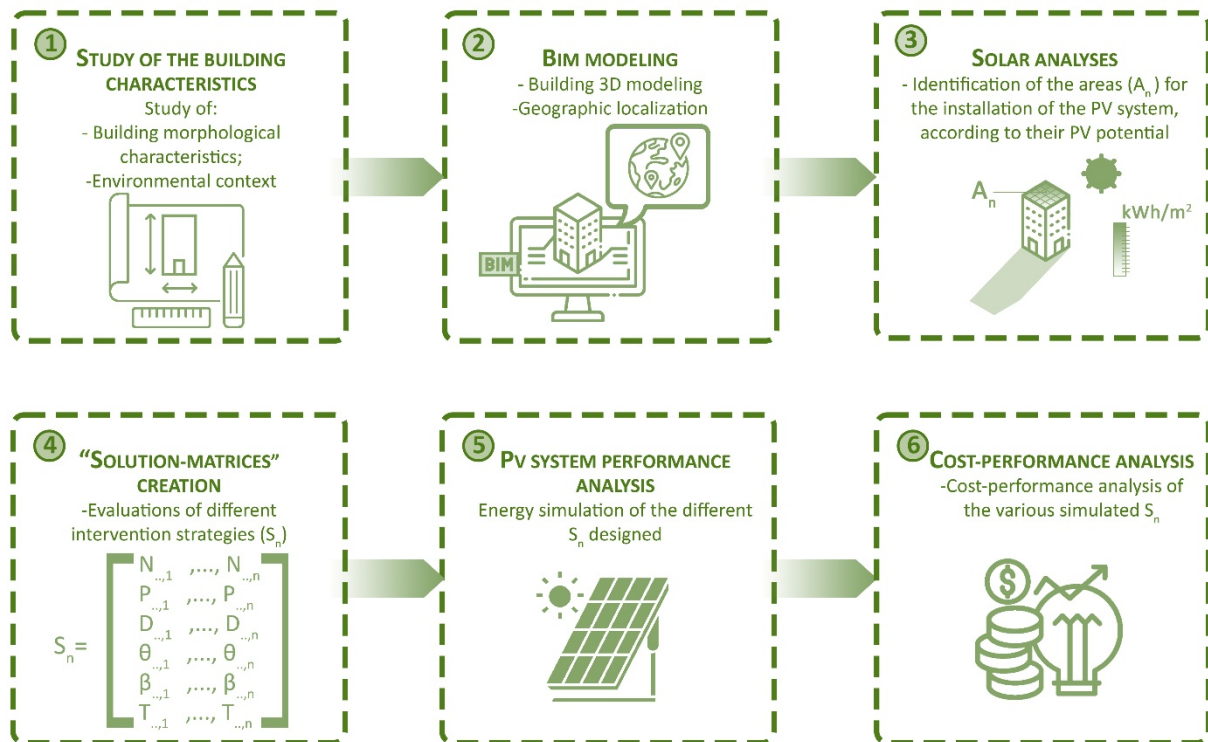


Figure 5. Schematic of the workflow for the design of a PV system based on the BIM methodology.

Finally, the potential of BIM for the creation of Digital Twins was explored with the following objectives: (i) To propose a monitoring technique that has a user-friendly interface accessible to everyone, optimizing the real-time data visualization and processing phase and exceeding the limits of traditional approaches. (ii) To explain in detail the proposed workflow and define a standardized procedure that can be applied for any circumstance and case study, guiding the professional in choosing the most suitable technologies capable of communicating with each other fluidly and without interruptions. (iii) To experiment with the concept of “Living Lab” by choosing an office building as a case study, which is also used as an academic laboratory.

To achieve the aforementioned objectives, a real-time connection between the physical and virtual building was created, thanks to the use of a middleware tool that allowed a continuous exchange of information between the wireless sensors installed in the building and the BIM model of the building itself. The proposed workflow can be substantially divided into three macro phases, which can be described as follows.

- **Phase 1 - Physical Building study:**
study of the characteristics of the case study building through technical drawings and surveys.
- **Phase 2a—WSN configuration:**
 - installation of wireless sensors in the physical environment of the building to detect air temperature and humidity;
 - network connection of the sensors via Wi-Fi router;
 - sending the data detected by the sensors to a remote server.
- **Phase 2b—BIM modeling:**
 - three-dimensional informative BIM modeling of the chosen building using Autodesk Revit;
 - partition of the internal spaces of the building with an indication of the rooms and their intended uses.
- **Phase 3—Digital twin creation:**
 - importing the BIM model of the building onto an online platform to be used as a middleware tool (in this specific case Autodesk Tandem);
 - constant acquisition of data recorded by sensors and real-time processing of the trend of environmental parameters over time.

Figure 6 shows the architecture of the proposed system.

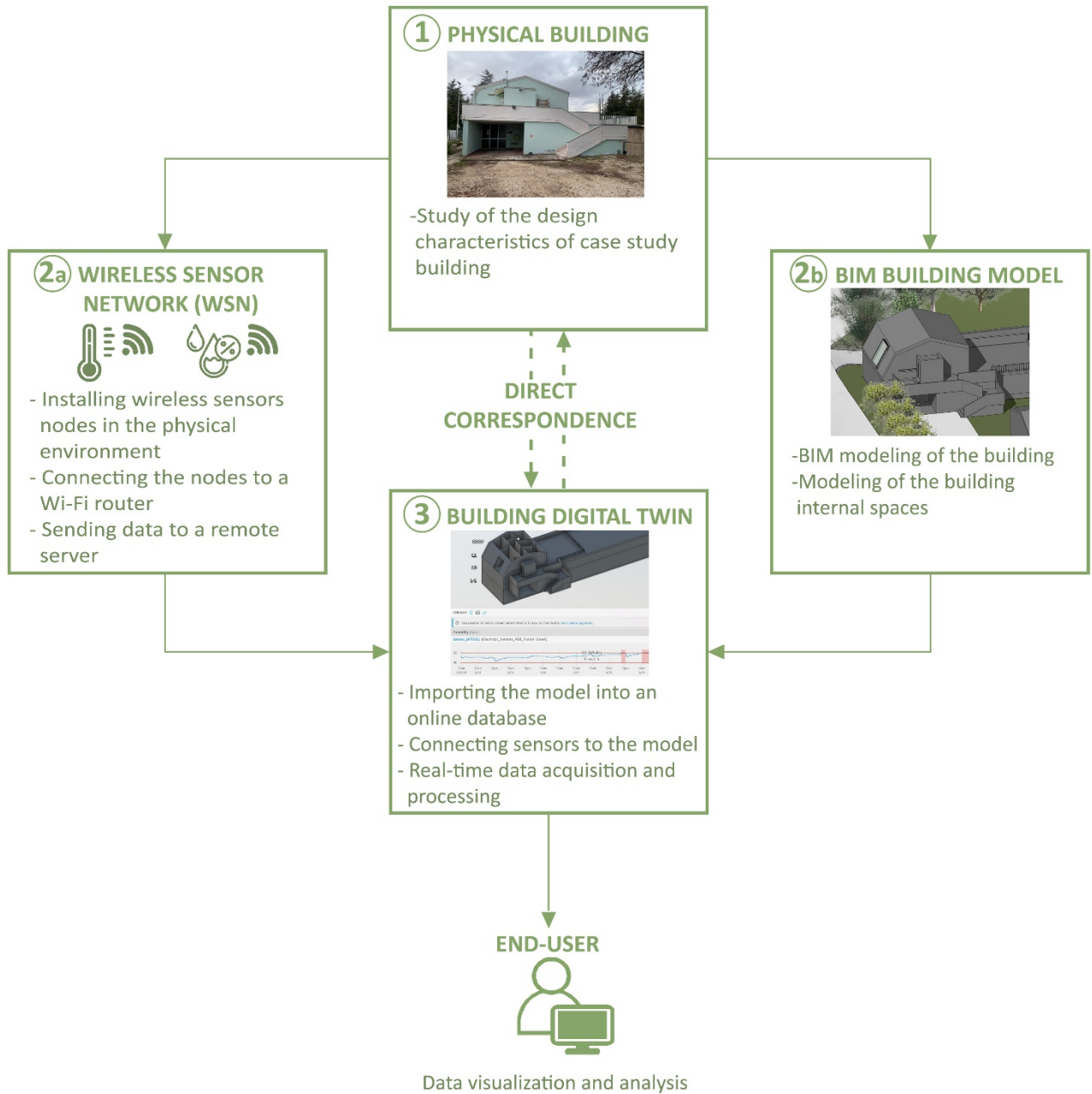


Figure 6. Schematic of the workflow for the BIM-based Digital Twin creation.

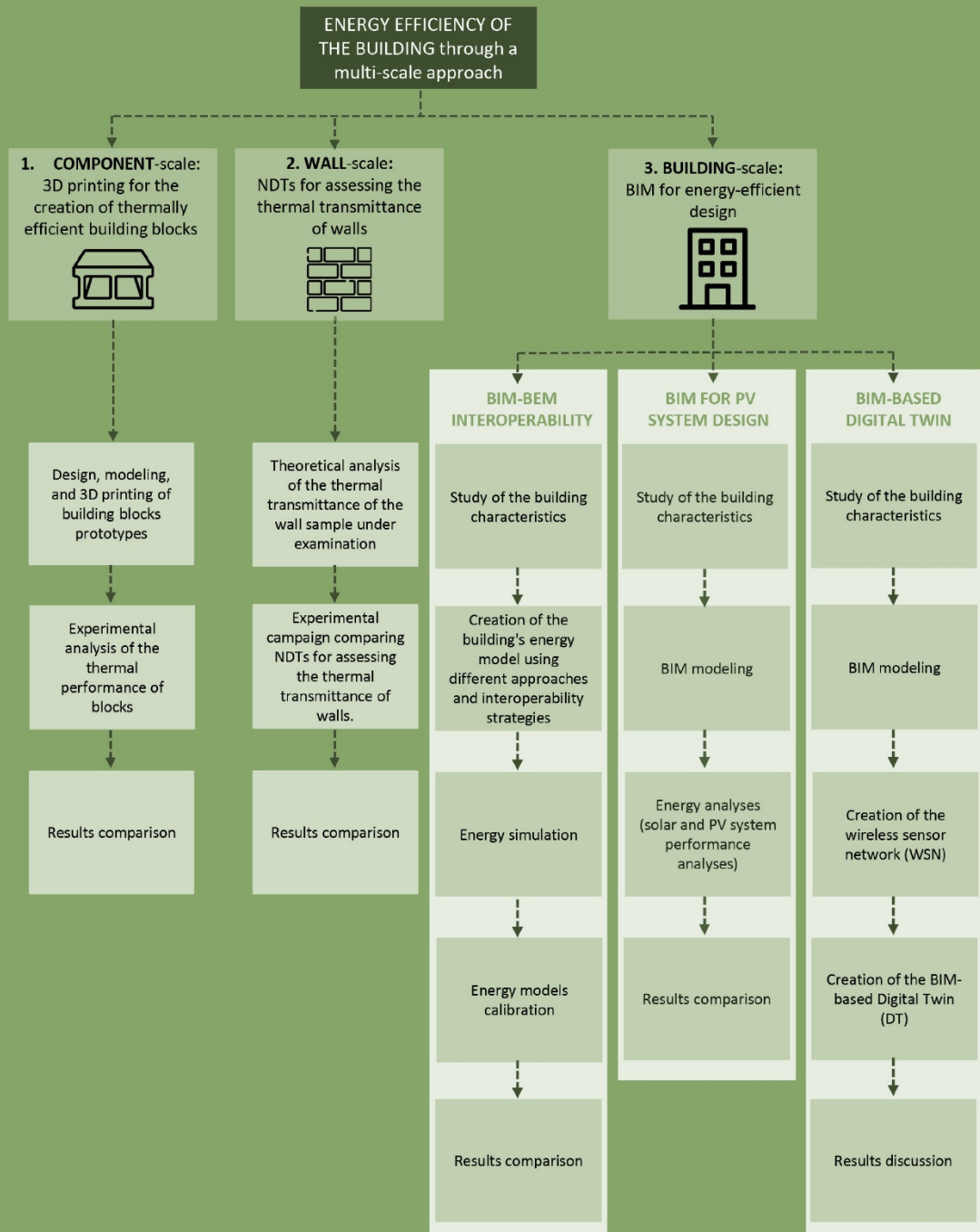
SUMMARY

3.1 Overview of the multiscale approach

The research was developed through a multiscale approach, encompassing several interconnected levels of investigation that progressed from the individual building component to the architectural element, and ultimately to the building as a whole.

3.2 Method and tools for applying the approach

The research work developed gradually from the micro-scale of the building component to the macro-scale of the entire building.



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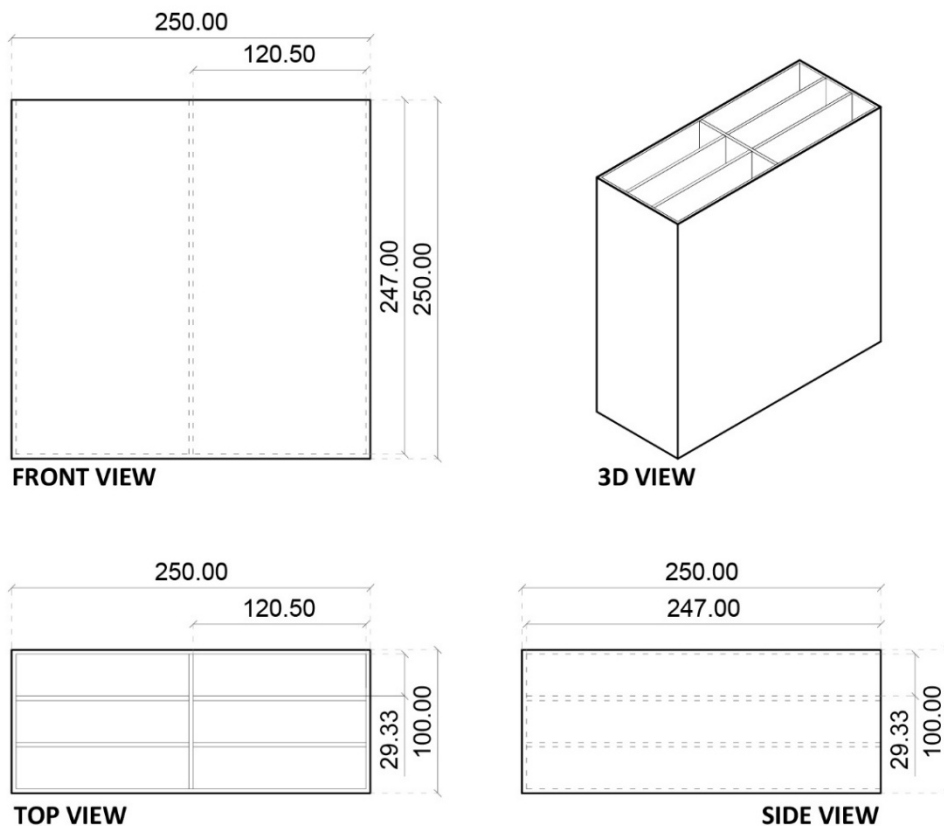
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4. COMPONENT-SCALE ANALYSIS: THERMALLY EFFICIENT 3D PRINTED BLOCKS

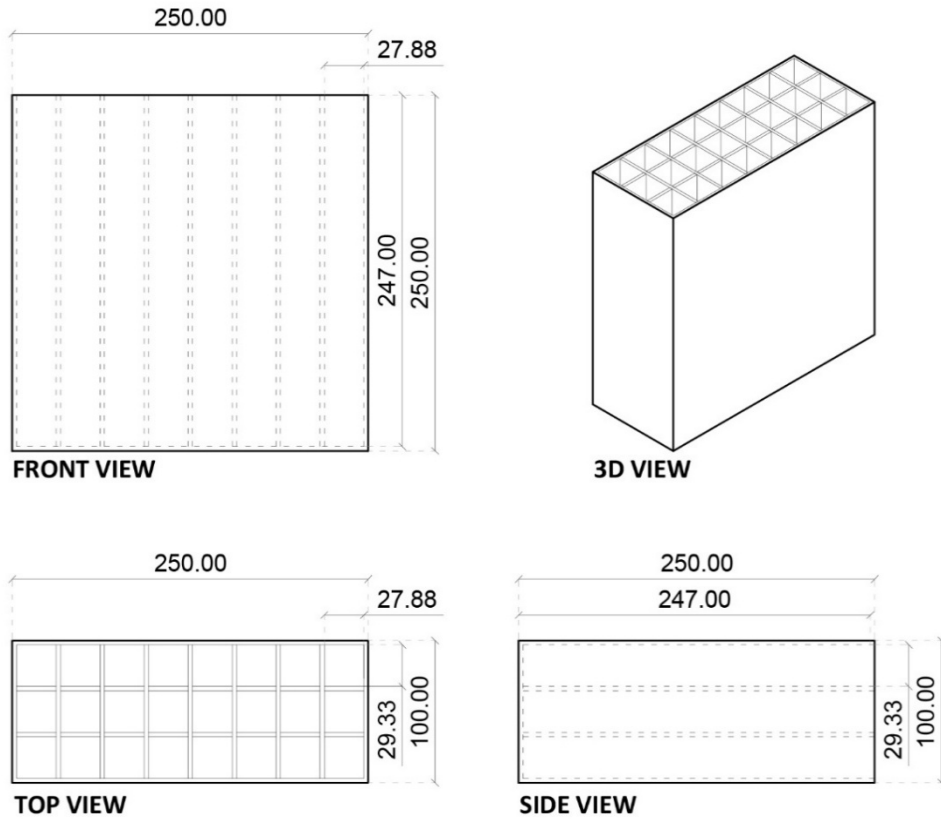
3DP within the construction sector has underscored its potential to significantly reduce the energy footprint of buildings. By leveraging complex geometries and advanced materials, 3DP has demonstrated the ability to optimize the thermal performance of walls, yielding substantial benefits for overall building energy efficiency. Despite these encouraging outcomes, research in this field remains at an early stage. Therefore, further efforts are needed to conduct comprehensive investigations into building thermal optimization through 3DP. For this reason, the aim of this research is to exploit additive manufacturing to create thermally efficient building components, highlighting how localized design choices play a crucial role in improving the energy efficiency of the building envelope and, ultimately, the entire structure.

4.1 DESIGN AND CONSTRUCTION OF BLOCKS USING 3D PRINTING

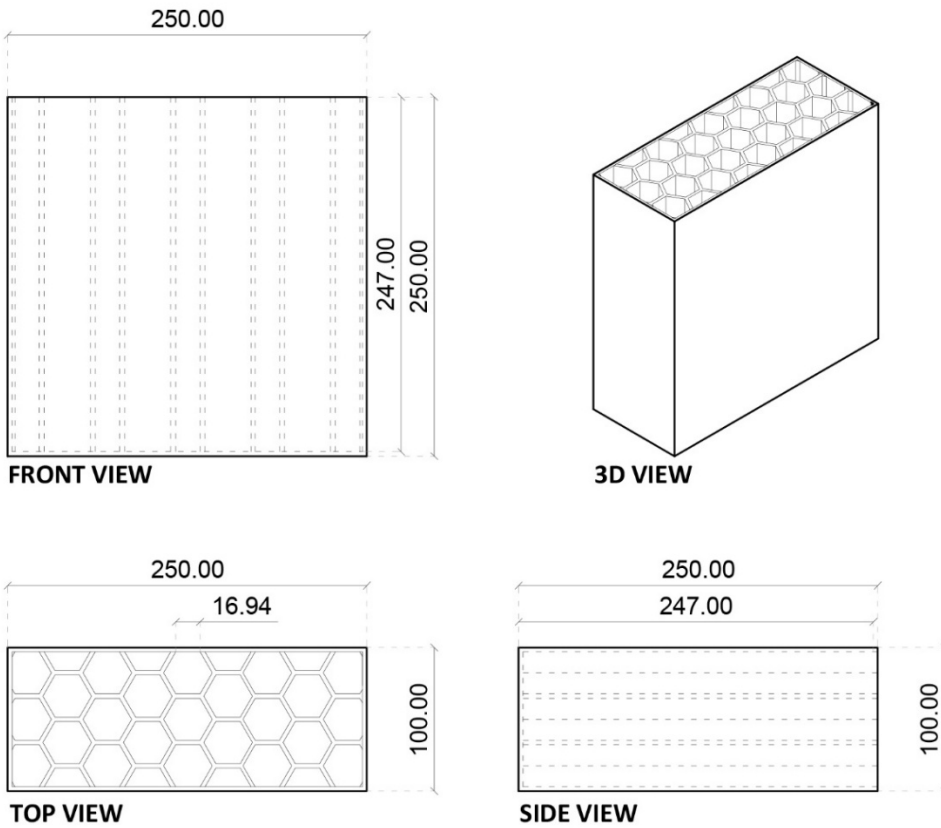
Initially, taking into account the size limits imposed by the printer (300 x 300 x 400 mm), three blocks with different internal structures were designed: (i) a multi-row structure (Block 1), (ii) a square structure (Block 2), and (iii) a hexagonal structure (Block 3a). All of the blocks had the same dimensions of 250 x 250 x 100 mm (width x height x depth). The first block (Figure 1a) was characterized by longitudinal partitions to form six rectangular cavities with dimensions equal to 120.5 x 247.0 x 29.3 mm (width x height x depth). The second block (Figure 1b) had an internal square structure characterized by twenty-four rectangular cavities, each with dimensions equal to 27.9 x 247.0 x 29.3 mm (width x height x depth). The third block (Figure 1c), finally, was characterized by a hexagonal cell structure, formed by hexagonal cavities, with sides of 16.9 mm and a height of 247.0 mm, which were arranged in three rows.



(a)



(b)



(c)

Figure 1. 2D and 3D blocks' design. (a) Multi-row structure. (b) Square structure. (c) Hexagonal structure. (measurements in millimeters). PLA thickness is equal to 3 mm.

To get a preliminary idea of the thermal performance of the designed blocks, these were examined using THERM software, a Lawrence Berkeley National Laboratory (LBNL) software for analyzing two-dimensional heat transfer through building components, which is based on the finite element method [1]. Clearly, the thermal phenomena under the real conditions develop in three dimensions. However, the two-dimensional numerical simulation was carried out with the only objective of preliminarily evaluating the thermal behavior of the designed blocks. Since PLA was chosen for the block printing and the software library does not contain the thermophysical properties of this material, the PLA's thermal characteristics were manually entered (e.g., the thermal conductivity λ was equal to 0.28 W/mK). The cavities of the blocks (Figure 2) have been modeled as "Frame Cavity" by inserting air as a filling gas. The cavity model employed by the software refers to the ISO 15099 standard [2].

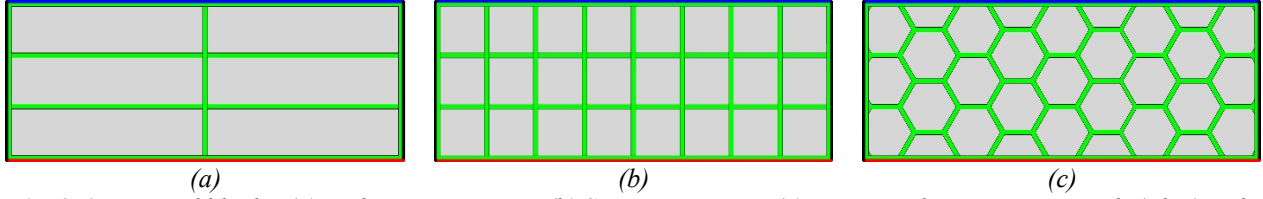


Fig. 2. 3D printed blocks. (a) Multi-row structure. (b) Square structure. (c) Hexagonal structure. Legend: (Blue) is the outer surface, (Red) is the inner surface, (Green) is the PLA, (Grey) is the air, and (Black) is the adiabatic surfaces.

According to the standard ISO 15099 [2], an unventilated frame cavity can be evaluated as though it contains an opaque solid. So, an “effective conductivity” can be assigned to this frame cavity, which accounts for both the radiative and convective heat transfer. The “effective conductivity” can be determined with Equation (1).

$$\lambda_{eff} = (h_c + h_r) \times L \text{ [W/mK]} \quad (1)$$

Where λ_{eff} is the effective conductivity, h_c is the convective heat transfer coefficient [W/m²K], h_r is the radiative heat transfer coefficient [W/m²K], and L is the thickness of the air cavity in the direction of the flow [m].

The convective heat transfer coefficient, h_c (Equation (2)), is calculated from the Nusselt number, Nu , which can be determined from various correlations depending on aspect ratio, orientation, and direction of the heat flow.

$$h_c = Nu \frac{\lambda_{air}}{L} \quad (2)$$

where λ_{air} is the thermal conductivity of the air. The radiative heat transfer coefficient, h_r , can be calculated using Equation (3) [2] by assuming a radiant heat flow in the horizontal direction.

$$h_r = \frac{4\sigma T_{ave}^3}{\frac{1}{\varepsilon_{cc}} + \frac{1}{\varepsilon_{ch}} - 2 + \frac{1}{\frac{1}{2} \left\{ \left[1 + \left(\frac{L}{H} \right)^2 \right]^{\frac{1}{2}} - \frac{L}{H} + 1 \right\}}} \quad (3)$$

where $T_{ave} = \frac{T_{cc} + T_{ch}}{2}$ [K], whereby T_{cc} and T_{ch} are the temperatures on the cold and hot sides, respectively, σ is the Stefan–Boltzmann constant [W/m²K⁴], ε_{cc} is the total hemispherical emissivity on the cold side, ε_{ch} is the total hemispherical emissivity on the hot side, and H and L are the cavity dimensions in the vertical and horizontal directions, respectively. Finally, the boundary conditions were defined, i.e., the relative temperature and film coefficient. In particular, the temperature assigned to the external surface of the block was 25 °C. The external film coefficient was 25 W/m²K, resulting from the inverse of the external surface thermal resistance, which, according to EN ISO 6946 [3], is equal to 0.04 m²K/W. For the internal surface of the blocks, the boundary conditions were the surface temperature being equal to 40 °C and a film coefficient of 7.69 W/m²K, deriving from the inverse of the internal surface thermal resistance, which was equal to 0.13 m²K/W [3]. Once the geometry of the section, the properties of the materials, and the boundary conditions were defined, the

THERM software automatically generated the mesh of the section to perform the 2D heat transfer analysis. The results obtained by the THERM simulations are shown in Table 1.

Table 1. Theoretical U-values obtained by the THERM simulations.

Block Type	Transmittance [W/m ² K]
Multi-row block (Block 1)	1.52
Square structure block (Block 2)	1.29
Hexagonal cell structure block (Block 3a)	1.23

In general, focusing on the heat transfer phenomenon, we can identify the following contributions to the heat flux through a block printed in PLA:

- Heat conduction through the PLA walls.
- Convective heat transfer through air.
- Radiation heat transfer through air.

Regarding heat conduction through the PLA walls, generally speaking, it is possible to argue that increasing the geometric complexity of the structure increases the effective path the heat has to travel by conduction, thus increasing the thermal resistance. This idea can be illustrated by considering Figure 2, showing the three blocks designed with increasingly complex geometry; as heat conduction is along the walls (in green), the blocks exhibit increasingly effective conductive paths.

Regarding heat transfer by radiation in the cavities, depending on the temperatures and emissivities of the internal surfaces and the view factors, it is not simple to analyze. As a basic approach, we may observe that planes parallel to the hot and cold surfaces (see Fig. 2) act as radiation shields. Therefore, a simple way to reduce the contribution to the heat flux could be the inclusion of surfaces that are opaque to radiation.

Finally, considering the convective heat flux q_c in an enclosure, it can be expressed through Equation (4).

$$q_c = h_c \Delta T \quad (4)$$

where h_c is expressed by Equation (2) and ΔT is the temperature difference between the hot and cold surfaces of the enclosure. The Nusselt number (Nu) can be determined from various correlations depending on the aspect ratio, orientation, and direction of the heat flow [4]. The enclosure isolates at its best in the pure conduction state, i.e. when $Nu = 1$. Nu is generally related to the Prandtl number Pr (depending on the fluid), the Rayleigh number Ra_H , and the aspect ratio H/L (ratio of the enclosure height H and the distance L between hot and cold surfaces). The Rayleigh number in cavities is based on the enclosure height [5], as shown by Eq. (5).

$$Ra_H = \frac{g \cdot \beta \cdot (T_h - T_c) \cdot H^3}{\alpha \nu} \quad (5)$$

where g is the gravitational acceleration, α is the thermal diffusivity, β is the coefficient of volume expansion, T_h is the temperature of the hot surface, T_c is the temperature of the cold surface, H is the characteristic length of the geometry, ν is the kinematic viscosity of the fluid. Moreover, Nu also depends on the aspect ratio H/L . Bejan [5] summarized several correlations for two-dimensional enclosures heated from the side by plotting the Nusselt number Nu as a function of the ratio H/L . Previous considerations are valid for singular enclosures. When cavities are grouped in a multicellular structure, there is heat transfer between cells.

Based on the theoretical background described above, it was decided not to stop at a study on the different geometric configurations of the cell openings (Figure 1), but to go further, investigating the thermal performance of the blocks by varying the configuration of the cells in height. Consequently, taking into consideration the block with hexagonal cells (Figure 1c), which resulted to be the best performing from a preliminary theoretical analysis (Table 1), some reasoning was conducted on the structure of its cells in elevation.

In particular, it was decided to perform three experiments, described below.

Experiment 1: Rotate Block 3a (Figure 3a) by 90° (Figure 3b) to obtain a different H/L ratio of the cells (Block 3b). The rationale for this rotation is linked to its influence on convective heat transfer. According to heat transfer theory, such rotation should mitigate convective heat transfer effects, especially if the air cavities tend to contract [5]. The block cavities, arranged in three rows, were characterized by sides of 16.9 mm and a height of 247.0 mm.

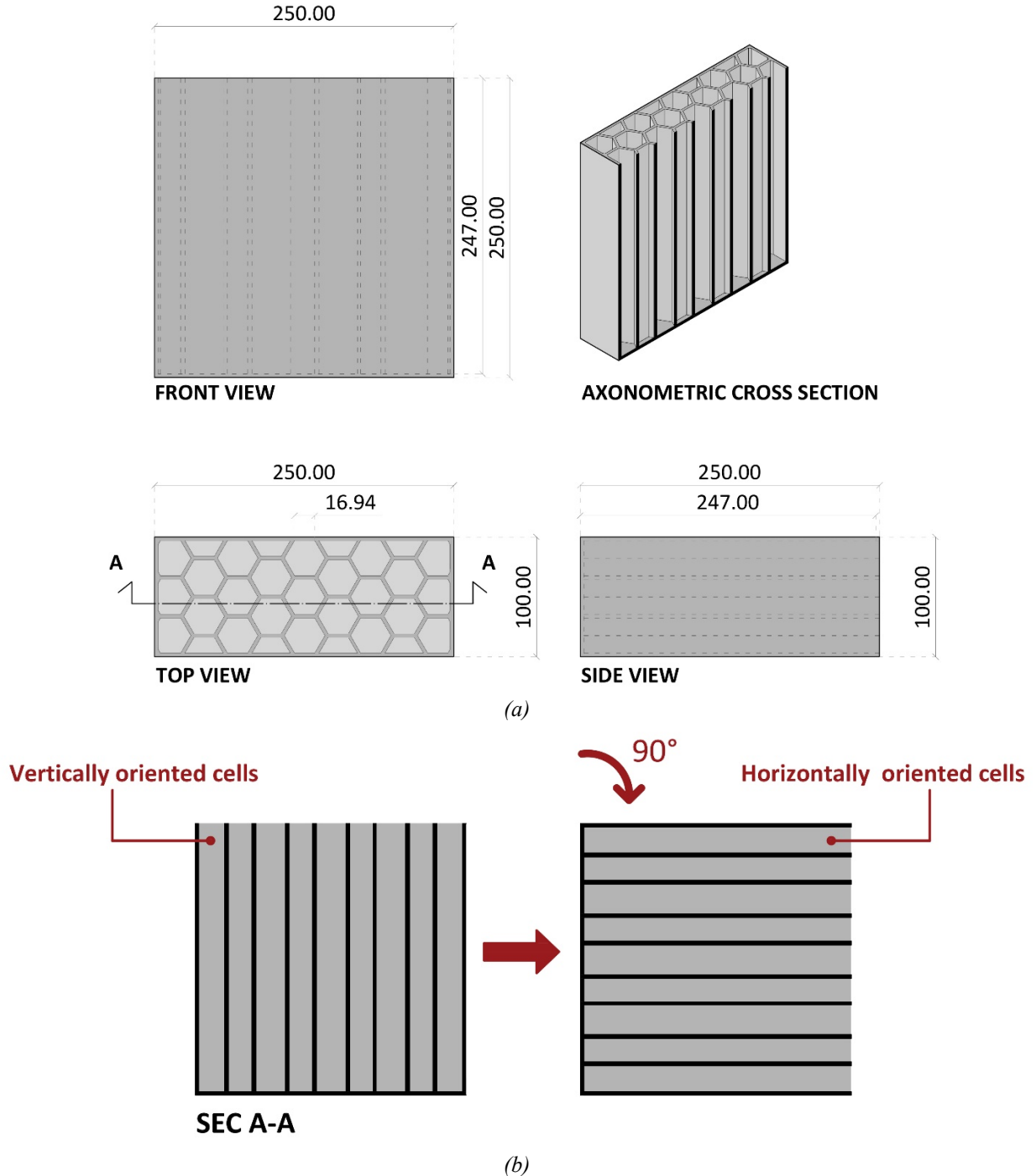


Figure 3. Block 3b with hexagonal cells and no horizontal partitioning. (a) 2D and 3D Block designs. (Measurements in millimeters). PLA thickness is equal to 3 mm. (b) The two configurations tested for the block: vertical and horizontal cell orientation.

Experiment 2: Create a new block with hexagonal cells (Figure 4a) by inserting horizontal partitions inside it (Figure 4b), capable of dividing the block into four equal sections (Block 4). Specifically, the partitions were

inserted to ensure that the proportions of the cavities adhered to those of a real honeycomb cell, where the height is approximately 2.5 times its width [6]. Therefore, starting from the size of the cell opening (“a” in Fig. 4b), the partitions were inserted at a distance ($x \cdot a$). This ensured that all cavities had the same height, closely approximating the dimension ($2.5 \cdot a$). Considering that “a” is equal to 29 mm, the aforementioned partitions were placed at a distance of ($2.1 \cdot a$) from each other. This arrangement resulted in four vertical rows of cells, all of equal height, measuring 59.5 mm.

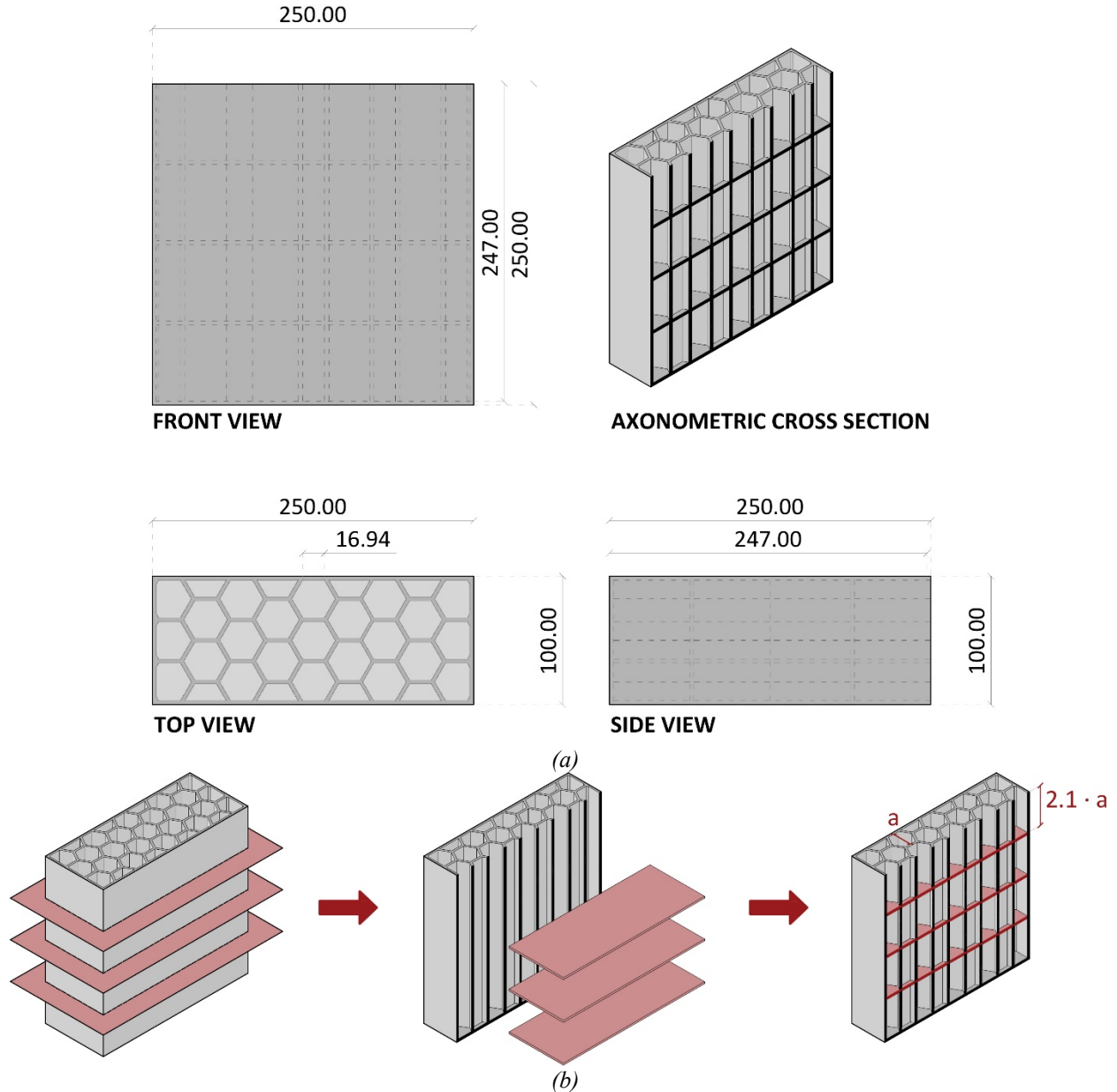


Figure 4. Block 4 with hexagonal cells and three horizontal partitions. (a) 2D and 3D Block designs. (Measurements in millimeters). PLA thickness is equal to 3 mm. (b) Placement of horizontal partitions.

Experiment 3: Create a block inspired by the intricate structure of honeycombs (Block 5), following the mathematical principles elucidated by Polachek [6]. In recent years, the quest for architectural solutions inspired by nature has burgeoned, with AM enabling us to push the boundaries of construction further. Biomimetic architecture has found application in thermal design, as evidenced by Andréen and Soar's research on the thermal properties of termite mounds [7]. The construction technique of a honeycomb is such that it is possible to keep the volume of the cells unchanged by reducing their surface area. Therefore, bees use less wax to obtain the same honey volume. Moreover, the cells of honeycombs are translated to each other for structural integrity (Figure 5).

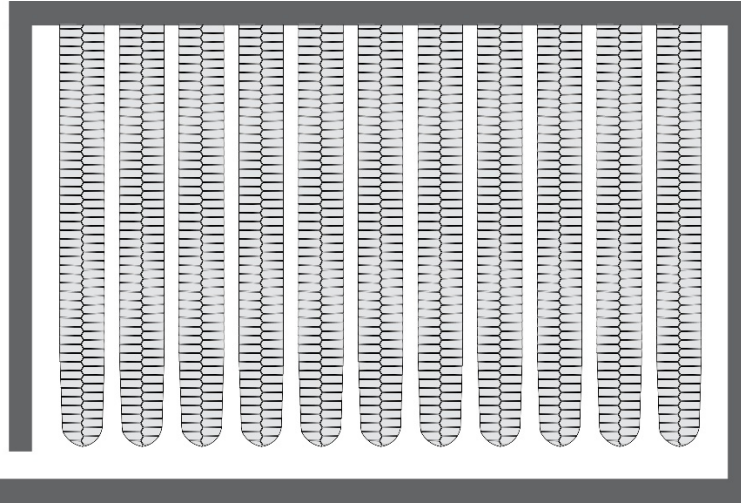


Fig. 5. Longitudinal section of the honeycombs in a hive. Adapted from Ref. [8].

In light of these considerations, the honeycomb structure has been reconfigured to emulate a condition like that analyzed for the hexagonal cells with horizontal partitions, as seen in Block 4. Figure 6 illustrates the honeycomb structure designed for Block 5.

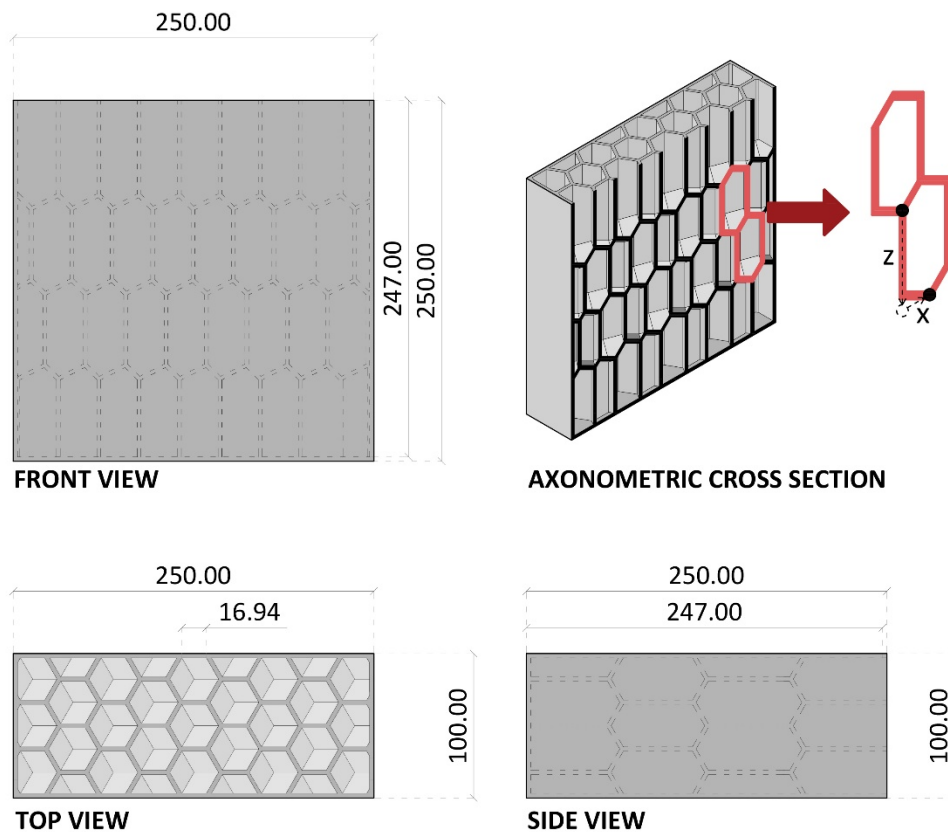


Figure 6. Block 5 with a honeycomb structure of the cells, horizontal partitions, and translation of the cells. (Measurements in millimeters). PLA thickness is equal to 3 mm.

As previously described, a honeycomb makes it possible to reduce the surface area of material while keeping the volume unchanged. This feature is attributed to geometric principles. Beginning with a cell featuring a hexagonal base (an eight-sided prism, as depicted in Fig. 7a), three pyramidal volumes are subtracted from the lower end (highlighted as red pyramids in Fig. 7b). These subtracted volumes are then repositioned (red pyramids in Fig. 7c) to form a trihedral pyramid base at the lower end (ten-sided prism, as depicted in Fig. 7d).

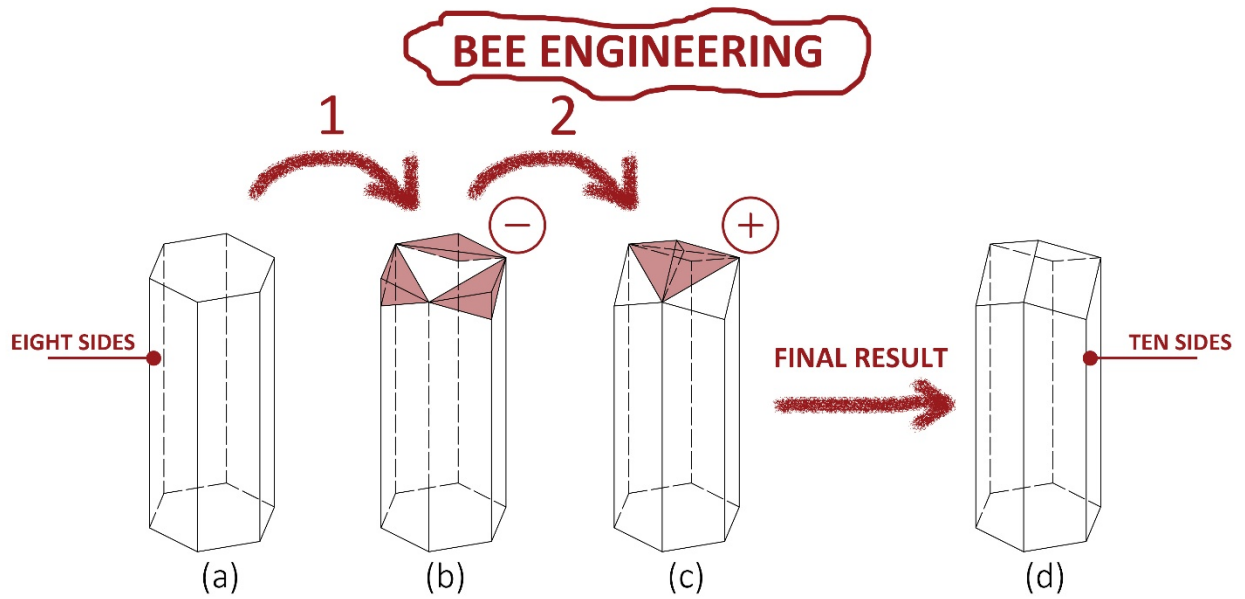


Figure 7. The honeycomb cell design process.

To clarify the vertical translation of the cells, the three-dimensional schematic is provided in Fig. 8.

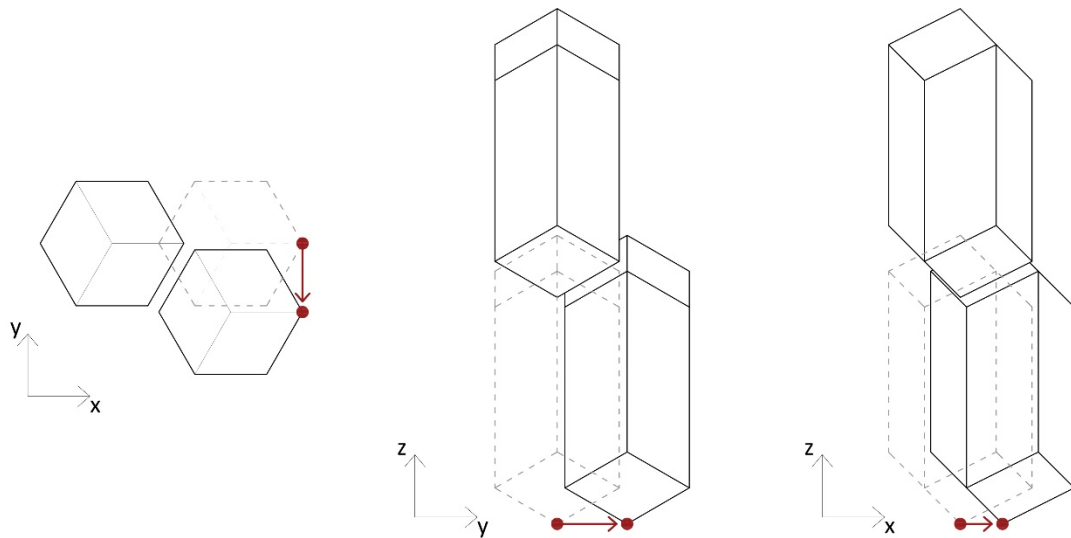


Figure 8. Schematic of honeycomb cell fitting.

The thermal behavior of Block 3a was also tested by inserting natural and recyclable waste-insulating materials into the cells. Returning to a purely theoretical examination of the heat transfer phenomenon, it can be stated that inserting insulating material into the air cavities helps to:

- reduce the conductive contribution to heat flow through the use of materials with low thermal conductivity λ ;
- eliminate or significantly reduce the convective contribution by hindering the air movements that occur in the empty cavities;
- eliminate or significantly reduce the radiative contribution by hindering radiative exchange between the cell walls.

After a thorough search in the literature [9-43], three waste-insulating materials were chosen for the study: (i) wood sawdust, (ii) sheep's wool, and (iii) hemp. Starting from the literature study, the choice was made based on the availability of the materials and the ease of inserting materials into the air cavities of the 3D-printed block with a hexagonal cell structure.

Wood sawdust (Figure 9a) is a plant-based insulating material considered sustainable when sourced from responsibly managed forests or wood-processing waste. It has a thermal conductivity ranging from 0.038 to 0.050 W/m·K, a specific heat that varies between 1.9 and 2.1 kJ/kgK, and a water vapor diffusion resistance factor (μ -value) ranging from 1.0 to 5.0 [9]. In this study, untreated wood residues from carpentry and wood processing were examined, promoting waste reuse, recyclability, and healthier indoor environments. Unlike energy-intensive processes using polyurethane binders, using local untreated wood waste reduces both energy consumption and CO₂ emissions [44].

The second material selected in this work is sheep's wool (Figure 9b). This material, virgin or recycled, has the highest ozone depletion potential. It is renewable, recyclable, and ecological. Furthermore, sheep's wool has excellent thermal and acoustic insulation properties [45]. Its thermal conductivity varies between 0.038 and 0.054 W/mK, its specific heat ranges from 1.3 to 1.7 kJ/kgK, its water vapor diffusion resistance factor (μ -value) is between 1.0 and 3.0 [9].

The last selected material is hemp (Figure 9c), which is a plant-based, renewable, and recyclable insulating material increasingly used in construction due to its good hygrothermal performance and soundproofing properties [46–50]. Its natural fibers store significant amounts of carbon [35], giving hemp a negative carbon footprint and acting as an effective carbon sink, with net sequestration of about 0.67 tons/ha per year [51]. Hemp's thermal conductivity ranges from 0.038 to 0.060 W/mK, specific heat from 1.9 to 2.1 kJ/kgK, and water vapor diffusion resistance factor (μ -value) from 1.0 to 2.0 [9].

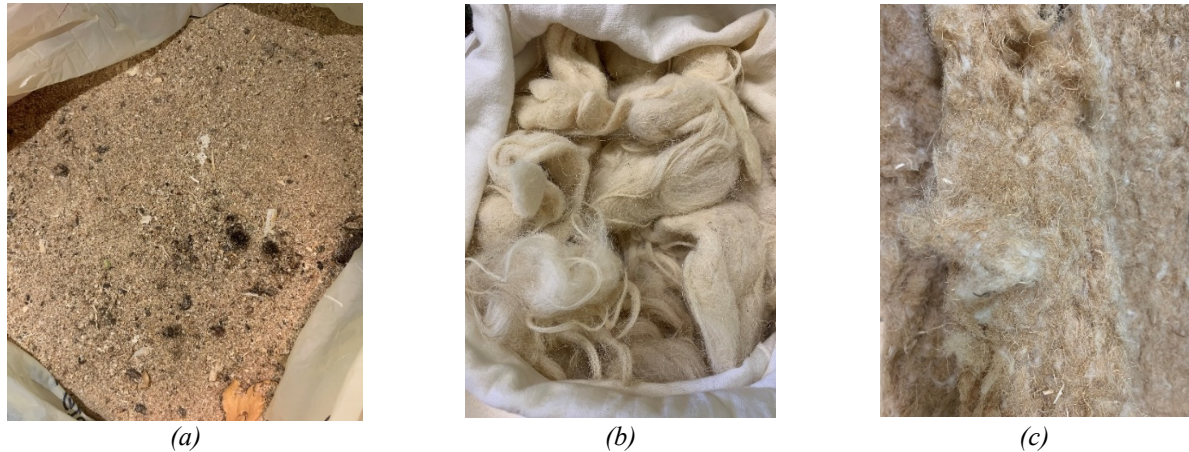


Figure 9. Materials chosen for the study. (a) Wood sawdust. (b) Sheep's wool. (c) Hemp.

Three samples were set up to conduct the experimental analysis. The first sample was filled with 1107.9 g of wood sawdust (Block 3c), the second with 339 g of sheep's wool (Block 3d), and the third with 427.3 g of hemp (Block 3e). Considering that the weight of the empty block is 571 g, the density of the filler wood sawdust is 237.32 kg/m³, that sheep's wool is 72.62 kg/m³ and that of hemp is 91.53 kg/m³.

With the aim of carrying out the pre-established experimental analyses, the blocks were realized using a 3D printer. To this end, the blocks were first modeled in 3D with an AutoCAD Inventor® (Figure 10).

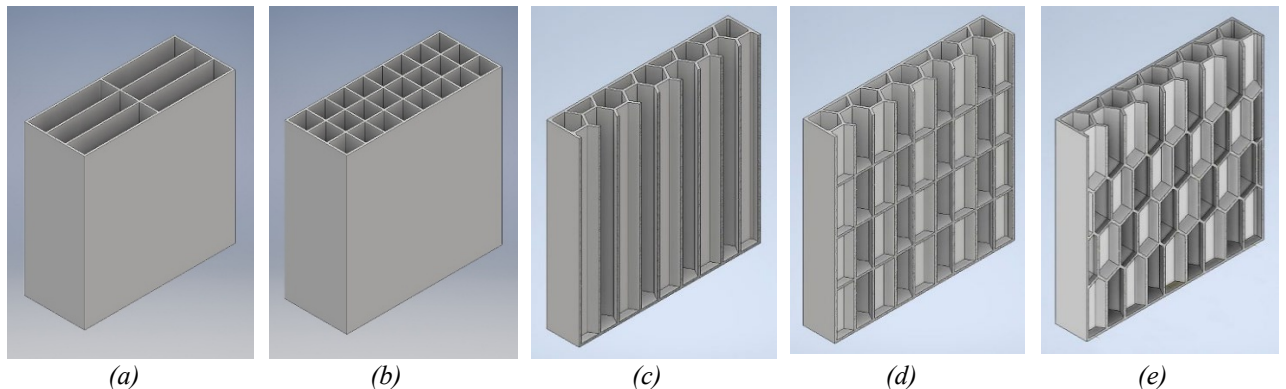


Figure 10. 3D models of the blocks on AutoCAD Inventor®. (a) Block 1. (b) Block 2. (c) Block 3. (d) Block 4. (e) Block 5.

Subsequently, with the Creality Slicer 4.2 slicing software, all of the printing parameters were defined, including the quality, the characteristics of the shell, those of the filling, the type of material used, the printing temperature and that of the print bed, the print speed, and the nozzle size. For the realization of the blocks, it was decided to use a brass nozzle with a diameter of 0.4 mm. The printing temperature, which was set at 210 °C, was defined based on the selected material, namely PLA, whose extrusion temperature varies between 200 °C and 230 °C. The print bed temperature, on the other hand, was set at 60 °C. Upon defining all printing parameters, the G-Code was generated (Figure 11).

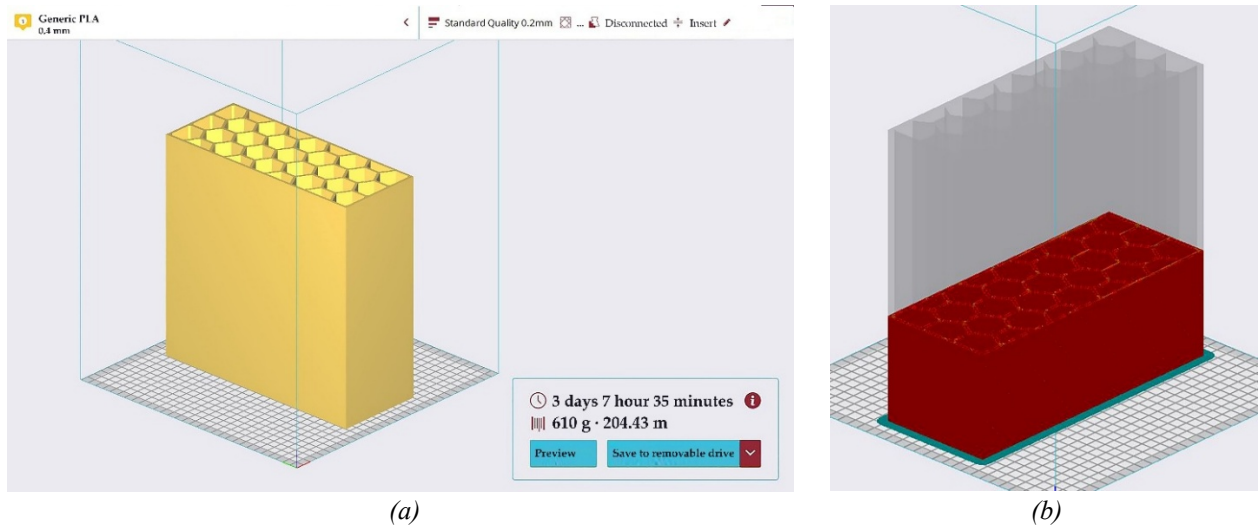


Figure 11. Definition of the printing parameters on Creality Slicer 4.2 for Block 3. (a) G-Code file generated. (b) Print layers visualization.

The G-Code file generated by Creality Slicer 4.2 provided the data that were needed by the Creality CR-3040 PRO 3D printer for the realization of the three blocks (Figure 12).

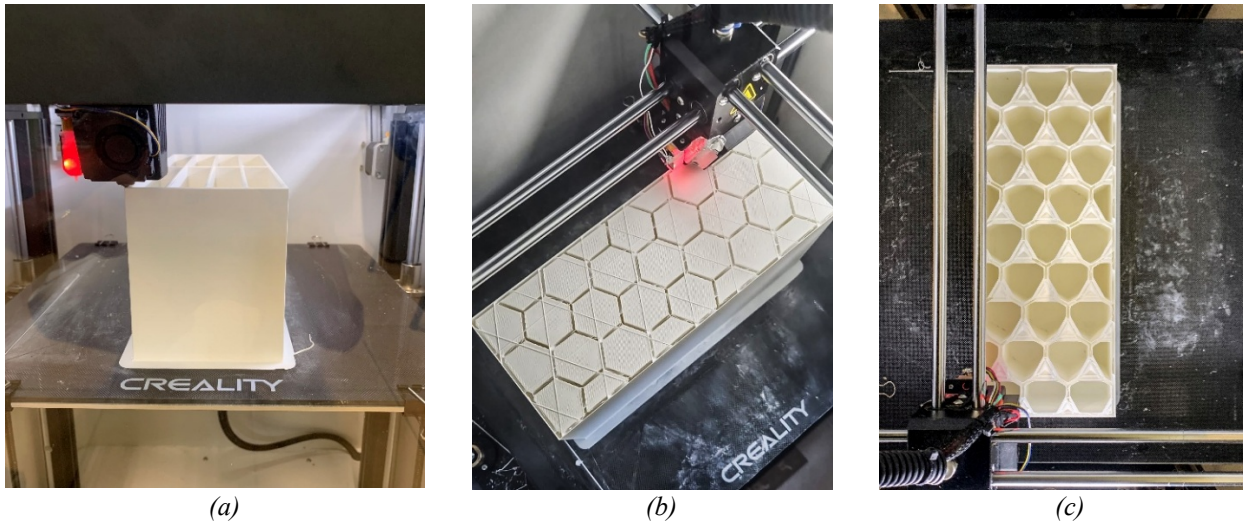


Figure 12. Picture of the printing process. (a) Block 1. (b) Block 4. (c) Block 5.

4.2 THERMAL PERFORMANCE ANALYSIS

The experimental phase was conducted using a specially constructed Hot Box designed to meet the dimensional constraints of 3D-printed blocks, which are 250 mm × 250 mm (width x height). This Hot Box facilitated experimental campaigns under steady-state conditions, ensuring controlled and repeatable testing environments. The design of the Hot Box builds upon the experience gained from the Guarded Hot Box developed at the “G. Parolini Laboratory” of the University of L’Aquila [52, 53]. The Hot Box employed in this study consists of a heated chamber, within which an electric heater is installed to achieve the necessary

temperature levels, ensuring sufficient temperature differences between the two surfaces of the 3D block. The Hot Box walls are constructed from insulating material and clad in sheet steel. A baffle is positioned near the inner surface of the 3D block to separate the region where thermal energy is supplied (hot chamber) from the measurement area (test chamber) and to facilitate the assessment of radiative heat transfer. Figure 13 is a schematic representation of the apparatus, whose dimensions are $640 \times 340 \times 360$ mm (length $\times$ height $\times$ width).

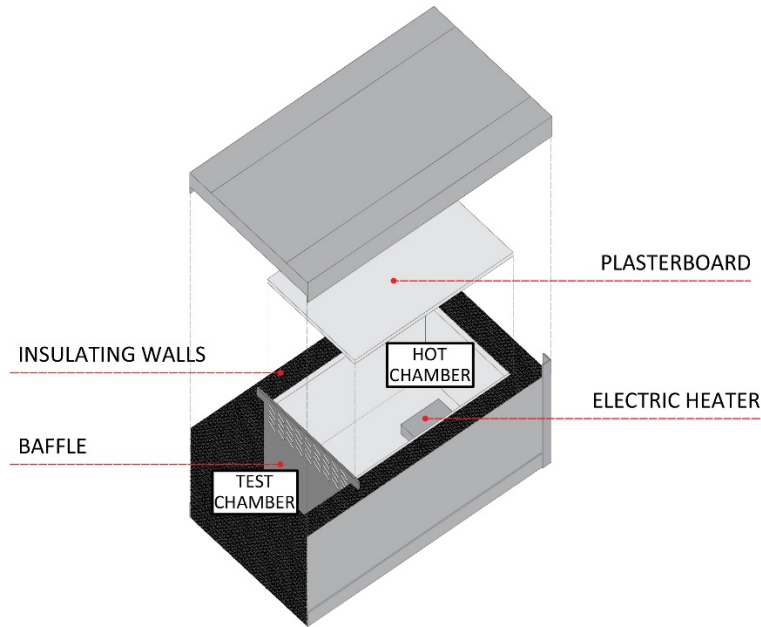
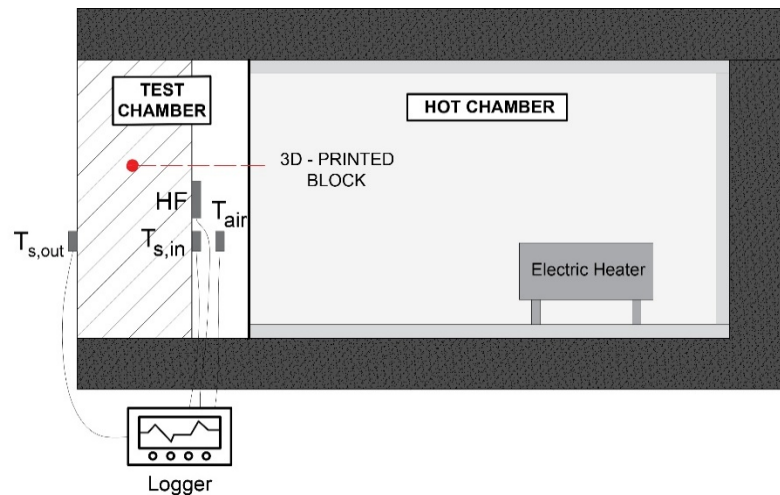


Figure 13. Schematic representation of the Hot Box components.

The Hot Box analysis was carried out with the use of two surface temperature probes, one air temperature probe inside the Hot Box, and one heat flow sensor (Figure 14a). The temperature probes were installed on both the surfaces of the block, both the internal and external ones, while the heat flow sensor was applied on the internal side of the sample. Fig. 14 illustrates the experimental setup employed for these measurements.



(a)



(b)

Figure 14. The experimental setup. (a) Schematic of the measuring instruments employed. (b) Setup picture.

The operating conditions of the experimental tests were imposed starting from the laboratory temperature. In particular, the electric heater inside the Hot Box was set to achieve a temperature difference of at least 20 °C between the surfaces of the blocks, which is in accordance with the provisions of the ISO 9869 standard [54]. The data logger was set to record the values of the heat flow, the internal and external surface temperatures, and the air temperature inside the Hot Box, at a frequency of 10 minutes. The experimental campaigns had a different duration for each block, depending on the period of time necessary to reach steady-state thermal conditions. All of the measured data were processed using the progressive average method, as indicated in the ISO 9869 standard [54], to obtain the conductance (Λ) and the thermal resistance (R) values, using Equations (6) and (7), respectively:

$$\Lambda = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{s,i,j} - T_{s,e,j})} \quad [W/m^2K] \quad (6)$$

$$R = \frac{\sum_{j=1}^n (T_{s,i,j} - T_{s,e,j})}{\sum_{j=1}^n q_j} \quad [m^2K/W] \quad (7)$$

where:

- $\sum_{j=1}^n (T_{s,i,j} - T_{s,e,j})$ is the progressive sum of the differences between the internal and external surface temperatures [°C];
- $\sum_{j=1}^n q_j$ is the progressive sum of the density of the heat flux [W/m²].

Finally, the transmittance value was calculated according to Equation (8):

$$U = \frac{1}{R_{tot}} \quad [W/m^2K] \quad (8)$$

where (R_{tot}) is the total thermal resistance which also includes ($R_{s,i}$) the internal and external ($R_{s,e}$) thermal resistances, from the EN ISO 6946 standard [3], which are equal to 0.13 m²K/W and 0.04 m²K/W, respectively. Then, the IRT technique was performed using a FLIR T1020 IR camera, according to the configuration schematized in Figure 15, after reaching a steady-state condition between the surfaces of the block. The survey was carried out at a distance of 1.50 m from the blocks.

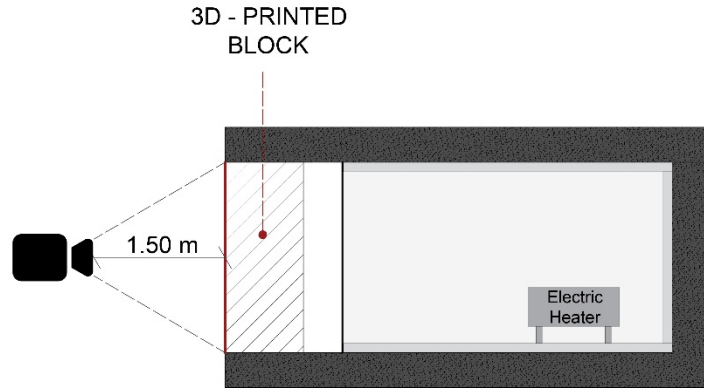


Figure 15. Schematic representation of the thermographic survey.

The instruments utilized for the experimental analyses are shown in Table 2.

Table 2. Technical specifications of the measuring instruments employed for the experimental analyses.

Sensor	Type	Measuring Range	Accuracy
Heat flow meter	Hukseflux HFP01	From -2000 to 2000 W/m ²	± 3%
Surface temperature	LSI Lastem DLE 124	From -40 to 80 °C	0.1 °C
Air Temperature	LSI Lastem DLA 033	From -40 to 80 °C	0.15 °C
IR camera	FLIR T1020	From -40 to 2000 °C	• ± 1 °C (5 to 150 °C) • ± 2 °C (up to 1200 °C)

The uncertainty analysis of the measured data was carried out following the Holman's method [55], as shown by Equation (9):

$$W_U = \left[\left(\frac{\partial U}{\partial x_1} \cdot w_1 \right)^2 + \left(\frac{\partial U}{\partial x_2} \cdot w_2 \right)^2 + \dots + \left(\frac{\partial U}{\partial x_n} \cdot w_n \right)^2 \right]^{1/2} \quad (9)$$

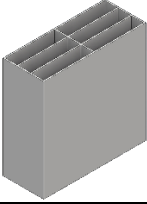
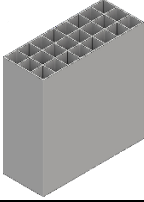
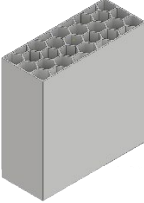
where:

- W_U is the uncertainty in the transmittance value calculated;
- $w_1, w_2, \dots, w_n$ are the uncertainties in the independent variables $x_1, x_2, \dots, x_n$, given by technical data sheets.

4.3 RESULTS AND DISCUSSION

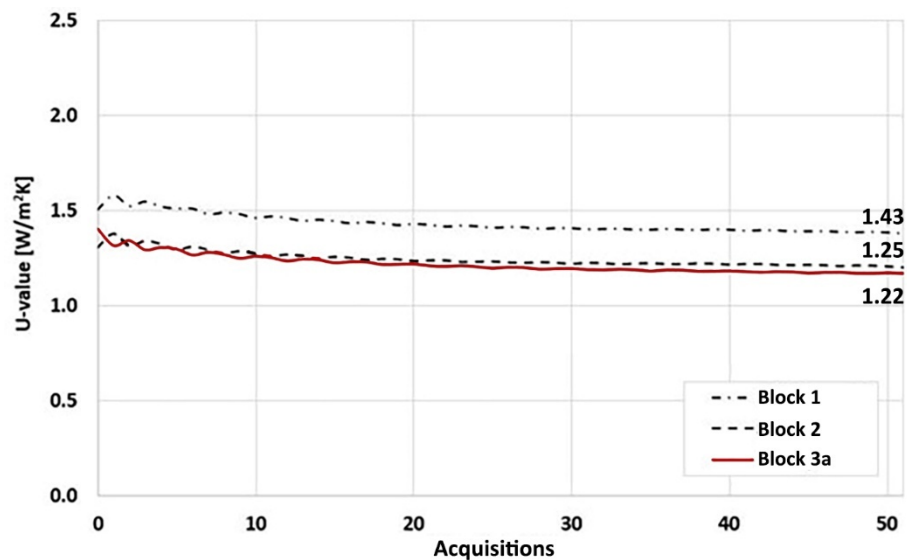
Table 3 shows the results of the first HFM campaign, focused on the comparison between different geometric configurations of the cell openings [56].

Table 3. Results of the first HFM campaign.

Block	Λ -value [W/m ² K]	U-value [W/m ² K]
Block 1 	1.89 ± 0.05	1.43 ± 0.05
Block 2 	1.58 ± 0.04	1.25 ± 0.04
Block 3a 	1.53 ± 0.04	1.22 ± 0.04

It is worth noting that the best thermal behavior was obtained with Block 3a, which is the block with a hexagonal structure.

To better understand the thermal performance differences between the three blocks, a U-value comparative graph is shown in Figure 16.

**Figure 16.** Results of the first HFM campaign.

The results obtained show that the U-value decreases as the internal geometry of the blocks becomes more complex and the air cavities become smaller. In fact, by comparing the U-values of the blocks with square and hexagonal structures with the multi-row block, reductions that are equal to -12.6% and -14.7%, respectively, can be observed. Although the percentage difference between the square structure and the hexagonal structure blocks is small (about 2.5%), the same result was obtained both in the preliminary numerical study (about 4.9%) and in the experimental results. This result turns out to be very interesting, since the main goal of the

work is to evaluate the potential of 3D printing for the creation of blocks that have progressively more complex geometries and optimized thermal performances.

When stable and steady thermal conditions between the two surfaces of the blocks were achieved, the IRT surveys allowed for a more detailed examination of the thermal behavior of the blocks (Figure 17).

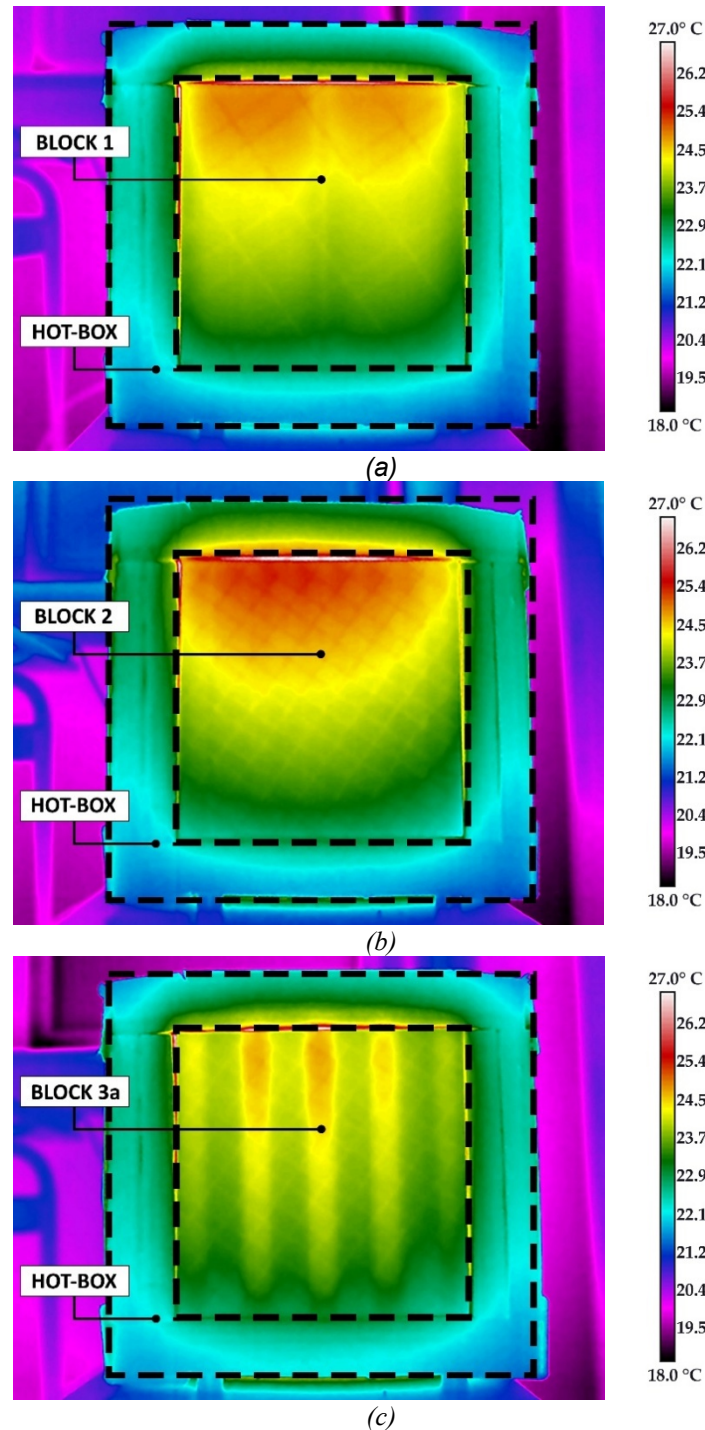


Figure 17. IR thermography results. (a) Block 1. (b) Block 2. (c) Block 3a. (Data in °C).

The thermograms show that Block 3a has less thermal stratification and a more homogeneous temperature trend on the external surface.

The second experimental campaign focused on the influence of the H/L ratio of the cells, and, more generally, on the elevation structure of the cells. Figure 18 shows the results of the second experimental campaign [57, 58].

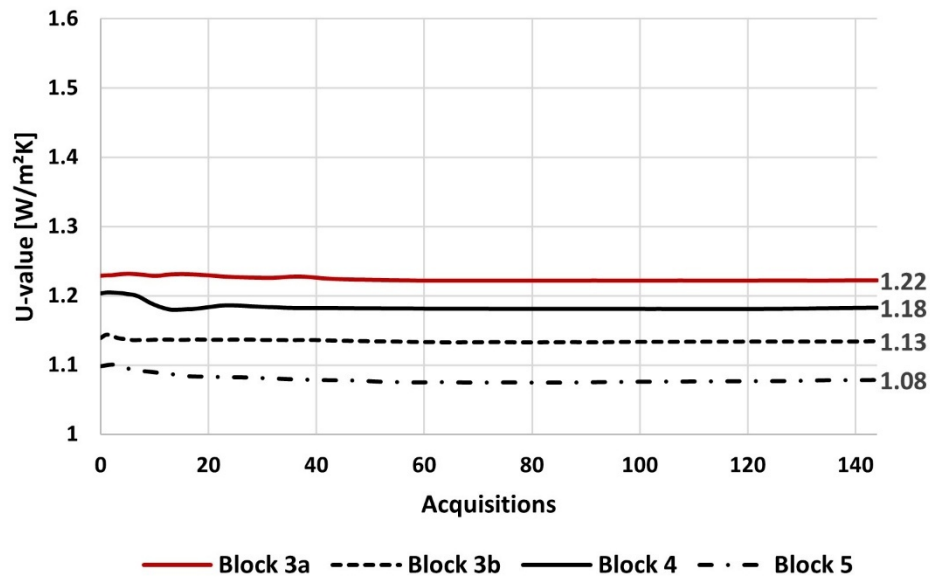
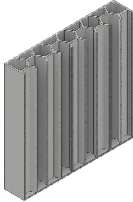
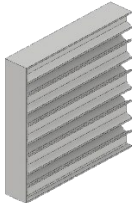
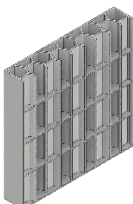


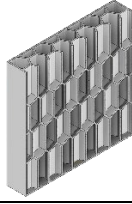
Figure 18. Results of the second HFM campaign.

It is worth noting that the honeycomb block (Block 5) exhibited the best performance, with a thermal transmittance of 1.08 ± 0.04 W/m²K. This is followed by the block featuring hexagonal cells without horizontal partitions, oriented horizontally (Block 3b) with a thermal transmittance of 1.13 ± 0.04 W/m²K. Conversely, the block with hexagonal cells without horizontal partitions, oriented vertically (Block 3a), demonstrated the poorest thermal performance, with a thermal transmittance of 1.22 ± 0.04 W/m²K.

Table 4 compares the U-values obtained with the configurations analyzed, highlighting the percentage difference compared to the results obtained for Block 3a.

Table 4. Results of the second HFM campaign.

Block	U-value [W/m ² K]	Percentage difference
Block 3a 	1.22 ± 0.04	-
Block 3b 	1.13 ± 0.04	- 7.4 %
Block 4 	1.18 ± 0.04	- 3.3 %
Block 5 	1.08 ± 0.04	- 11.5 %



The data indicate that the thermal transmittance obtained for Block 5 was 11.5 % lower than the value obtained for Block 1a. This result underscores the effectiveness of the insertion of horizontal partitions and the vertical translation of the cells in reducing the heat flow passing through the block.

The obtained results demonstrate what is described in Section 4.1 regarding the theoretical background, namely that:

- increasing the geometric complexity of the block attenuates thermal conduction through PLA, increasing thermal resistance;
- by varying the aspect ratio (H/L) and, in particular, the characteristic length (H), the Rayleigh number is modified, consequently affecting the Nusselt number. However, the results show that the block with reduced (H) (i.e., Block 4) is only marginally better than Block 1a. For a singular cavity, it is known [39] that reducing the ratio (L/H) reduces Nu . The difference in this case is most probably due to the mutual interference of the multicellular structure;
- considering the previous point, the best performance given by Block 5 is mostly due to the increased geometry complexity.

The IRT investigation conducted (Figure 19) highlighted the internal structure of the blocks, revealing the varied cavity configurations and internal thermal stratifications resulting from convective fluid motions. It's worth noting that in Block 5, the thermal distribution is significantly more homogeneous. Additionally, the air cavities reach lower temperatures. In contrast, Block 4, despite its horizontal partitions, shows considerable vertical thermal stratification.

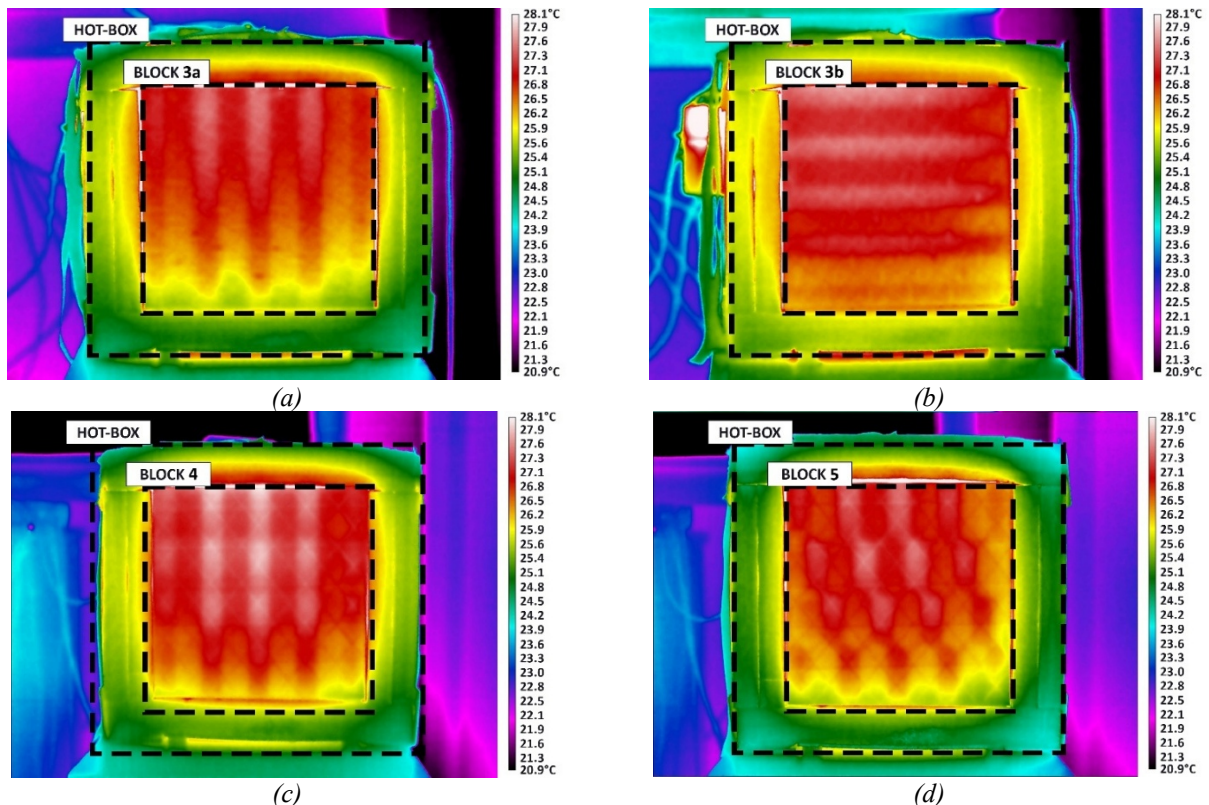
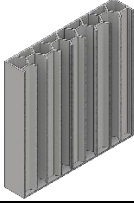


Figure 19. IR thermography results. (a) Block 3a. (b) Block 3b. (c) Block 4. (d) Block 5. (Data in °C).

The latest experimental campaign demonstrated the impact of inserting insulating material inside the cavities [59]. Again, the thermal transmittance results were compared with those for the empty Block 3a (Table 5).

Table 5. Results of the third HFM campaign.

Block	U-value [$\text{W}/\text{m}^2\text{K}$]	Percentage difference
Block 3a 	1.22 ± 0.04	-
Block 3c 	0.65 ± 0.02	- 47 %
Block 3d 	0.53 ± 0.02	- 57 %
Block 3e 	0.66 ± 0.02	- 46 %

The comparison was also made clearer by a graphic representation (Figure 20).

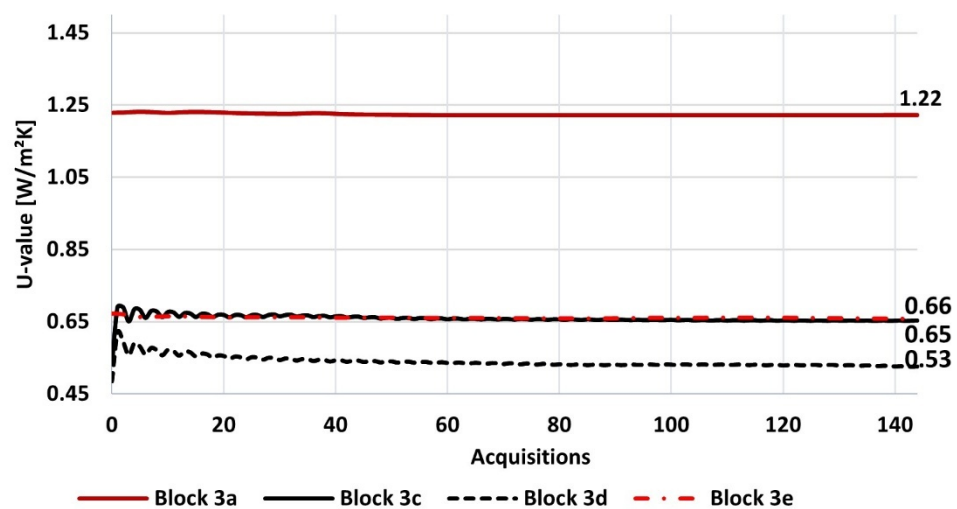


Figure 20. Results of the third HFM campaign.

The block filled with sheep's wool (Block 3d) is the one that showed the best thermal behavior among the blocks filled with insulating material. The transmittance value resulted in 18.5% lower than that of wood sawdust and 19.7% lower than that of hemp. It is worth noting that the thermal behavior of the block filled with wood sawdust and hemp was remarkably similar. Furthermore, the filling with sheep's wool optimized the thermal performance of the block with hexagonal cells (Block 3a), reducing the transmittance by 57%.

The IRT technique, performed after each HFM analysis, helped to highlight the thermal stratifications of each sample. The thermal images highlight that the block filled with wood sawdust (Block 3b) has less vertical thermal stratification and more homogeneous thermal distribution. These results are due to a better distribution of the insulating material inside the cavities. At the same time, the block filled with sheep's wool (Block 3c) has the lowest average surface temperature of the four, an indication of better insulating properties.

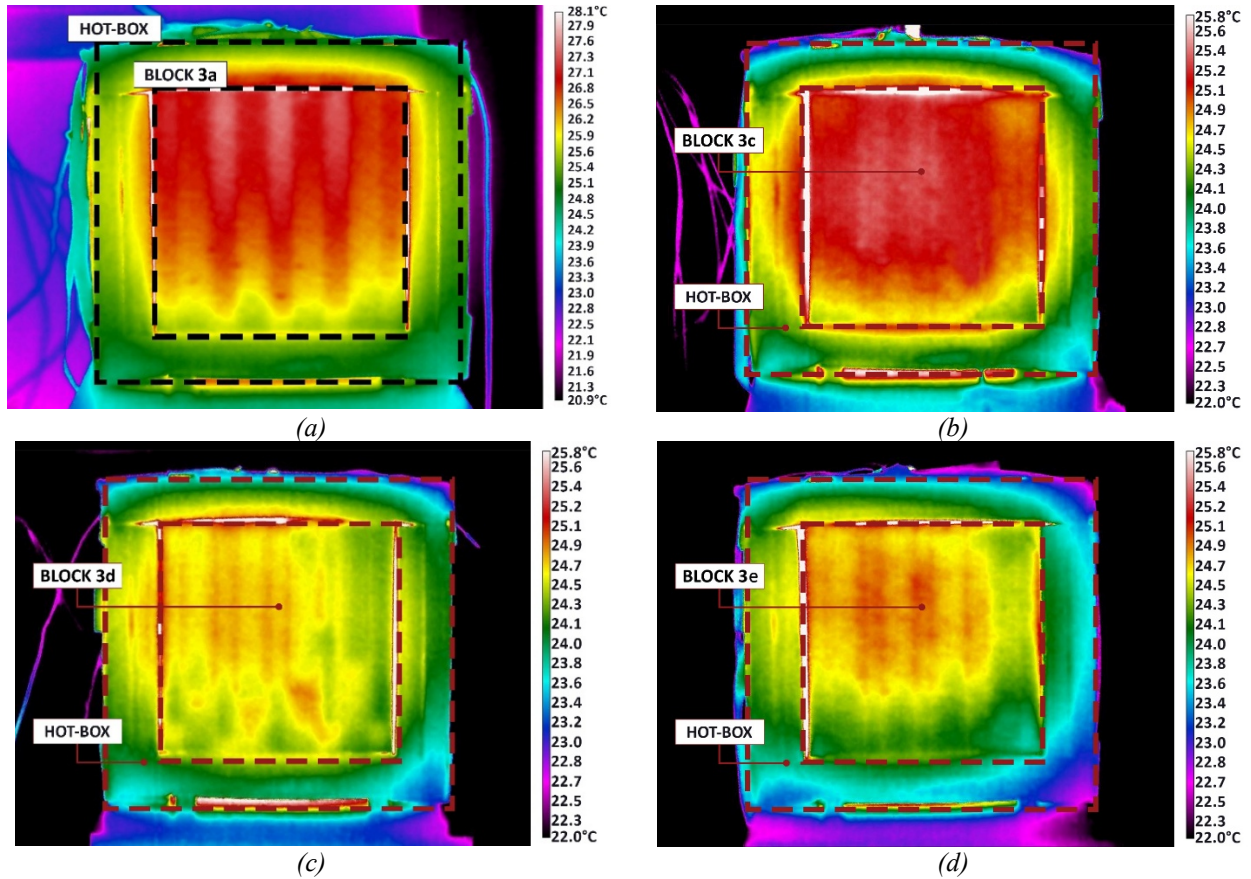


Figure 21. IR thermography results. (a) Block 3a. (b) Block 3c. (c) Block 3d. (d) Block 3e. (Data in °C).

4.4 CONCLUSIONS

The study aimed to highlight the potential of additive manufacturing in creating thermally efficient building components. In detail, three experimental campaigns were conducted testing the influence of the internal geometric structure and the insulating filling material on the thermal performance of some 3D-printed block samples. The first campaign showed that increasing the geometric complexity of the cell structure leads to lower thermal transmittance values, with the hexagonal configuration (Block 3a) achieving the best performance ($U = 1.22 \pm 0.04 \text{ W/m}^2\text{K}$), corresponding to a 14.7% reduction compared to the multi-row structure (Block 1). From a sustainability perspective, the ability to enhance thermal performance through geometric optimization alone is particularly relevant, as it allows for material-efficient solutions that reduce the overall amount of raw material required, while simultaneously lowering operational energy demand during the building life cycle. The second campaign, which investigated variations in the H/L ratio of the cells, and more generally in the elevation of the cells, further confirmed this trend: the most complex configuration, inspired by natural honeycombs (Block 5), exhibited the lowest U-value ($1.08 \pm 0.04 \text{ W/m}^2\text{K}$), highlighting

the role of geometric refinement in enhancing thermal resistance. Bio-inspired geometries, such as honeycomb-like structures, not only improve thermal behavior but also align with principles of sustainable design by maximizing performance with minimal material input and by offering forms that are well suited to additive manufacturing with reduced waste compared to conventional subtractive processes. Finally, the introduction of insulating materials inside the cavities produced a significant improvement in the U-value, particularly with sheep's wool (Block 3d), which reduced the U-value to $0.53 \pm 0.02 \text{ W/m}^2$, approximately 57% lower than the corresponding unfilled block (Block 3a). The use of sheep's wool, a renewable, biodegradable, and low-embodied-energy material, further strengthens the environmental profile of the proposed solutions, demonstrating that combining advanced manufacturing techniques with natural insulating materials can support the development of low-impact building components. These results confirm the theoretical predictions regarding the relationship between geometry, air cavity structure, and heat transfer mechanisms, and they emphasize the potential of additive manufacturing for the design of optimized, thermally efficient building components. In addition, additive manufacturing enables on-demand production, customization, and the possibility of using recycled or bio-based polymers, which can contribute to reducing construction waste, transportation impacts, and overall carbon footprint.

The results obtained are promising, even if they are still far from the properties requested for high-performance building envelopes. Future research should focus on developing new geometries, exploring alternative sustainable fillers and printing materials, and evaluating the mechanical performance of the blocks under real operating conditions to test the real applicability of 3D printing in the building sector. Future developments should also include life-cycle assessment (LCA) studies to quantitatively compare the environmental impacts of 3D-printed components with those of traditional masonry systems, ensuring that improvements in thermal performance are accompanied by verifiable sustainability benefits.

SUMMARY

4.1 Design and construction of blocks using 3D printing

Taking into account the size limits imposed by the printer (300 x 300 x 400 mm), several prototype blocks were designed, with the aim of comparing both different geometric configurations of the internal structure and different insulating material fillings within the cells. All of the blocks had the same dimensions of 250 x 250 x 100 mm (width x height x depth).

DIFFERENT GEOMETRIC CONFIGURATION OF THE CELLS OPENING

- 1 Multi-row structure block
- 2 Square structure block
- 3a Hexagonal structure block

DIFFERENT GEOMETRIC CONFIGURATION OF THE CELLS ELEVATION

- 3a Hexagonal structure block
- 3b Hexagonal structure block rotated 90°
- 4 Hexagonal structure block with horizontal partitions
- 5 Honeycomb block

3c

3d

3e

3a *

3b

4

5

DIFFERENT INSULATING MATERIALS FILLINGS

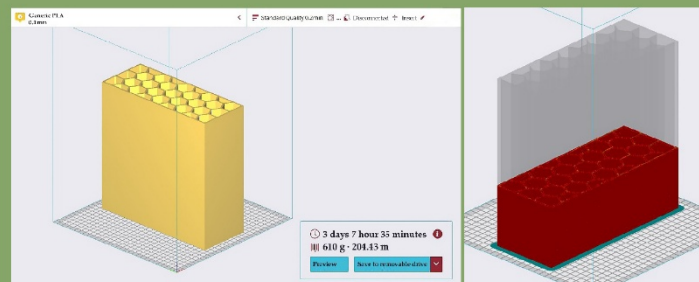
- 3c Hexagonal structure block filled with wood sawdust
- 3d Hexagonal structure block filled with sheep's wool
- 3e Hexagonal structure block filled with hemp

2

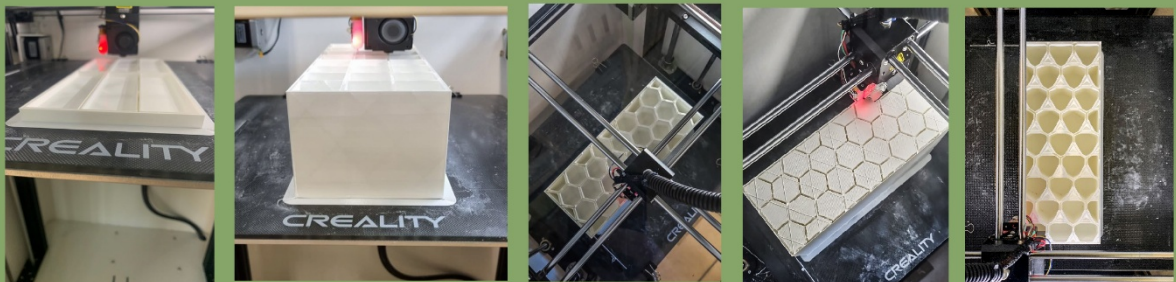
* Block 3a, having resulted the best performing compared to Blocks 1 and 2, from a preliminary theoretical analysis, was taken into consideration in all the experimental campaigns carried out, as a benchmark.

With the aim of carrying out the pre-established experimental analyses, the blocks were realized using a 3D printer. To this end, the blocks were first modeled three-dimensionally with an AutoCAD Inventor®.

Subsequently, with the Creality Slicer 4.2 slicing software, all of the printing parameters were defined, including the quality, the characteristics of the shell, those of the filling, the type of material used, the printing temperature and that of the print bed, the print speed, and the nozzle size. Upon defining all printing parameters, the G-Code was generated.

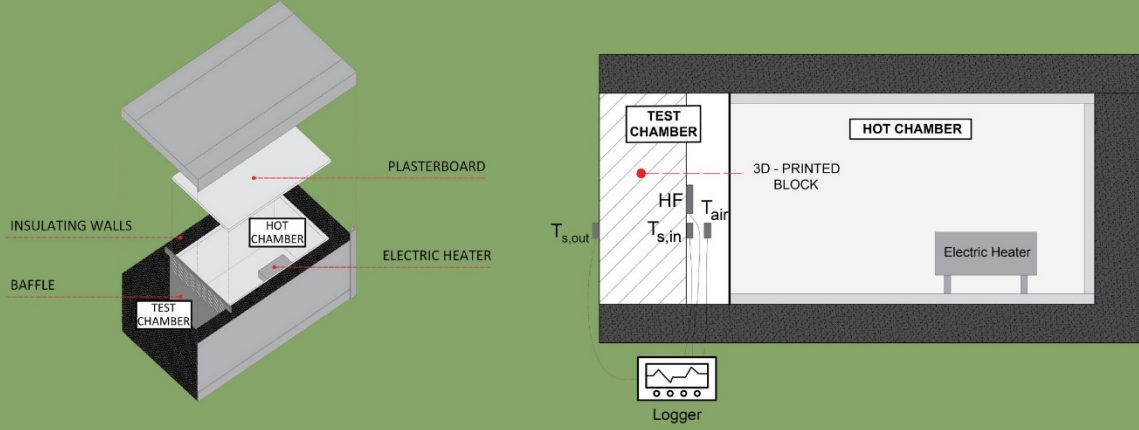


The G-Code file generated by Creality Slicer 4.2 provided the data that were needed by the Creality CR-3040 PRO 3D printer for the realization of the three blocks.



4.2 Thermal performance analysis

The experimental phase used a custom-built Hot Box designed for 3D-printed blocks measuring 250×250 mm. It enabled steady-state testing in a controlled and repeatable environment, based on the Guarded Hot Box developed at the University of L'Aquila. The setup included a heated chamber with an electric heater to create temperature differences across the block. The Hot Box was made of insulated walls clad in sheet steel and featured a baffle separating the heating zone (hot chamber) from the measurement area (test chamber) to analyze radiative heat transfer. Measurements were taken using two surface temperature probes (on both block faces), one air temperature probe inside the Hot Box, and one heat flow sensor applied to the internal block surface.



The experimental tests began at laboratory temperature, with the Hot Box's electric heater adjusted to create a minimum 20°C temperature difference between block surfaces, following ISO 9869 standards. A data logger recorded heat flow, surface temperatures, and internal air temperature every 10 minutes. Each test lasted until steady-state thermal conditions were achieved, varying by block. The collected data were processed using the progressive average method (as per ISO 9869) to calculate thermal conductance (A) and thermal resistance (R), using Equations (1) and (2), respectively:

$$A = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{s,in,j} - T_{s,out,j})} \quad [\text{W}/\text{m}^2 \text{K}] \quad (1)$$

$$R = \frac{\sum_{j=1}^n (T_{s,in,j} - T_{s,out,j})}{\sum_{j=1}^n q_j} \quad [\text{m}^2 \text{K}/\text{W}] \quad (2)$$

where:

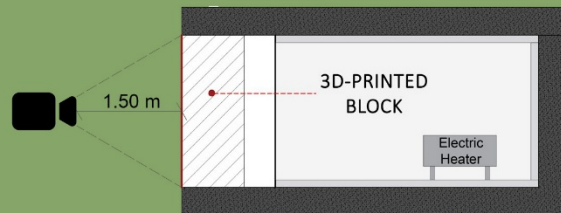
- $\sum_{j=1}^n (T_{s,in,j} - T_{s,out,j})$ is the progressive sum of the differences between the internal and external surface temperatures [$^\circ\text{C}$];
- $\sum_{j=1}^n q_j$ is the progressive sum of the density of the heat flux [W/m^2].

Finally, the transmittance value was calculated according to Equation (3):

$$U = \frac{1}{R_{tot}} \quad [\text{W}/\text{m}^2 \text{K}] \quad (3)$$

where (R_{tot}) is the total thermal resistance which also includes ($R_{s,i}$) the internal and external ($R_{s,e}$) thermal resistances, which were taken from the EN ISO 6946 standard, which are equal to $0.13 \text{ m}^2\text{K}/\text{W}$ and $0.04 \text{ m}^2\text{K}/\text{W}$, respectively.

Then, the IRT technique was performed using a FLIR T1020 IR camera, after reaching a steady-state condition between the surfaces of the block. The survey was carried out at a distance of 1.50 m from the blocks.

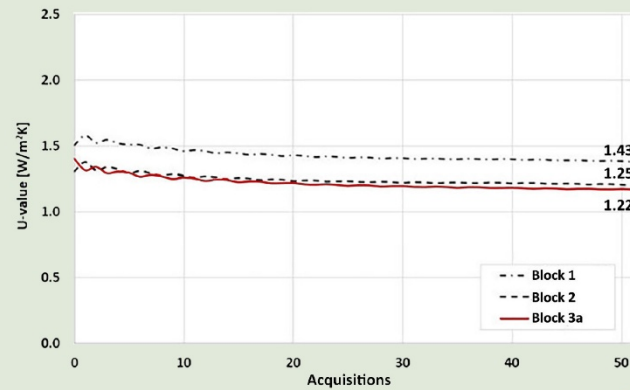


4.3 Results

1st EXPERIMENTAL CAMPAIGN: DIFFERENT GEOMETRIC CONFIGURATION OF THE CELLS OPENING

Table 1. Results of the first HFM campaign.

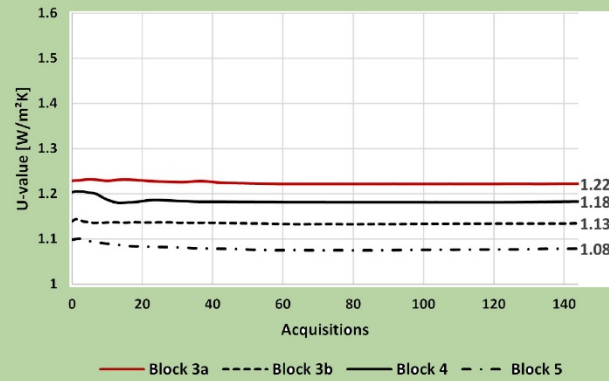
BLOCK	Δ -value [W/m ² K]	U-value [W/m ² K]
Block 1	1.89 ± 0.05	1.43 ± 0.05
Block 2	1.58 ± 0.04	1.25 ± 0.04
Block 3a	1.53 ± 0.04	1.22 ± 0.04



2nd EXPERIMENTAL CAMPAIGN: DIFFERENT GEOMETRIC CONFIGURATION OF THE CELLS ELEVATION

Table 2. Results of the second HFM campaign.

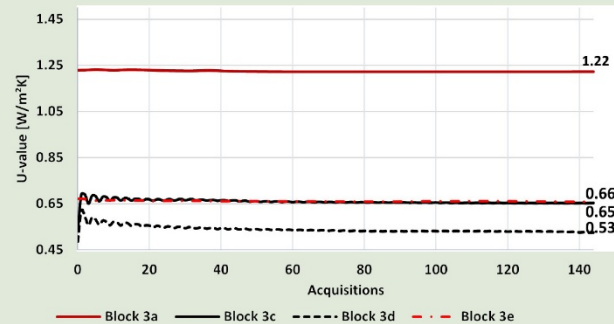
BLOCK	U-value [W/m ² K]	Percentage difference
Block 3a	1.22 ± 0.04	-
Block 3b	1.13 ± 0.04	- 7.4 %
Block 4	1.18 ± 0.04	- 3.3 %
Block 5	1.08 ± 0.04	- 11.5 %



3th EXPERIMENTAL CAMPAIGN: DIFFERENT INSULATING MATERIALS FILLINGS

Table 3. Results of the third HFM campaign.

BLOCK	U-value [W/m ² K]	Percentage difference
Block 3a	1.22 ± 0.04	-
Block 3c	0.65 ± 0.02	- 47 %
Block 3d	0.53 ± 0.02	- 57 %
Block 3e	0.66 ± 0.02	- 46 %



4.4 Conclusions

The **first campaign** showed that increasing the geometric complexity of the cell structure reduces thermal transmittance, with the hexagonal configuration (Block 3a) achieving the best performance ($U = 1.22 \pm 0.04$ W/m²K), corresponding to a 14.7% reduction compared to the multi-row structure (Block 1). The **second campaign**, focused on the variation of the H/L ratio of the cells, confirmed this trend: the most complex configuration, inspired by natural honeycombs (Block 5), reached the lowest U-value (1.08 ± 0.04 W/m²K), highlighting the importance of geometric refinement in improving thermal resistance. Finally, the **third campaign** investigated the effect of inserting insulating materials into the cavities, revealing a significant improvement—especially with sheep's wool (Block 3d)—which lowered the U-value to 0.53 ± 0.02 W/m²K, about 57% lower than the corresponding unfilled block (Block 3a).

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5. WALL-SCALE ANALYSIS: NDTs FOR ASSESSING THE U-VALUE OF WALLS

A correct determination of the thermal characteristics of the building envelope is essential to identify the most suitable intervention strategies to improve the energy performance of the building. In this context, NDTs play a crucial role in the analysis of the thermal transmittance (U-value) of the building envelope, as they allow examinations without causing damage to the structure. In this work, resuming the line of research of the “G. Parolini Laboratory” [1], two measurement methods were tested under controlled and repeatable conditions to assess their validity. The methods in question are i) M1: heat flux meter (HFM); ii) M2: Infrared Thermography (IRT). The two approaches were tested on a sample wall with real dimensions (300 cm x 300 cm) inside a Guarded Hot Box (GHB) apparatus.

The thermal transmittance values obtained were discussed with reference to the design U-value calculated theoretically.

The wall is made up of a double-insulated X-lam load-bearing element known as CLT (Cross Laminated Timber). The side of the wall facing the hot chamber was insulated with rock wool, while the side facing the cold chamber was insulated with cork panels. The wall was sandwiched between double layers of plasterboard (Figure 1).



Figure 1. Sample wall configuration.

Table 1 reports the characteristics of the wall layers, from the cold chamber to the hot chamber.

Table 1. Characteristics of the sample wall layers.

Description	Thickness [cm]	Density [kg/m ³]	Conductivity [W/mK]	Resistance [m ² K/W]
External surface resistance (EN ISO 6946)	-	-	-	0.04
Plasterboard (double layer)	2.50	900	0.210	0.12
Cork panel	10.00	150	0.041	2.44
X-lam panel	10.00	470	0.130	0.77
Rock wool	5.00	135	0.039	1.28
Plasterboard (double layer)	2.50	900	0.210	0.12
Internal surface resistance (EN ISO 6946)	-	-	-	0.13

5.1 EVALUATION OF THE DESIGN U-VALUE

Following the theoretical approach, the design U-value of the sample wall was calculated as the reciprocal of the total wall thermal resistance (R_{tot}), according to equation (1):

$$U = \frac{1}{R_{tot}} [W/m^2K] \quad (1)$$

R_{tot} was obtained using Ohm's law, adding the various contributions expressed in equation (2):

$$R_{tot} = R_{s,i} + \sum R_{cond,n} + R_{s,e} [m^2K/W] \quad (2)$$

where:

- $R_{s,i}$ and $R_{s,e}$ are the internal and external surface resistances [m^2K/W], equal to $0.13 m^2K/W$ and $0.04 m^2K/W$, respectively, as indicated by EN ISO 6946 standard [2];
- $R_{cond,n}$ is the conductive thermal resistance of each layer [m^2K/W].

Once the U-value of the wall has been calculated, the heat flow was obtained from equation (3), assuming a temperature difference (ΔT) of $20^\circ C$ between the inner and the outer surfaces.

$$q = U \cdot \Delta T [W/m^2] \quad (3)$$

5.2 EXPERIMENTAL APPROACH

The experimental analyses were conducted using a GHB, built according to the UNI EN ISO 8990 [3], made of a cold chamber and a hot chamber (guard box) containing a metering box (Figure 2). Hot and cold chambers are separated by the investigated specimen wall. A detailed description of the apparatus can be found in previous studies [1, 4, 5]. The GHB method enables precise control and regulation of temperatures within the chambers, ensuring consistent and repeatable conditions. Additionally, it facilitates the assessment of how boundary conditions affect the thermal behavior of the tested building component [6].

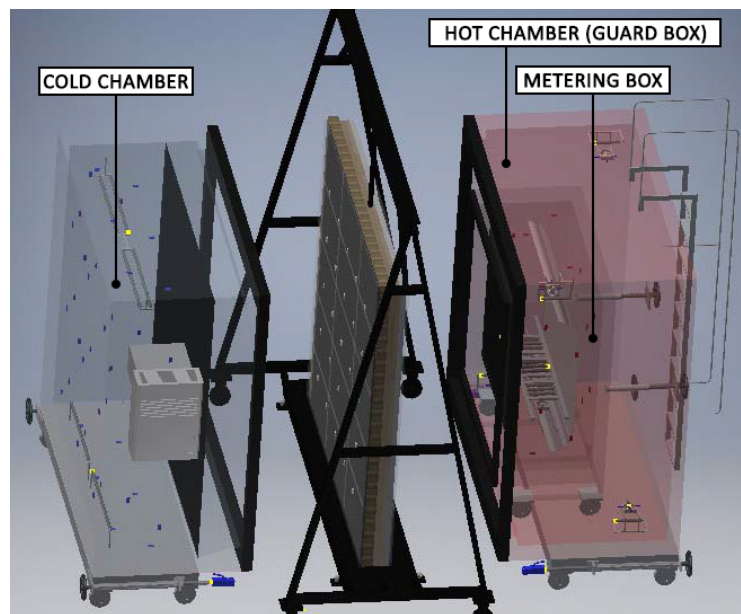


Figure 2. Axonometric cross-section of the GHB.

The setups used to test the different measurement methods are shown in Figure 3.

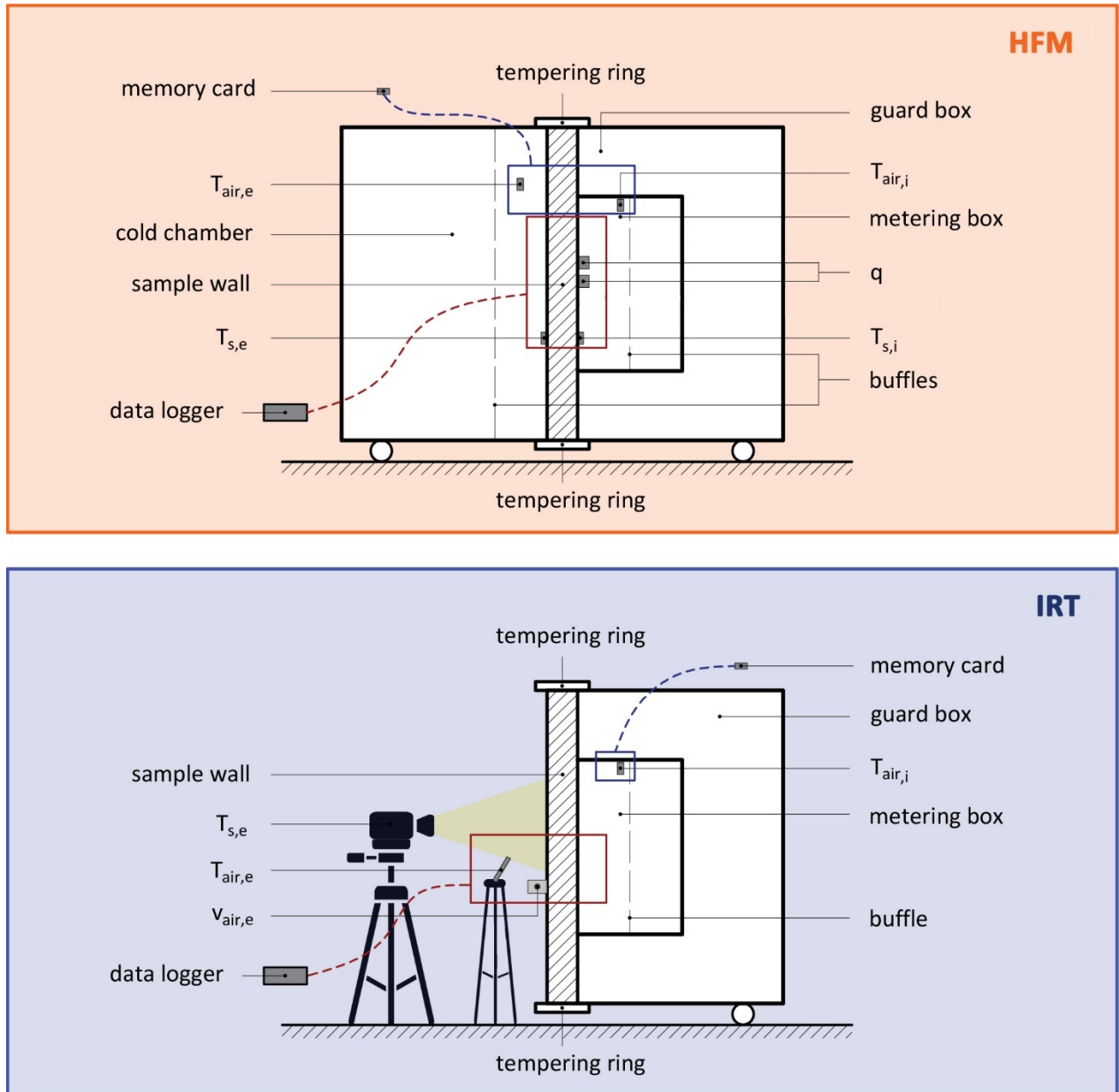


Figure 3. Comparison between the experimental setups.

The experimental campaigns lasted one week for the HFM method, while the IRT measurements were instantaneous. Specifically, the tests for the first method were conducted from March 6 to 12, 2024, while the IRT measurements were taken on January 13, 2025.

5.2.1 M1: Heat Flux Meter (HFM) method

The HFM method was tested by installing two different heat flux probes on the hot side: HFP03 and HFP01. HFP03 is an ultra-sensitive sensor particularly suitable for the measurement of small heat fluxes, while HFP01 is the world's most popular sensor for heat flux measurement.

In addition to the flow probes, an air temperature probe and a surface temperature probe were installed in the measuring chamber. In the cold chamber, however, only the two temperature probes were installed.

A data logger recorded the data of the various parameters every ten minutes, except for the air temperature data, which were saved on a memory card with the same time interval. By using electrical resistances and adding thermal energy to the hot chamber, the temperature was maintained at the target value of 20°C. In contrast, the cold chamber's thermal conditions were controlled by a refrigeration unit, which brought the

temperature down to the set point of 0°C, to obtain a ΔT of 20 °C, in line with the indications of the ISO 9869 standard [7]. All the measured data were subsequently processed using the progressive average method, in accordance with the ISO 9869 standard [7], to calculate the conductance (Λ) and thermal resistance (R) values, according to Equations (4) and (5), respectively.

$$\Lambda = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{s,i,j} - T_{s,e,j})} \quad [W/m^2 K] \quad (4)$$

$$R = \frac{\sum_{j=1}^n (T_{s,i,j} - T_{s,e,j})}{\sum_{j=1}^n q_j} \quad [m^2 K/W] \quad (5)$$

where:

- $\sum_{j=1}^n (T_{s,i,j} - T_{s,e,j})$ is the progressive sum of the differences between internal and external surface temperatures;
- $\sum_{j=1}^n q_j$ is the progressive sum of the density of the heat flux.

Finally, the transmittance was calculated as the inverse of (5), after adding the surface thermal resistances [2] to R .

The technical specifications of the instruments used for the application of the M1 method are shown in Table 2.

Table 2. Characteristics of the measuring instruments used for the application of the M1 method.

Sensor	Type	Measuring Range	Accuracy
Heat flow meter	Hukseflux HFP03	-2000 to 2000 W/m ²	± 6%
Heat flow meter	Hukseflux HFP01	-2000 to 2000 W/m ²	± 3%
Surface temperature	LSI Lastem DLE 124A	-100 to 200 °C	± 0.1 K
Air temperature	DS18B20	-55 to 150 °C	± 0.5 K

Table 3 presents the positions of the measuring instruments used for the method's application.

Table 3. Position of measuring instruments.

Instrument	Location	Height from the ground	Distance from the wall
Hukseflux HFP03	measuring chamber	150 cm	0 cm
Hukseflux HFP01	measuring chamber	150 cm	0 cm
LSI Lastem DLE 124A	measuring chamber + cold chamber	150 cm	0 cm
DS18B20	measuring chamber + cold chamber	150 cm	10,00 cm

5.2.2 M2: Infrared Thermography (IRT) method

To test the IRT method, the cold chamber of the GHB was opened to allow measurements with the infrared (IR) camera. Consequently, the temperature of the measurement chamber was set to 40 °C to establish an adequate ΔT between the two sides of the wall, considering that the temperature of the cold side coincided with that of the laboratory, equal to 20 °C.

The experimental setup of the second measurement method (Figure 4) included the presence of a IR camera, an air temperature probe, and an anemometer on the cold side and only an air temperature probe on the hot side.



Figure 4. Experimental setup for the application of the M2 method. Cold side view.

The experimental setup was designed in anticipation of the application of the Albatici Tonelli equation [8], expressed below (11):

$$U = \frac{\varepsilon\sigma(T_{s,e}^4 - T_{air,e}^4) + 3.8054v(T_{s,e} - T_e)}{T_{air,i} - T_{air,e}} \quad [W/m^2K] \quad (11)$$

where:

- ε is the wall spectral emissivity, that is, the wall emissivity in the IR camera spectral range;
- σ is the Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-8} \text{ W/m}^2\text{K}^4$;
- $T_{s,e}$ is the external surface temperature;
- $T_{air,e}$ is the external air temperature;
- $T_{air,i}$ is the internal air temperature;
- $3.8054v$ is the convective heat transfer coefficient h_c with v = external air speed.

The technical specifications of the instruments used to apply the M2 method are shown in Table 4.

Table 4. Characteristics of the measuring instruments used for the application of the M3 method.

Sensor	Type	Measuring Range	Accuracy
Surface temperature	FLIR T1020	-40 to 2000 °C	• $\pm 1 \text{ K}$ (5 to 150 °C) • $\pm 2 \text{ K}$ (up to 1200 °C)
External air temperature	DMA033A	-50 to 70 °C	$\pm 0.15 \text{ K}$
Internal air temperature	DS18B20	-55 to 150 °C	$\pm 0.5 \text{ K}$
Air speed	LSI Lastem ESV108	0.01 to 20 m/s	• NA (0 to 0.1 m/s) • $\pm 0.06 \text{ m/s}$ (0.1 to 0.4 m/s) • $\pm 0.08 \text{ m/s}$ (0.4 to 3.0 m/s) • $\pm 0.035 \text{ m/s}$ (3.0 to 20 m/s)

Table 5 shows the positions of the measuring instruments used for the application of the method.

Table 5. *Position of measuring instruments.*

Instrument	Location	Height from the ground	Distance from the wall
FLIR T1020	cold side	150 cm	1,50 m
DMA033A	cold chamber	150 cm	75,00 cm
DS18B20	measuring chamber	150 cm	10,00 cm
LSI Lastem ESV108	cold chamber	150 cm	1,00 cm

5.3. RESULTS AND DISCUSSION

Table 6 summarizes the results obtained from the application of the different NDTs tested.

Table 6. *Experimental results.*

Method	q [W/m ²]	U [W/m ² K]
Theoretical	4.08	0.20
HFM	3.07 (q_{HFP03})	0.17
	3.18 (q_{HFP01})	0.17
IRT	3.13	0.16

The method that gave results closest to the design U-values is the HFM. A 3% difference emerged between the flux measurements with HFP01 and HFP03, but this difference did not affect the final transmittance measurement. In general, values obtained with the HFM differ from those obtained with the IRT by a percentage between 0% and 3% in the q-value and between 6% and 11% in the U-value, demonstrating agreement between the two measurement techniques.

Regarding measurement uncertainty, assuming that the analyses were conducted in a nearly steady state, and relying on the literature [1, 8, 9], we can argue that:

- in the case of the HFM, the uncertainty can reach up to 5% [9],
- in the case of the IRT, the uncertainty is estimated at around 10% [1, 8].

However, if the measurements were performed under real and variable conditions, the uncertainty of the HFM would reach 28% [10], while that of the IRT would get 58% [8].

5.4. Conclusions

This study assessed two experimental methods for the thermal transmittance (U-value) evaluation - M1) Heat Flux Meter (HFM), M2) Infrared Thermography (IRT) - under strictly controlled and repeatable laboratory conditions. Tests were conducted on a full-scale wall specimen placed within a Guarded Hot Box (GHB) apparatus, which ensured stable and uniform boundary conditions, thereby enabling a reliable comparison between techniques. The experimental results were benchmarked against theoretical values of heat flux (q) and thermal transmittance (U), allowing a critical evaluation of the accuracy, sensitivity, and limitations of each approach.

Overall, the outcomes demonstrated that HFM provided the most consistent estimations of both heat flux and thermal transmittance when compared to the theoretical approach. The HFM method achieved the closest agreement, with deviations between 22–25% for heat flux and of approximately 15% for U-value. Conversely, although IRT returned comparable values, the associated measurement uncertainty is significantly higher [1, 8, 9]. Nonetheless, controlled laboratory conditions significantly mitigated the variability of IRT results, reinforcing the method's potential when boundary conditions are well managed. This outcome highlights the importance of correctly considering boundary conditions.

The experimental findings confirm evidence reported in the literature:

- HFM, to date, can be considered a robust technique for determining thermal transmittance, provided that appropriate instrumentation, compliance with standardized procedures, and rigorous data processing are ensured [11].
- IRT offers a valuable alternative for non-contact and expeditious evaluation of the U-value [1], capable of producing reliable results when used in a controlled environment, despite its higher measurement uncertainty [8].

In conclusion, the study confirms that method selection should be guided by the intended application, required accuracy, and environmental controllability. While HFM should be preferred for high-precision laboratory or on-site verification tasks, IRT represents a promising complementary tool - particularly in scenarios where intrusive measurements are not feasible, time is limited and environmental variability can be minimized. Future research should focus on extending comparative validation to real in-situ building environments to assess the robustness of these techniques under non-ideal boundary conditions.

SUMMARY

Two measurement methods were tested under controlled and repeatable conditions to highlight the potential and limitations of each. The methods in question are i) M1: heat flux meter (HFM); ii) M2: Infrared Thermography (IRT). The two approaches were tested on a sample wall with real dimensions (300 cm x 300 cm) inside a Guarded Hot Box (GHB) apparatus. The thermal transmittance values obtained were compared with those resulting from the theoretical approach.

Below is the main information about the sample (Table 1).



Table 1. Characteristics of the sample wall layers.

Description	Thickness [cm]	Density [kg/m ³]	Conductivity [W/mK]	Resistance [m ² K/W]
External surface resistance (EN ISO 6946)	-	-	-	0.04
Plasterboard (double layer)	2.50	900	0.210	0.12
Cork panel	10.00	150	0.041	2.44
X-lam panel	10.00	470	0.130	0.77
Rock wool	5.00	135	0.039	1.28
Plasterboard (double layer)	2.50	900	0.210	0.12
Internal surface resistance (EN ISO 6946)	-	-	-	0.13

5.1. Theoretical approach

Following the theoretical approach, the thermal transmittance of the sample wall was calculated as the reciprocal of the total wall resistance (R_{tot}), according to equation (1):

$$U = \frac{1}{R_{tot}} [W/m^2K] \quad (1)$$

R_{tot} was obtained using Ohm's law, adding the various contributions expressed in equation (2):

$$R_{tot} = R_{s,i} + \sum R_{cond,n} + R_{s,e} [m^2K/W] \quad (2)$$

where:

- $R_{s,i}$ and $R_{s,e}$ are the internal and external surface resistances [m^2K/W], equal to $0.13 m^2K/W$ and $0.04 m^2K/W$, respectively, as indicated by EN ISO 6946 standard [1];

- $R_{cond,n}$ is the conductive thermal resistance of each layer [m^2K/W].

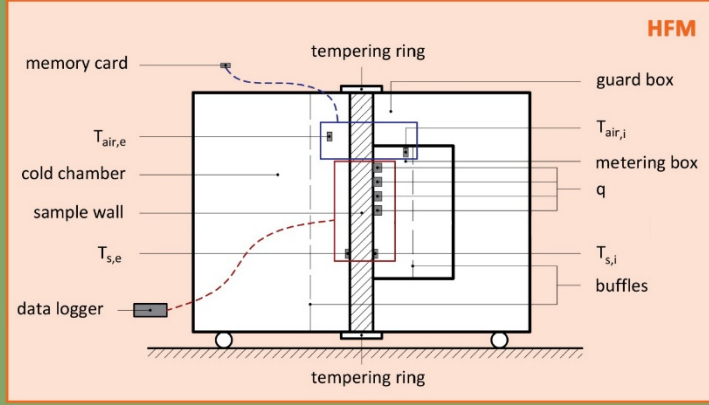
Once the U-value of the wall has been calculated, the heat flow was obtained from equation (3), assuming a temperature difference (ΔT) of $20^\circ C$ between the inner and the outer surfaces.

$$q = U \cdot \Delta T \quad (3)$$

5.2. Experimental approach

The experimental analyses were conducted using a GHB, built according to the UNI EN ISO 8990 [2], made of a cold chamber and a hot chamber (guard box) containing a metering. The experimental campaigns lasted one week for the HFM method, while the IRT measurements were instantaneous. Specifically, the tests for the first two methods were conducted simultaneously from March 6 to 12, 2024, while the IRT measurements were taken on January 13, 2025.

Below are the setups used to test different measurement methods.



In the hot chamber there were:

- two different heat flow probes: HFP03, and HFP01;
- an air temperature probe;
- a surface temperature probe.

In the cold chamber there were:

- an air temperature probe;
- a surface temperature probe.

After setting a ΔT of 20 °C between the two chambers, data were recorded every 10 minutes, following ISO 9869 [8] standards. A data logger recorded heat flow, surface temperatures, and internal air temperature every 10 minutes. The collected data were processed using the progressive average method (as per ISO 9869 [8]) to calculate thermal conductance (Λ) and thermal resistance (R), using Equations (4) and (5), respectively:

$$\Lambda = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{s,in,j} - T_{s,out,j})} \quad [W/m^2 K] \quad (4)$$

$$R = \frac{\sum_{j=1}^n (T_{s,in,j} - T_{s,out,j})}{\sum_{j=1}^n q_j} \quad [m^2 K/W] \quad (5)$$

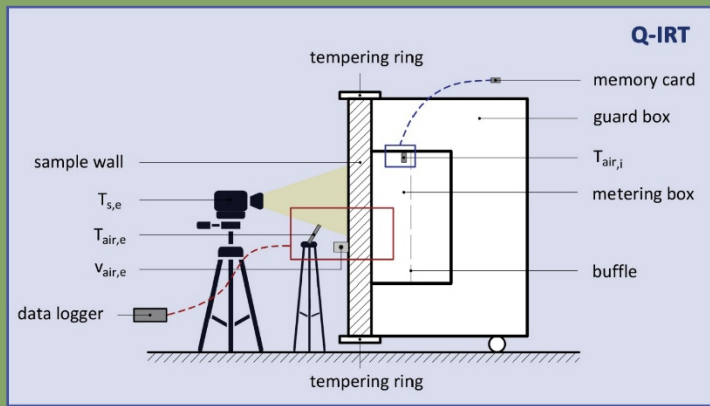
where:

- $\sum_{j=1}^n (T_{s,in,j} - T_{s,out,j})$ is the progressive sum of the differences between the internal and external surface temperatures [°C];
- $\sum_{j=1}^n q_j$ is the progressive sum of the density of the heat flux [W/m²].

Finally, the transmittance value was calculated according to Equation (6):

$$U = \frac{1}{R_{tot}} \quad [W/m^2 K] \quad (6)$$

where (R_{tot}) is the total thermal resistance with the addition of the surface thermal resistances [1].



In the case of IRT, the setup used does not require the installation of flow probes.

In the hot chamber there were:

- an air temperature probe.

In the cold chamber there were:

- a infrared (IR) camera
- an air temperature probe;
- an anemometer.

To test the IRT method, the cold chamber of the GHB was opened to allow measurements with the IR camera. Consequently, the temperature of the measurement chamber was set to 40 °C to establish an adequate ΔT between the two sides of the wall, considering that the temperature of the cold side coincided with that of the laboratory, equal to 20 °C. The experimental setup was designed in anticipation of the application of the Albatici Tonelli equation [9], expressed below (11):

$$U = \frac{\varepsilon \sigma (T_{s,e}^4 - T_{air,e}^4) + 3.8054v(T_{s,e} - T_e)}{T_{air,i} - T_{air,e}} [W/m^2 K] \quad (11)$$

where:

- ε is the surface integral emissivity;
- σ is the Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-8} W/m^2 K^4$;
- $T_{s,e}$ is the external surface temperature;
- $T_{air,e}$ is the external air temperature;
- $T_{air,i}$ is the internal air temperature;
- $3.8054v$ is the convective heat transfer coefficient h_c with v = external air speed.

5.3. Results

Table 2. Summary of results.

Method	q		U	
	Value [W/m ²]	Percentage difference with the theoretical method [%]	Value [W/m ² K]	Percentage difference with the theoretical method [%]
Theoretical	4.08	-	0.20	-
HFM	3.07 (q _{HFP03})	25	0.17	15
	3.18 (q _{HFP01})	22	0.17	
IRT	3.13	23	0.16	20

5.4. Conclusions

This study assessed three experimental methods for the thermal transmittance (U-value) evaluation - M1) Heat Flux Meter (HFM), M2) Infrared Thermography (IRT) - under strictly controlled and repeatable laboratory conditions. Tests were conducted on a full-scale wall specimen placed within a Guarded Hot Box (GHB) apparatus, which ensured stable and uniform boundary conditions, thereby enabling a reliable comparison between techniques.

The experimental results were benchmarked against theoretical values of heat flux (q) and thermal transmittance (U), allowing a critical evaluation of the accuracy, sensitivity, and limitations of each approach.

Overall, the outcomes demonstrated that HFM provided the most consistent estimations of both heat flux and thermal transmittance when compared to the theoretical approach. The HFM method achieved the closest agreement, with deviations between 22–25% for heat flux and of approximately 15% for U-value. Conversely, although IRT returned comparable values, the associated measurement uncertainty is significantly higher [3, 8, 9]. Nonetheless, controlled laboratory conditions significantly mitigated the variability of IRT results, reinforcing the method's potential when boundary conditions are well managed. This outcome highlights the importance of correctly considering boundary conditions.

The experimental findings confirm evidence reported in the literature:

- HFM, to date, can be considered a robust technique for determining thermal transmittance, provided that appropriate instrumentation, compliance with standardized procedures, and rigorous data processing are ensured [11].
- IRT offers a valuable alternative for non-contact and expeditious evaluation of the U-value [1], capable of producing reliable results when used in a controlled environment, despite its higher measurement uncertainty [8].

In conclusion, the study confirms that method selection should be guided by the intended application, required accuracy, and environmental controllability. While HFM should be preferred for high-precision laboratory or on-site verification tasks, IRT represents a promising complementary tool - particularly in scenarios where intrusive measurements are not feasible, time is limited and environmental variability can be minimized. Future research should focus on extending comparative validation to real in-situ building environments to assess the robustness of these techniques under non-ideal boundary conditions.

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6. BUILDING-SCALE ANALYSIS: THE ROLE OF BIM IN ENERGY-CONSCIOUS DESIGN

Building Information Modeling (BIM) has the potential to transform the construction industry by enabling the delivery of complete, coherent, and well-organized projects. Through detailed 3D modeling, BIM offers a highly accurate visualization of building components, helping professionals manage every aspect of a project more effectively. It serves as a valuable tool throughout the entire lifecycle of a building—from initial design all the way through demolition or renovation. However, this tool is currently mainly linked to the architectural field, and its potential in the energy field has not yet been fully explored.

6.1 BIM–BEM INTEROPERABILITY

This work examines how BIM and Building Energy Modeling (BEM) can support early-stage energy analysis while addressing interoperability challenges. Two integration strategies—real-time connection (S1) and standardized exchange formats (S2)*—were tested using a case study building. The resulting energy models were calibrated with experimental energy consumption data and compared with a traditional BEM approach to validate the BIM-to-BEM workflow.

*As emerges from chapter 2 of this thesis, among the various strategies, Real-time connection (S1) and Standardized exchange formats (S2) allow an open and direct exchange between the two software [1]. The potential automation of the BIM-to-BEM process determined the choice of the two aforementioned strategies for experimentation.

6.1.1 Case study analysis

During the first phase of work, an in-depth analysis of the case study was conducted in order to subsequently create a thermal model as accurate as possible.

The case study is the “Solar House” at the University of L’Aquila’s Engineering Campus in Monteluco di Roio. Built in the 1970s, it is a reinforced concrete building with three floors: a basement and two above-ground levels. Although the entire building was modeled, the energy analysis focused on the top floor, housing the Las.E.R and G. Parolini Laboratories (boxed in red in Fig. 1).



Figure 1. Front view of the sample building.

Figure 2 provides an overview of the plan, showing the layout of internal spaces, their intended uses, and the thermal characteristics of the building envelope, determined based on the UNI 10351 standard [2] for the opaque envelope and the UNI EN ISO 10077–1 standard [3] for the transparent one.

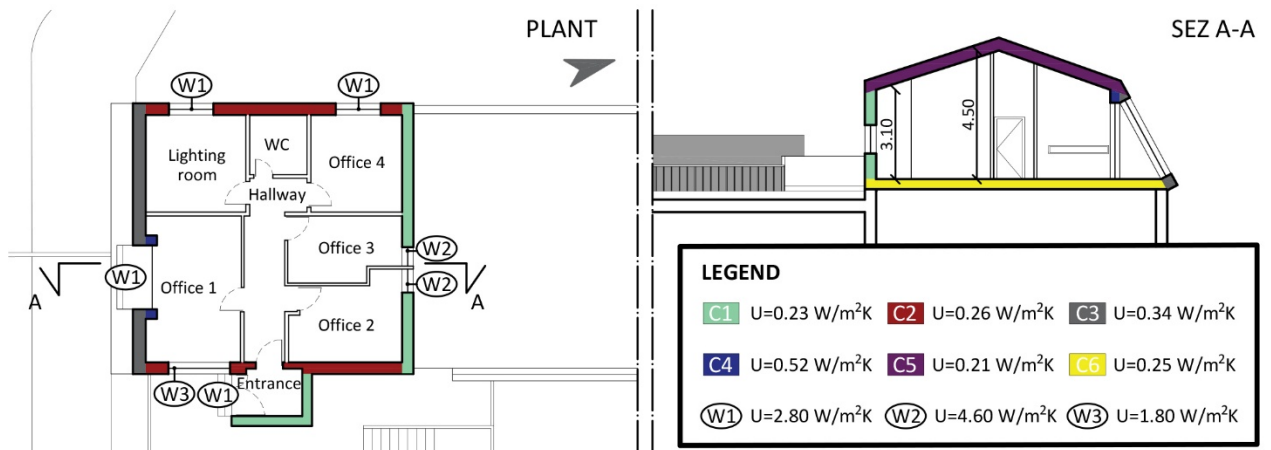


Figure 2. Main information on the plan under consideration.

Remark 1. The thermal transmittance of the W3, a glass block window, was determined based on the manufacturer's technical data sheet [4].

The building's heating system uses a condensing boiler with radiant panels and operates continuously during the heating season from October 15 to April 15 in L'Aquila [5], with technical details listed in Table 1.

Table 1. Technical characteristics of the boiler.

Fuel type	Natural gas
Nominal capacity	25 kW
Thermal efficiency	0.893 %

6.1.2 Energy model realization

The building's energy model was developed using two distinct approaches: BIM-to-BEM (A1) and a widely-used EnergyPlus dynamic energy modeling (A2).

A1: BIM-to-BEM approach

The BIM-to-BEM approach was evaluated using two interoperability strategies. A detailed BIM model of the Solar House was first created in Autodesk Revit [6] (Figure 3), accurately representing its geometry and thermal properties, and then used to test the two methods for transferring the model from BIM to BEM.

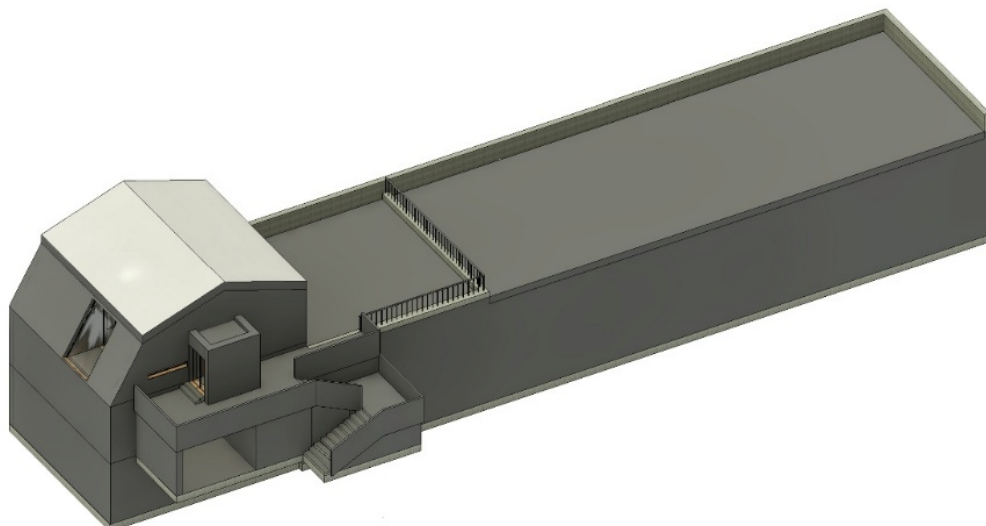


Figure 3. BIM-based model.

- Strategy 1 – Real-time connection

The "Real-time connection" strategy was tested by creating the energy model directly in BIM using Autodesk Insight 360, selected based on a literature review for its widespread use. Since the plug-in does not allow customization of weather data, the analysis utilized the data from the closest weather station available on Revit's localization service, which is located in Bazzano, about 5.7 km away from the building (Fig. 4).

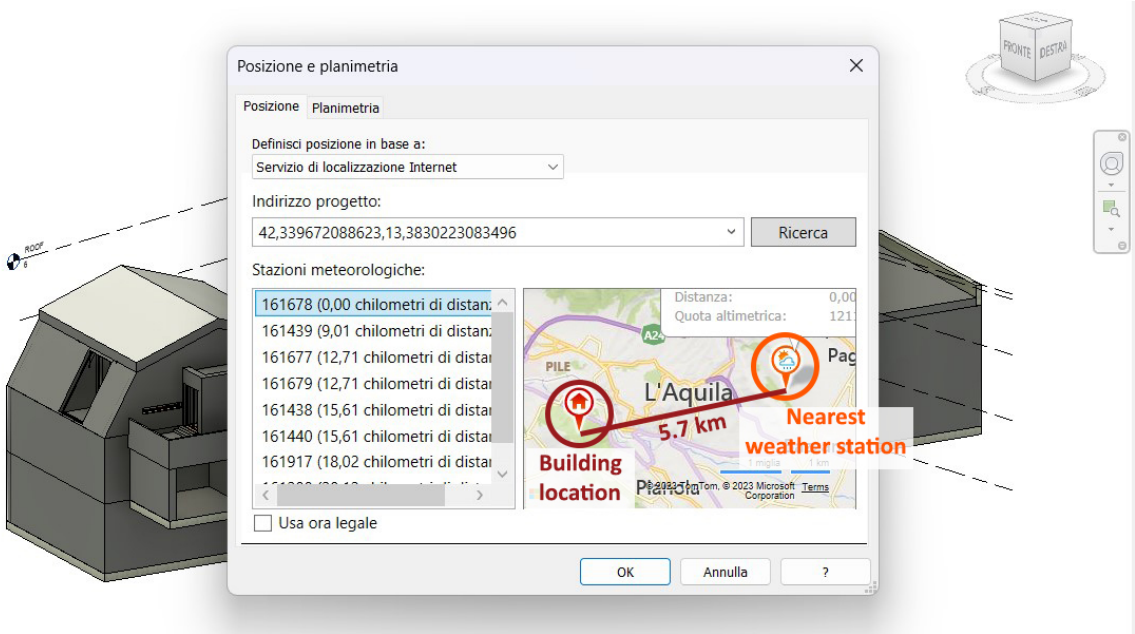


Figure 4. Geolocation of the building.

A major limitation of the real-time connection strategy was its lack of customization for advanced energy settings (Table 2), such as HVAC type and building schedules. Because the available options did not match the building's actual configuration, energy analysis could not be performed using this approach.

Table 2. Main energy settings.

Basic settings	Modes for creating the energy analytical model	Use Building Elements
	Indication of the ground floor (between the levels created in the model)	Level 0 (L0)
	Indication of the project phase	Existing
Advanced settings	Definition of the building envelope	Through Function Parameter
	Definition of the building system	Centralized warming: radiant floor
	Building type	Office
	Building use schedule	12 h/ 5 days Facility *
	HVAC System	Pipe Fan Coil System, Chiller 5.96 COP, Boilers 84.5 eff **
	Data export category	Spaces
	Material Thermal Properties	Detailed elements (the stratigraphies created manually by the user are taken into consideration for the analysis)***

* The chosen building use schedule is the one that comes closest to the real condition. In any case, the data set in the individual spaces are taken into consideration for energy analysis.

** None of the systems listed in the "HVAC System" section represents the building's actual configuration.

*** This setting was essential for the subsequent export of thermal properties to the BEM software.

- Strategy 2 – Standardized exchange formats

Using the S2, the Revit BIM model was exported to DesignBuilder 7.3.0.040 [7] (powered by EnergyPlus 9.4) via the gbXML format for energy analysis, with import options as specified in Table 3. A custom weather file was created from local Center of Excellence (CETEMPS) data [8], as no file for the building's location existed in the EnergyPlus library.

Table 3. Import options.

View	Axonometric
Import mode	1-Surface
Adjacency separation tolerance	0.010
External geometry uses centreline convention	✓
Create storey blocks	✓
Import thermal properties	✓
Allow open manifold building blocks	✓
Import as building blocks	✓
Merge adjacent surface openings	✓
Import shade surfaces	✓
Merge coplanar surfaces	✓

The initial import encountered two primary challenges: i) Geometric Errors: the imported model exhibited inaccuracies in its geometry; ii) Room Definitions Issues: the software incorrectly interpreted the Revit defined rooms, treating them as isolated blocks not communicating with each other, even if located on the same floor (Fig. 5).

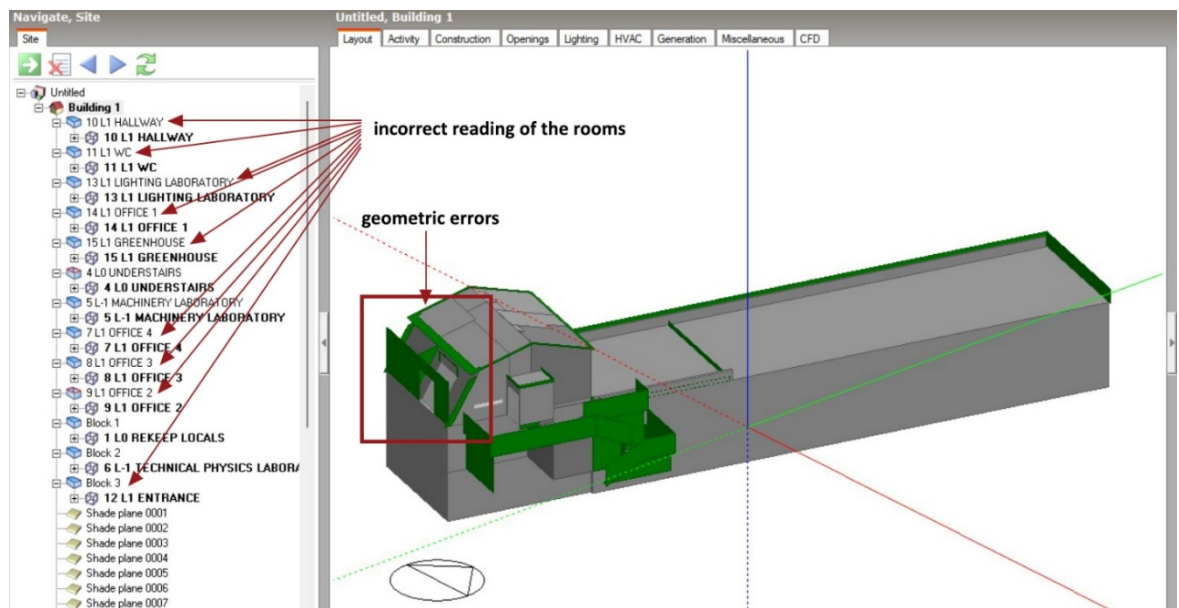


Figure 5. First attempt to import the model.

Literature shows that exporting BIM models often causes geometric errors and data loss. For the most part, simple geometries can be fixed by manual simplification [9- 11]. On the other hand, many researchers have experimented with the use of middleware tools able to optimize the export formats (IFC or gbXML) by implementing them with the missing information or correcting geometric inaccuracies [12- 15]. In our case, dealing with a simple geometry, manually simplifying the BIM model was effective, reducing potential BEM issues. Combining rooms on the same floor into a single zone prevented DesignBuilder from treating them as separate spaces. However, merging areas of different heights caused errors (Figure 6a), which could be avoided using the "Spaces" import mode (Table 3), though this might create gaps due to misread wall and floor thicknesses (Figure 6b).

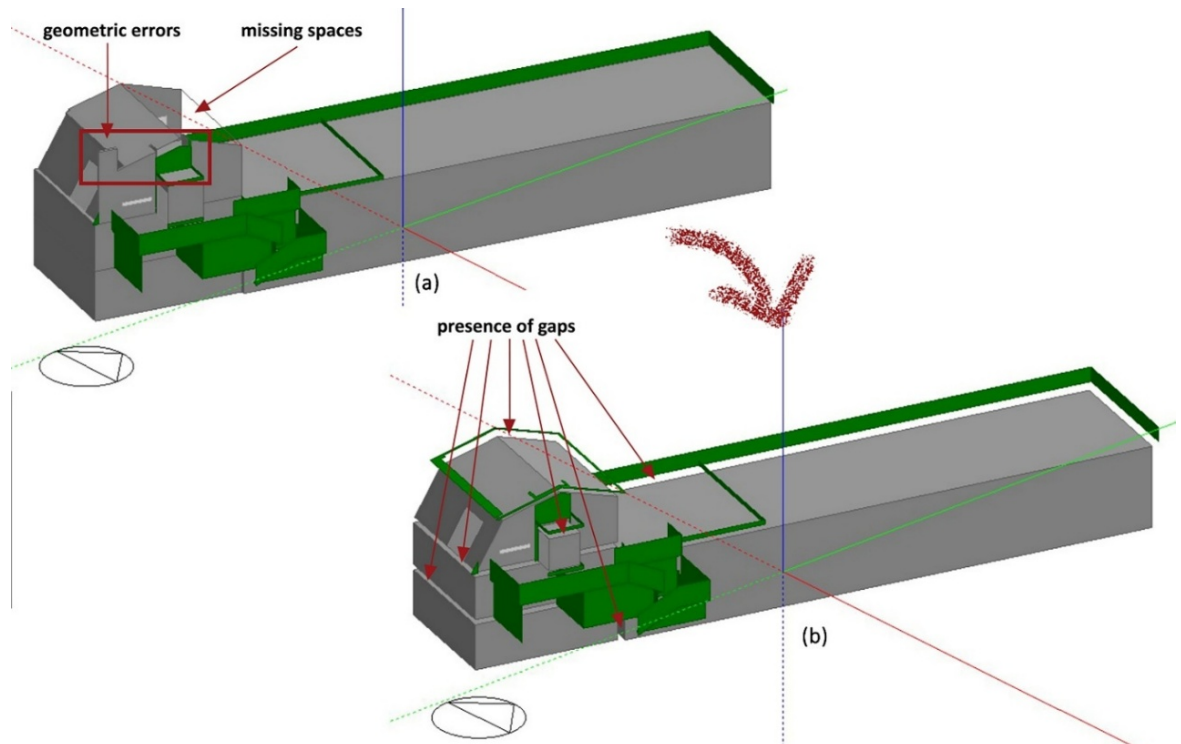


Figure 6. Second attempt to import the model. (a) Using “Surfaces” as import mode. (b) Using “Spaces” as import mode.

Consequently, the union of the entrance with the rest of the floor was carried out directly within DesignBuilder. Unlike the geometric features, the thermal properties of the envelope were successfully imported into the BEM, as requested in the Import Options (Table 3), so it was not necessary to intervene on the transmittance values. The main advantage of this strategy is its HVAC modeling: unlike Revit, DesignBuilder allows full customization of system templates and schedules, with EnergyPlus automatically sizing the system based on building design, weather, and thermostat settings.

A2: traditional BEM-based approach

Following the most common approach, the energy model was created within DesignBuilder from scratch. In the BIM-to-BEM approach, during the model import process in the BEM environment, the software automatically reduces the level of architectural detail based on the needs required by an energy study. In detail, all the building components that do not contribute to thermal performance are transformed by default into shading surfaces in DesignBuilder. Using the traditional approach, instead, every geometric simplification necessary to build the model on the BEM was conducted manually, according to completely personal criteria. The modeling was conducted on the basis of CAD files, imported in .dxf format into the software. The definition of the building’s characteristics was carried out following the modular approach proposed by DesignBuilder, through the compilation of the various modules present in the software (Activities, Construction, Openings, Lighting, HVAC, Generation, Economics, Miscellaneous and Computational Fluid Dynamics-CFD). Figure 7 shows the model created entirely in the BEM environment, using the modules it provides.

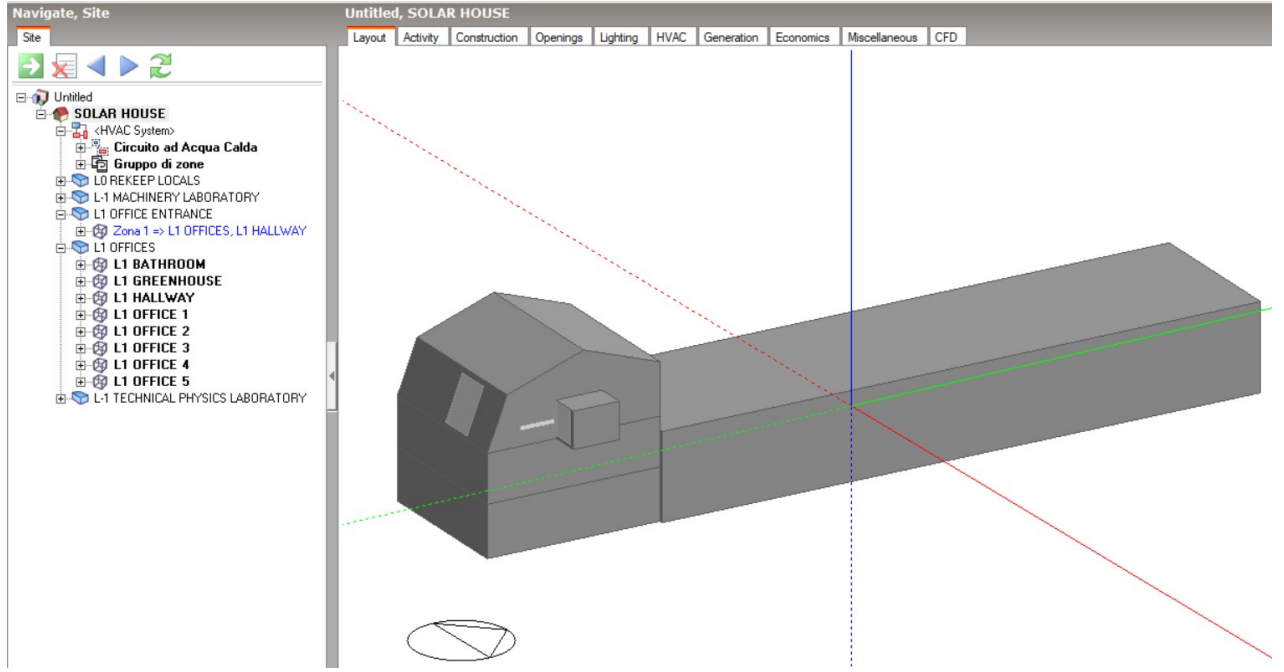


Figure 7. Energy model directly created in DesignBuilder.

6.1.3 Energy analysis

Once the energy modeling was finished, the simulations were conducted with EnergyPlus, with the aim of obtaining the annual thermal consumption of the building.

6.1.4 Models' calibration

To enhance the reliability of the energy analysis, the thermal models were calibrated based on real building consumption obtained from a monitoring lasting one month (March 15th to April 15th, 2023), a time interval that allowed us to collect a sufficient amount of data to conduct an accurate calibration in accordance with the ASHRAE M&V guidelines [16- 18]. Calibration data was acquired at the rate of one minute by means of a heat meter installed on the supply pipeline of the distribution network feeding the heating plant. The heat meter comprises two thermocouples for measuring flow and return fluid temperatures, a turbine flowmeter installed on the return pipe, and a display unit. The model used was the Conteca 755405, provided by Caleffi (Heat meter, 2025). The energy consumption for domestic hot water production was not considered in this study. The heat meter calculates thermal energy consumption ($\dot{Q}$) according to the following Eq. (1):

$$\dot{Q} = 0.2777698 \cdot 10^{-3} \cdot \rho \cdot \Delta V \cdot c_p \cdot \Delta T \quad (1)$$

Where $\dot{Q}$ is the thermal energy consumption [Wh], (ρ) is the water density [kg/m³], ΔV the water volume variation [m³] measured by the turbine flowmeter, c_p is the specific heat of water at constant pressure (4.186 kJ/(kgK)), ΔT is the temperature difference between flow and return water temperatures [K], and 0.2777698×10^{-3} is a dimensionless conversion factor.

The model calibration followed the ASHRAE M&V guidelines [16- 18], using the hourly calibration approach. Based on these guidelines, a simulated model is considered calibrated when the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error [CV(RMSE)], two statistical indices defined in Eqs. (2) and (3), are below the acceptable calibration thresholds, which are $\pm 10\%$ for MBE and 30% for CV(RMSE).

$$MBE (\%) = \frac{\sum_{Period} (S - M)_{Interval}}{\sum_{Period} M_{Interval}} \times 100 \quad (2)$$

$$CV(RMSE_{Period}) = \frac{RMSE_{Period}}{A_{Period}} \times 100 = \sqrt{\sum \frac{(S - M)_{Interval}^2}{N_{Interval}} \times \frac{1}{A_{Period}}} \times 100 \quad (3)$$

Where:

- M is the measured kilowatt-hours;
- S is the simulated kilowatt-hours;
- $N_{Interval}$ is the number of time intervals in the monitoring period;
- A_{Period} is the mean of the measured data for the period, calculated using Eq. (4).

$$A_{Period} = \frac{\sum_{Period} M_{Interval}}{N_{Interval}} \quad (4)$$

6.1.5 Results and discussion

The calibrated models showed good agreement with measured data. The BIM-to-BEM approach had an MBE of -10% and a CV(RMSE) of 19%, while the traditional method had an MBE of -4% and a CV(RMSE) of 20%. Figure 8 shows a comparison of simulated and measured values.

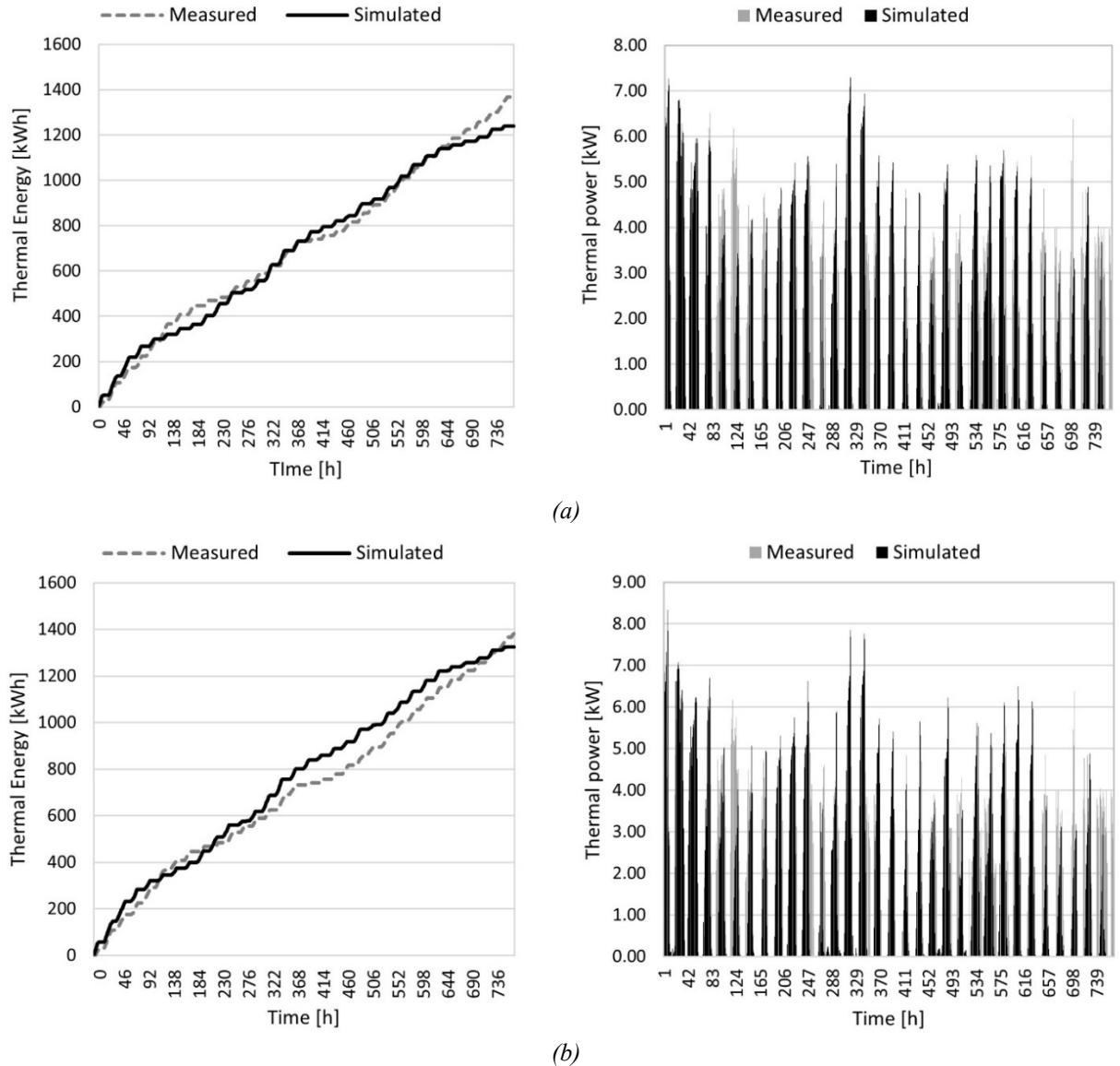


Figure 8. Comparison of simulated and measured results. (a) BIM-to-BEM approach. (b) BEM-based approach.

Remark 2. For thermal energy a cumulative value is given.

The energy analysis revealed a total annual thermal energy consumption of 14.7 MWh for the BIM-to-BEM model and 15.0 MWh for the BEM-based model, highlighting a difference of approximately 2%. This result proves that the two approaches have very similar performance, having been calibrated to the same data. Figure 9 shows the comparative thermal energy consumption results for both models. As evident from the figure, the consumptions are concentrated during the heating season (from October 15th to April 15th), with peak occurring in December and January, the coldest months in L'Aquila.

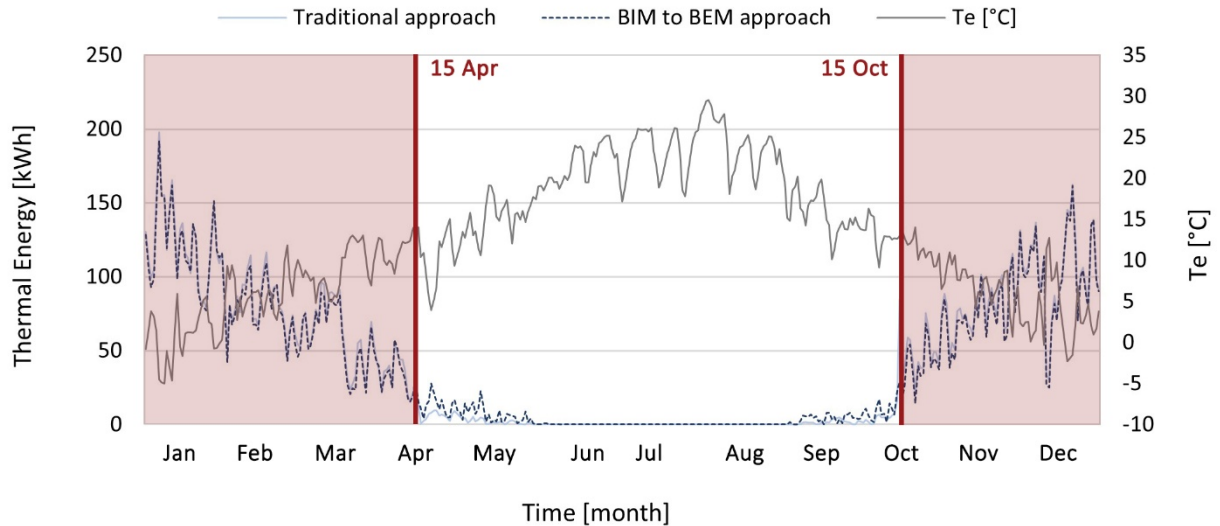


Figure 9. Comparison of the results obtained with the two approaches.

Table 4 summarizes the monthly consumption during the heating period for the models built using the two approaches, once calibrated, with the relative percentage differences.

Table 4. Comparison of monthly consumption obtained for each energy model after calibration.

Approach	Thermal energy [kWh]					Oct (15-31)	Nov	Dec
	Jan	Feb	Mar	Apr (1-15)	Outside heating period			
A1: BIM-to-BEM	3708	2162	1778	465	-	647	2225	3156
A2: Traditional BEM-based	3780	2254	1890	488	-	788	2368	3231
Percentage difference	2%	4%	6%	5%	-	18%	6%	2%

The results show that the S1 is unsuitable due to limited customization, making the building's actual HVAC system incompatible and preventing energy analysis. In contrast, the S2 enabled accurate and reliable energy analysis, though geometric issues arose during the BIM-to-BEM transfer. However, these issues were solved by applying some changes to the architectural model, dealing with a building with a rather simple geometry. We would expect that for more complex geometries, export errors could increase, undermining the effectiveness of the S1. Figure 10 compares the two tested strategies by evaluating a set of parameters useful for determining their efficiency.

PARAMETERS STRATEGIES	EFFICIENT AUTOMATIC DATA EXPORT (export data without errors)	REAL TIME CONNECTION OF BIM AND BEM MODELS	POSSIBILITY OF CUSTOMIZATION OF OPERATIONS	POTENTIAL APPLICABILITY TO A WIDE RANGE OF CASE STUDIES	POSSIBILITY TO CARRY OUT DETAILED ENERGY ANALYSES
REAL-TIME CONNECTION (S1)	✓	✓	✗	✗	N.A.
STANDARDIZED EXCHANGE FORMATS (S2)	✗	✗	✓	✓	✓

Figure 10. Comparison between the two interoperability strategies.

The BIM-to-BEM approach produces results comparable to the traditional BEM method, with only about a 2% difference in annual thermal energy consumption. In both cases, model calibration against real data demonstrated a high degree of accuracy, validating the effectiveness of both methodologies.

While advantages of BIM-to-BEM are less pronounced for simple buildings like the “Solar House,” they could become more significant for complex, large-scale projects. Table 5 summarizes the advantages and disadvantages of using the BIM-to-BEM approach compared to the traditional one.

Table 5. Pros and Cons of the BIM-to-BEM approach.

PROS	CONS
- creating a shared environment [19] where the different professionals involved in the project can communicate and exchange data more easily - improved integration between architectural and energy design [9, 20] - reduced modeling time [19, 21- 25]	- possibility of data loss or incorrect reading in the transition from BIM to BEM (more or less serious depending on the complexity of the model) [1, 9, 19, 20, 26, 27] - need for a partial knowledge of BIM software by the BEM user

The BIM-to-BEM methodology has great potential both in the case of energy retrofits of existing buildings and in the iterative process of a new project. In the first case, in fact, having a BIM model of an existing building complete with thermal information can represent an important wealth for carrying out energy analyses, especially in the absence of documentation relating to its current construction characteristics (for example, in the case of undocumented variations to the initial project). In the second case, however, being able to move a model from one software to another allows the architectural characteristics to be continuously updated based on variations in the energy ones and vice versa, in such a way as to optimize the coherence between the two aspects, improving collaboration between professionals and ensuring the delivery of an efficient building project.

6.1.6 Conclusions

An efficient interoperability between BIM and BEM could be the key to better integrate architectural and energy aspects, revolutionizing the design process according to current energy saving objectives. To date, the communication between the two software presents problems that, in several works analyzed in the literature, are identified but often not addressed in practice. Furthermore, there is a tendency to study the different approaches to energy modeling individually, without comparing them with each other. Finally, poor attention, if any, is given to the calibration of the results on the basis of real data, not allowing a verification of the reliability of the models created. Consequently, our work contributes to the topic by:

- proposing operational strategies capable of reducing the problems that occur in the transition from BIM to BEM;
- testing different interoperability strategies on the same case study to clearly highlight the potential and limitations of each one;

iii) comparing the BIM-to-BEM approach (A1) with the traditional BEM-based modeling (A2) to verify the actual advantage that could derive from the optimization of the data exchange process between the two software;

iv) performing a calibration of the results, emphasizing the importance of model validation in evaluating the different modeling methods tested.

In detail, two interoperability strategies, *Real-time connection* (S1) and *Standardized exchange formats* (S2), have been tested. Strategy S1 exhibited limitations due to a lack of customization flexibility. The inability to customize key parameters, such as the HVAC system in this case study, hindered its applicability for realistic energy analyses.

Otherwise, strategy S2 proved highly effective. It has proved to be a good interoperability strategy, ensuring reliable results. Furthermore, the study found that the energy model generated using S2 exhibited strong agreement with the model created using the common BEM-based approach (A2), with a difference of approximately 2% in annual thermal energy consumption, resulting in 14.7 MWh for the BIM-to-BEM model (A1) and 15.0 MWh for the BEM-based model (A2). However, the BIM-to-BEM approach (A1) has proven to have the potential to bring great advantages in the field of green construction, linked to the various benefits that its use involves, including:

- reduced modeling times;
- improved integration between architectural and energy design aspects;
- enhanced communication and collaboration among design professionals;
- optimization of the building retrofit process;
- optimization of the iterative building design process.

The main limit of this work is that BIM-BEM interoperability has been tested on a case study with simple geometry. Future research will investigate the applicability of these interoperability strategies to more complex building geometries, to further evaluate their effectiveness and potential.

6.2 BIM FOR PHOTOVOLTAIC (PV) SYSTEM DESIGN

BIM, allowing for highly accurate and realistic performance simulations [28], is increasingly being utilized for PV system design and integration in buildings [29], facilitating multi-scenario analyses involving solar studies [30] and panel performance assessments. However, although the applications of BIM in the energy sector are constantly growing, research in this area is still emerging and the absence of standardized design procedures [31] for PV integration within BIM workflows remains a critical barrier to widespread and consistent adoption. In this context, a BIM-based workflow for photovoltaic system design (see Figure 5, Chapter 3) is proposed and tested on two sample buildings with completely different architectural and climatic characteristics. In detail, the selected case studies are (i) B1: “Palazzo Silone”, in L’Aquila (IT), and (ii) B2: “Malaysian Institute of Architects”, in Kuala Lumpur (MY).

6.2.1 Workflow Equipment

The software used for the creation of the workflow are Autodesk Revit [6], the Photovoltaic Geographical Information System (PVGIS) [32], and Solarius-PV [33]. The main features of the above tools are reported below.

Autodesk Revit

Autodesk Revit [6] is an advanced BIM platform that integrates architectural, structural, and MEP design. In this study, it was used for 3D modeling of the building and its surroundings and for preliminary analysis of solar radiation on roof surfaces. Solar radiation assessment was performed using the Insight plug-in in Revit, which applies the Perez Solar Model [34] for calculations.

$$D_e [W/m^2] = D_h [W/m^2] \{ (1 - F_1) [1 + \cos(S)] / 2 + F_1 (a/b) + F_2 \sin(S) \} \quad (5)$$

where:

- D_c is the diffuse irradiance received by a tilted surface of slope S ,
- D_b is the horizontal diffuse irradiance,
- F_1 and F_2 are, respectively, the circumsolar and horizon “reduced” brightness coefficients,
- a and b are two terms describing the incidence-weighted solid angle sustained by the circumsolar region as seen by the tilted surface and the horizontal, respectively.

For more information on the calculation of the various parameters present in Equation (5), please refer to the work [34]. The data used by the solar analysis software comes from the weather stations set via the geolocation service offered by Revit, as will be specified in more detail in Section 6.2.3.

Photovoltaic Geographical Information System (PVGIS)

PVGIS (Joint Research Centre, Bruxelles, Belgium) [32] is an online platform by the European Commission for analyzing solar energy potential and PV system performance. It uses solar radiation data from two climate reanalysis databases:

- Surface Radiation Dataset—Heliosat—Edition 3 (SARAH3) [35],
- ECMWF Reanalysis v5 (ERA5) [36].

In this study, SARAH3 [35] was selected, providing satellite-based data derived from Meteosat satellite observations.

In the developed workflow, PVGIS is used to determine the optimal panel inclination (β) and orientation (θ), which maximize annual energy output based on satellite data [35, 36]. Detailed guidance is available in the PVGIS user manual [37].

Solarius-PV

Solarius-PV (ACCA software S.p.A., Avellino, Italy) [33] is capable of estimating the photovoltaic solar production of a plant starting from concrete solar irradiation data, taken from the main reference climatic databases:

- UNI 10349 [38] and ENEA for the whole Italian territory;
- PVGIS [32] for Europe, Africa, the Mediterranean Basin, and south-west Asia.

It calculates annual energy output based on incident solar radiation (site, orientation θ , and inclination β), shading, module characteristics (power, efficiency, temperature coefficient, mismatch losses), and balance of system (BOS) components, which account for additional losses such as reflection, shading, inverter, and AC circuit losses.

Specifically, the calculation of the total annual energy produced by the plant is calculated by the software following Equation (6).

$$E \text{ [kWh]} = G_i \text{ [kWh/m}^2\text{]} A_p \text{ [m}^2\text{]} \eta_p C_{sh} \text{ BOS} \quad (6)$$

where:

- E is the energy produced;
- G_i is the solar radiation on the module surface;
- A_p is the panel surface;
- η_p is the panel efficiency;
- C_{sh} is the shading coefficient;
- BOS is the balance of system, mentioned above.

6.2.2 PV System-Sizing Criteria

PV system sizing can follow two main approaches: (i) self-consumption-oriented, based on energy demand and historical/forecast load profiles [39], and (ii) grid feed-in-oriented, aimed at maximizing the use of available surface and solar potential. The choice depends on the building type: self-consumption is suited for private buildings with limited space and high energy use, while grid feed-in is ideal for public buildings with large surfaces and lower consumption. For the two public case-study buildings, the design strategy chosen was maximizing surface exploitation to evaluate their full photovoltaic potential.

6.2.3 Workflow Application

This section explains in detail the work phases presented in the flow diagram reported in Figure 5 of Chapter 3.

Phase 1 - Study of the building characteristics

The proposed workflow, presented in Section 3.2.3. of Chapter 3, was validated on two case studies with different characteristics to highlight how external and internal factors of a PV system influence its performance and consequently impact the design choices.

The buildings chosen for the analysis are (i) B1: “Palazzo Silone”, in L’Aquila (IT), and (ii) B2: “Malaysian Institute of Architects”, in Kuala Lumpur (MY).

- B1: “Palazzo Silone”, L’Aquila (IT)

Palazzo Silone is the seat of the regional council and presidency of the Abruzzo Region in Italy. It is located on the western outskirts of L’Aquila (Figure 11) and has no buildings in its immediate vicinity, so it can be said that it is located in a relatively isolated context.

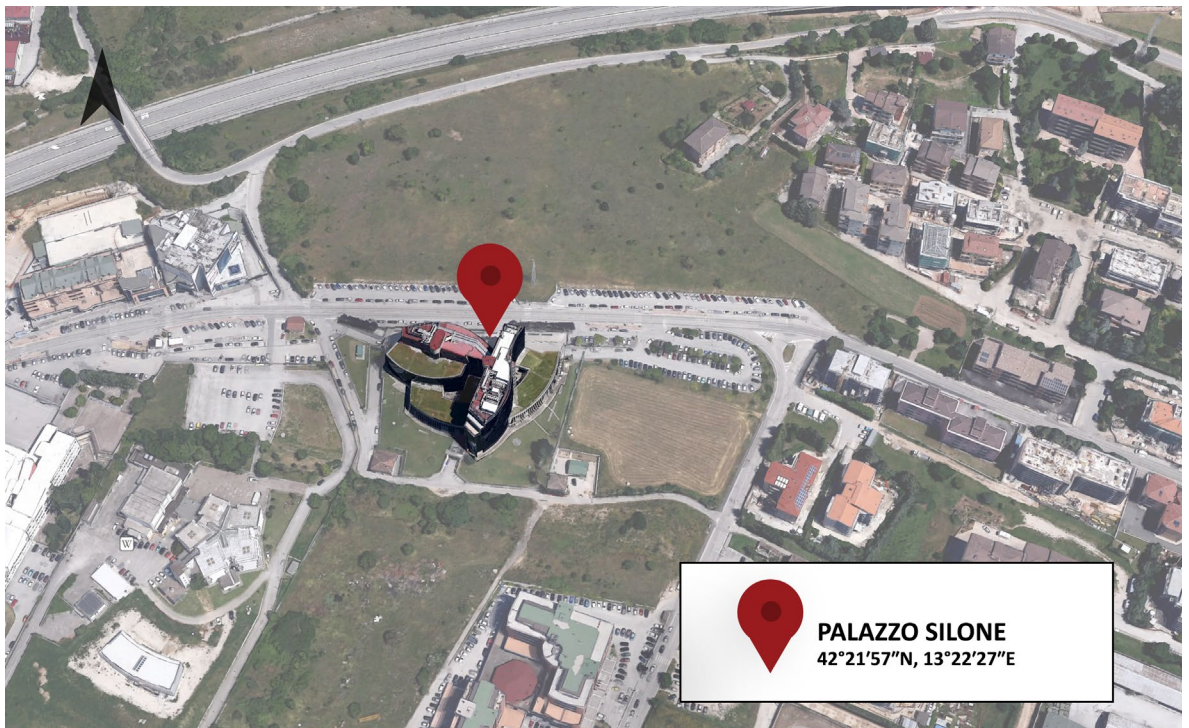


Figure 11. “Palazzo Silone” location (L’Aquila, Italy).

The ground floor of the building occupies approximately 2714 m². The structure is characterized by three volumes, two of which are parallel to Leonardo Da Vinci Street, at different heights, and one

orthogonal volume placed on the eastern side. The main facade, along which the entrance to the building is located, faces Leonardo Da Vinci Street and has a northeast orientation. The building (Figure 12) has eight levels for a maximum height of over 30 m, which makes it one of the tallest buildings in L'Aquila [40]. The different heights and shapes of the structure volumes make the roofing of the building extremely complex.



Figure 12. View of “Palazzo Silone”, south-west side.

The climate that characterizes the city of L'Aquila, where Palazzo Silone is located, is a temperate subcontinental climate, characterized by hot and relatively dry summers, with harsh and rainy winters [41]. For the location in question, the annual solar radiation on the horizontal plane is on average 1492.53 kWh/m² [38].

Remark 1. *The annual solar radiation may vary from case study to case study depending on several factors, including the presence of nearby physical obstacles, orientation and inclination of building surfaces, local albedo, altitude, and local microclimates.*

- B2: “Malaysian Institute of Architects”, Kuala Lumpur (MY)

The Pertubuhan Akitek Malaysia (PAM) Centre, headquarters of the Malaysian Institute of Architects, is a platinum green-rated building located in Kuala Lumpur (MY) (Figure 13) [42].

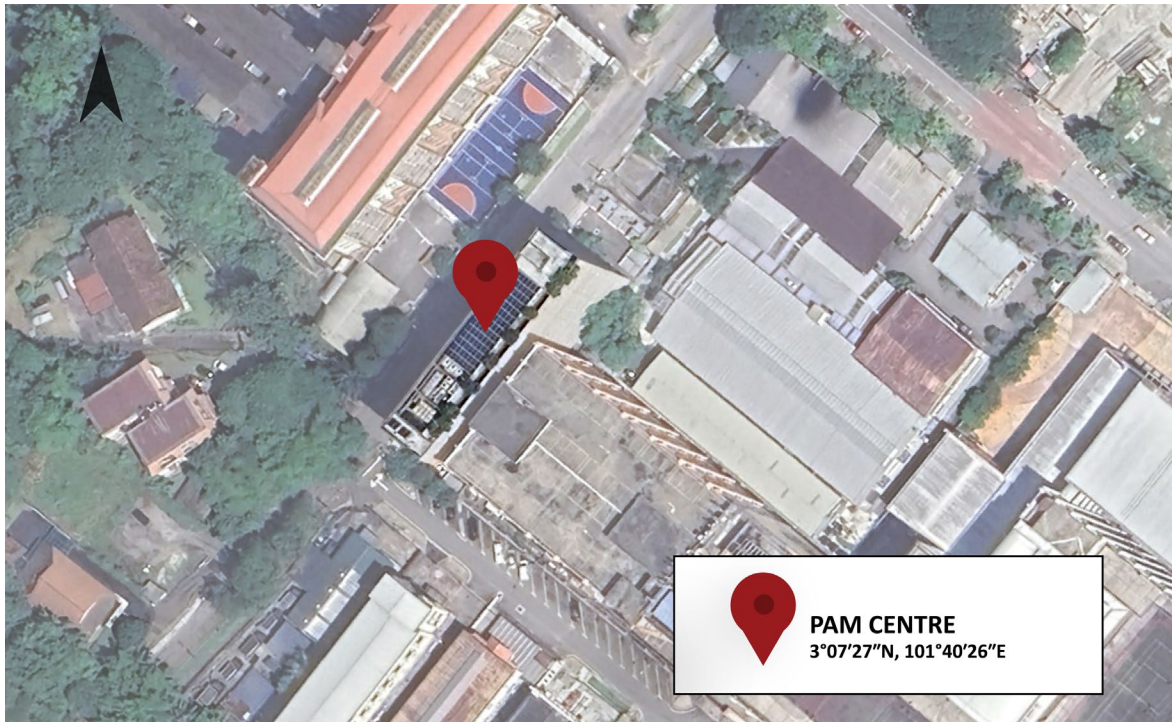


Figure 13. “PAM Centre” location (Kuala Lumpur, Malaysia).

The building, appearing as a single parallelepiped with an area of about 525 m² and a uniform height of about 31 m, is configured as a volume with an extremely simple geometry (Figure 14). The main facade, along which the entrance to the building is located, faces Jalan Kurau Street and has a north-west orientation [43]. At the back of the PAM Centre, 4 m away, there is a building of the same height, while at the front, 30 m away, there is a building of approximately 23 m. Although there is currently a photovoltaic system on the roof, it was not taken into consideration in the study.

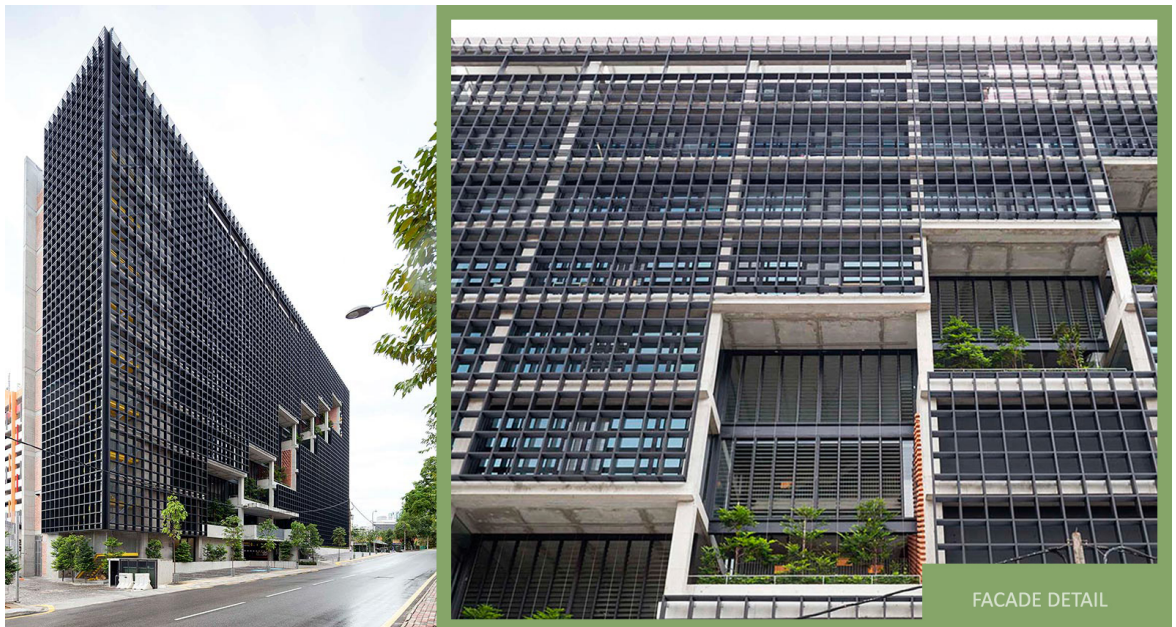


Figure 14. PAM Centre. Axonometric view and detail of the facade.

The climate that characterizes Kuala Lumpur is a tropical climate, characterized by high temperatures, constant presence of humidity, frequent rainfall, and monsoons [44]. For the city of Kuala Lumpur, the annual solar radiation on the horizontal plane is on average 1809.60 kWh/m² [32].

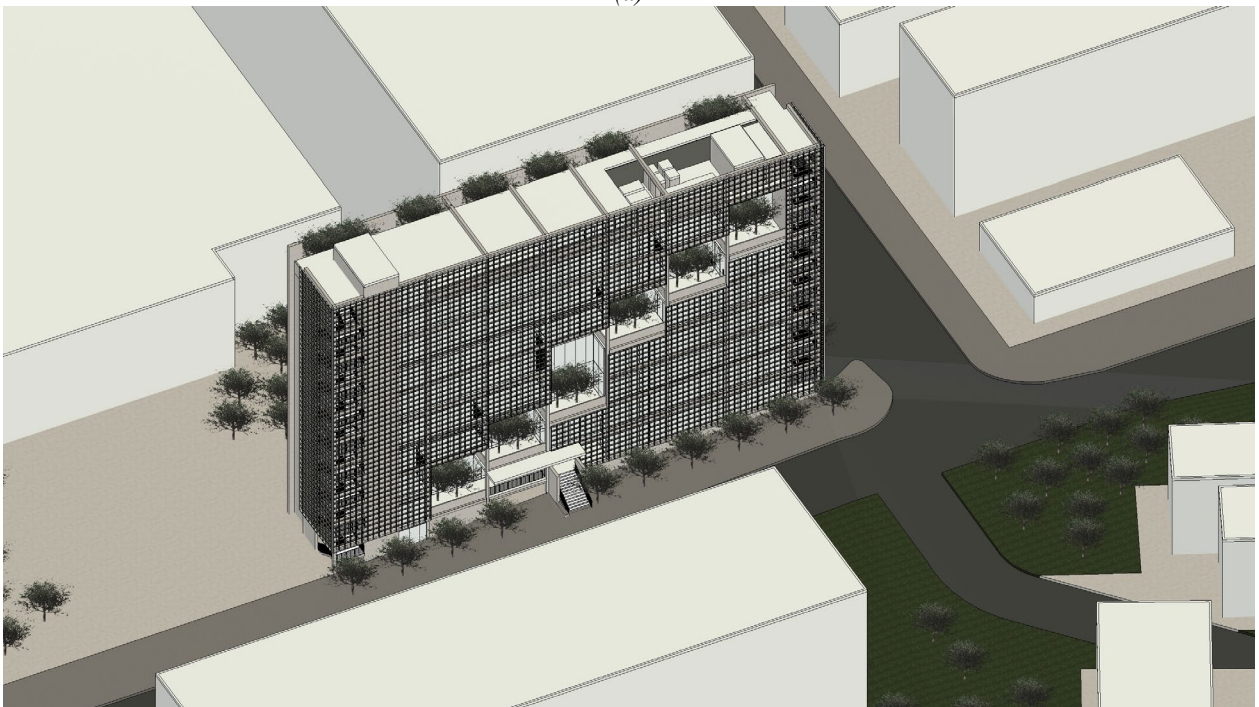
Remark 2. *The annual solar radiation may vary from case study to case study depending on several factors, including the presence of nearby physical obstacles, orientation and inclination of building surfaces, local albedo, altitude, and local microclimates.*

Phase 2 - BIM Modeling

BIM modeling of the two buildings (Figure 15) was performed using Autodesk Revit 2024. The two models were considered in detail, taking into account the context in which the buildings under examination are located, to have a complete vision of the totality of shading elements present that could compromise the performance of the system.



(a)



(b)

Figure 15. *BIM modeling of case studies. (a) B1. (b) B2.*

Through the geolocation service present in Revit, each building was associated with the local weather station closest to its geographical position. The distance as the crow flies of the meteorological stations from the case studies is about 6 km for B1 and about 3 km for B2.

Phase 3 - Solar Analyses

For the Italian building B1, areas A1, A2, and A3 (Figure 17b) were identified as the most suitable for PV installation, receiving up to 1246 kWh/m² per year of solar radiation (Figure 17a). The aforementioned surfaces, presenting a favorable orientation, are not compromised by particular shading deriving from the highest volumes of the building. Following this, it can be stated that the three roofs in question can be used in their entirety for the creation of a PV system, trying to avoid, as far as possible, the part of the area A2 directly adjacent to the highest glass volume, as it is characterized by a slightly lower incident solar radiation value (Figure 16b).

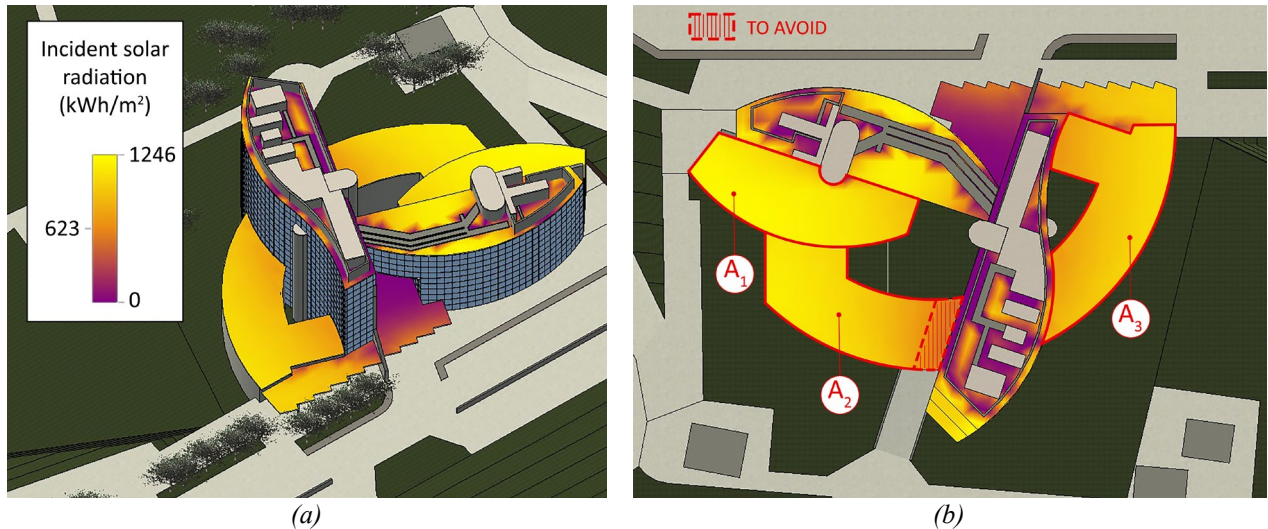


Figure 16. (a) Value of incident solar radiation for B1. (b) Selected areas for PV system installation.

As for the Malaysian building, B2, the analysis revealed an almost homogeneous photovoltaic potential on the roof, resulting in a maximum incident radiation value equal to 1673 kWh/m² per year (Figure 17a). Also in this case, the surface can be exploited in its entirety for the installation of modules, trying to avoid the areas directly adjacent to the extrados beams and the raised volume positioned on the north-east side of the roof (Figure 17b). The areas considered for the installation of the panels for building B2 are shown in Figure 18b.

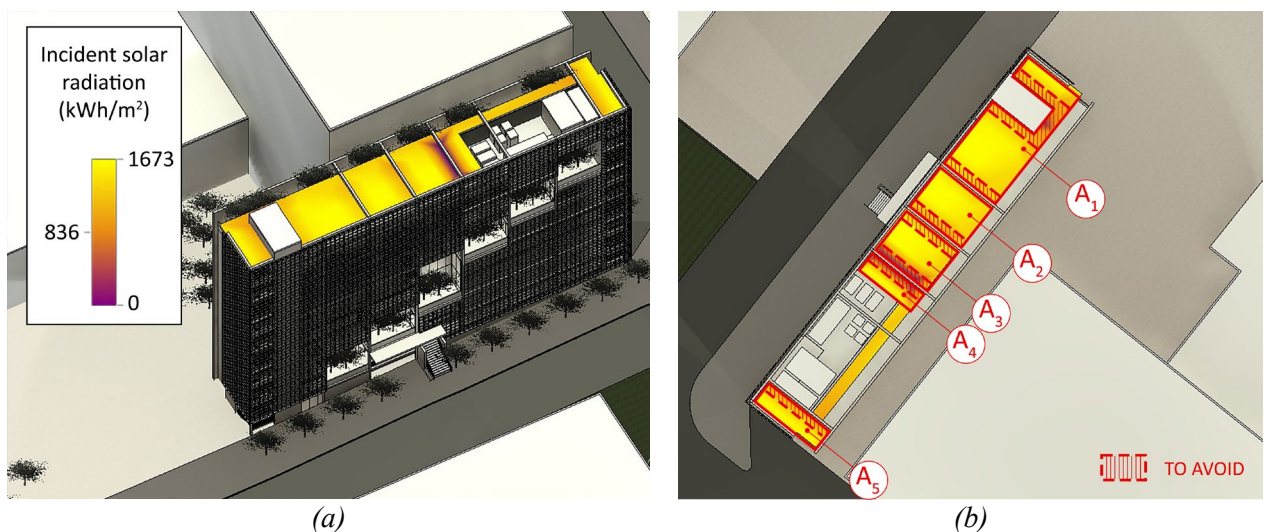


Figure 17. (a) Value of incident solar radiation for B2. (b) Selected areas for PV system installation.

Phase 4 - “Solution-Matrices” Creation

Once the photovoltaic potential of the building’s roofs had been studied and the most suitable location for installing the panels had been identified, an analysis of the system’s performance was conducted.

First of all, with the support of the PVGIS [32], the optimal orientation (θ) and inclination (β) of the PV modules were identified based on the location of the buildings under examination. For B1 θ and β , the optimal values were 0° and 36° , respectively, while for B2, they were 0° and 3° . For the analyses, β was set to 35° for building B1 and 5° for B2 to use standard inclinations.

Subsequently, different photovoltaic system design solutions (S_n) were conceived, each characterized by a different choice of quantity, PV technology, positioning, inclination, and orientation of the panels. The S_n were designed on the areas selected on the basis of previous solar analyses, taking into account the possibility of avoiding the parts characterized by slightly lower incident solar radiation, as mentioned in Section “Phase 4”. The quantity of panels chosen for each S_n respects the criterion of maximum filling of the selected areas, as far as possible, also taking into account the distances between modules foreseen in some S_n . The chosen θ s represent a compromise between optimal orientation of the modules and adaptation to the geometric shapes of the roofs, in order to allow greater filling of the surfaces. The β s were selected based on the criterion of maximum filling of the areas or based on the optimal inclination of the panels. Finally, the chosen PV technologies, selected among the emerging ones, are as follows: (T1) Half Cut Cells (HCC), (T2) Passivated Emitter and Rear Cell (PERC), (T3) Bifacial HCC. In all the S_n containing the T3, a minimum β of 10° was guaranteed to ensure efficient operation of the bifacial technology [45]. The PV panels of all S_n , regardless of the technology that characterizes them, have the same nominal power, i.e., 375 W_p, a value included in the medium range. The type of panels chosen for each technology and the main technical characteristics are reported in Table 6.

Table 6. Technical characteristics of the panels.

Technology	Panel Type	Nominal Power	Efficiency	Temperature	Operating Temperature Range	Temperature Coefficient of P_{max}
T1	FU375M Silk Pro	375 W _p	20.59%	45 °C	~40~85 °C	−0.35%/°C
T2	CSPL72-MonoPerc 375W	375 W _p	19.20%	45 ± 2 °C	~40~85 °C	−0.38%/°C
T3	BN72 Bifacial Modules 375W	375 W _p	19.05%	43.78 ± 2 °C	~40~85 °C	−0.38%/°C

For more information, the technical data sheets of the panels can be consulted on the official websites [46–48].

Each S_n conceived led to the creation of a “solution-matrix” capable of systematically expressing all the technical characteristics necessary to accurately designate the conformation of the system.

The matrices are composed of a series of elements $A_{i,j}$, where:

- A represents each analyzed parameter, i.e., N = number of panels, P = power of the panels (W), D = distance between panels (cm), Θ = azimuth of panels ($^\circ$), β = tilt of panels ($^\circ$), T = PV technology (1 = HCC, 2 = PERC, 3 = Bifacial HCC);
- i represents the value of the analyzed parameter;
- j indicates the area for installation of the panels, based on the solar analyses (3 for building B1, 5 for B2).

For example, “N_{10,1}” indicates that there are 10 panels in area 1.

The process followed for creating the matrices is shown in Figure 18.

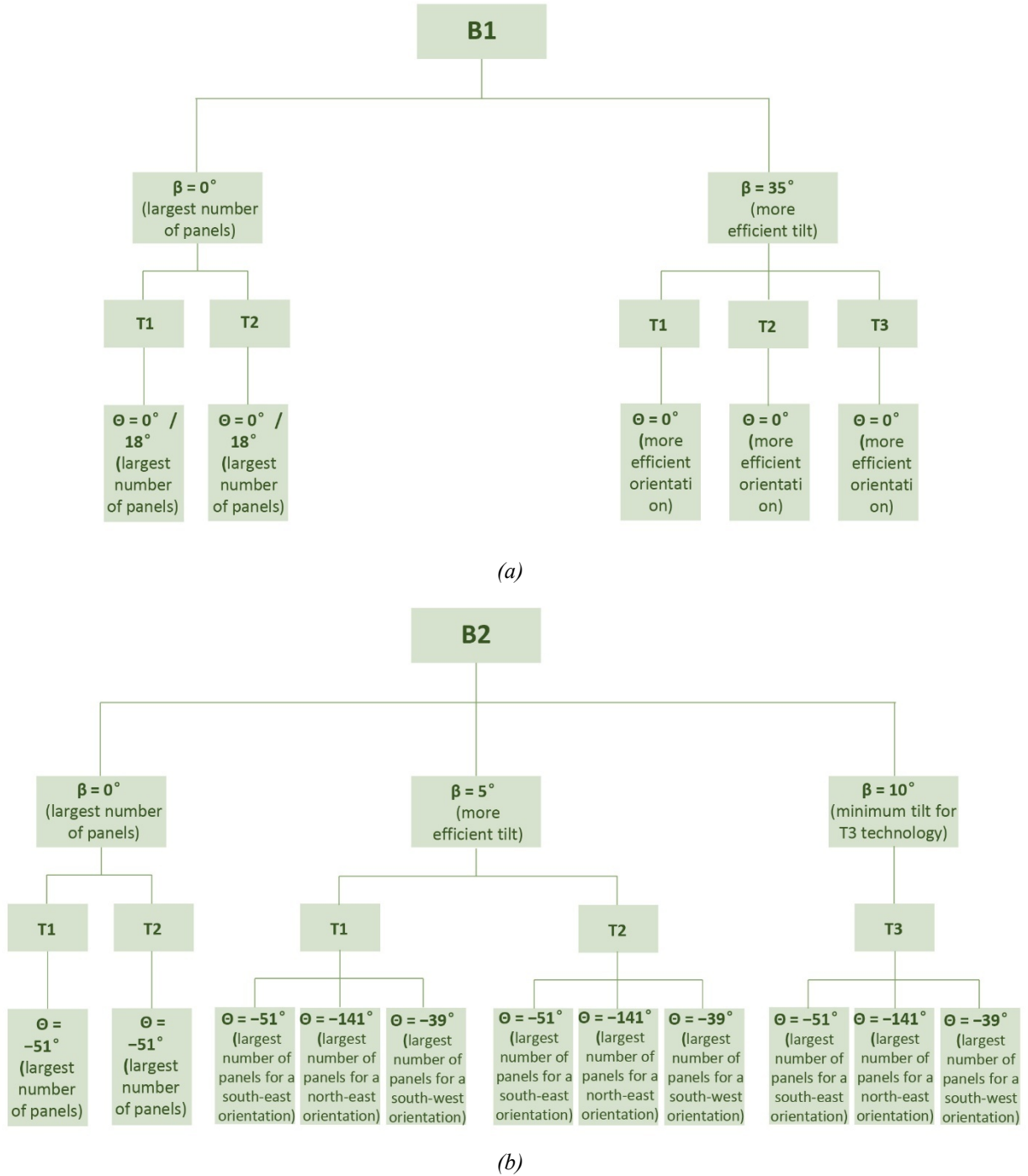
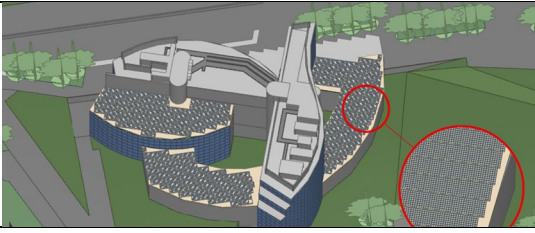
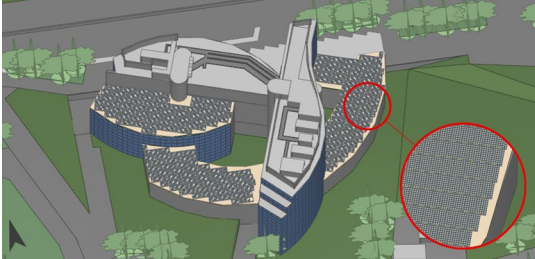
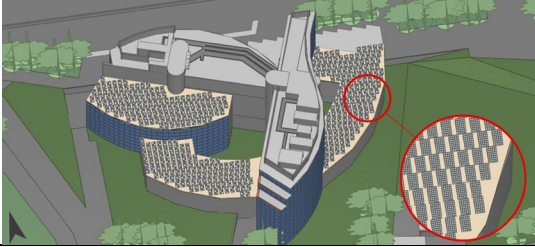
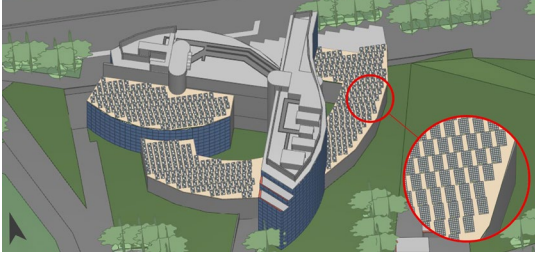
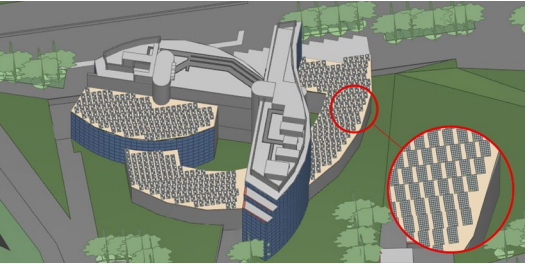
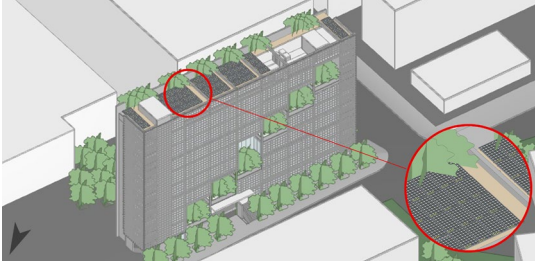


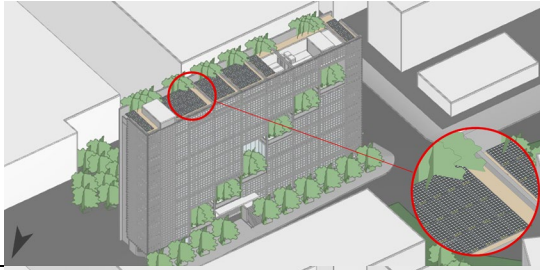
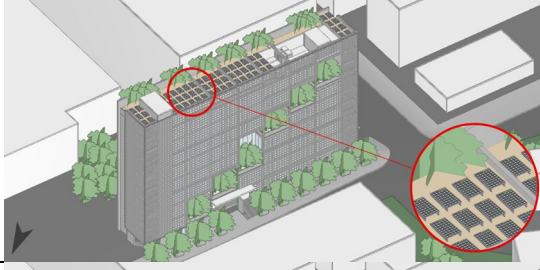
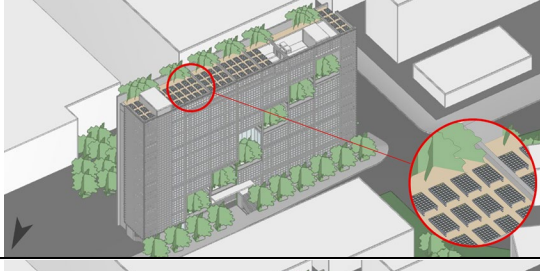
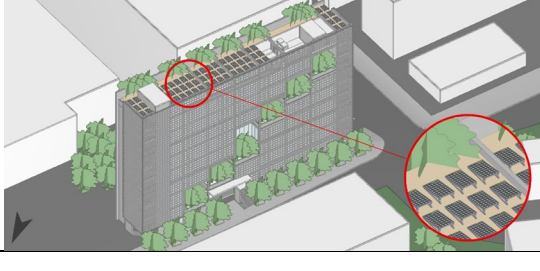
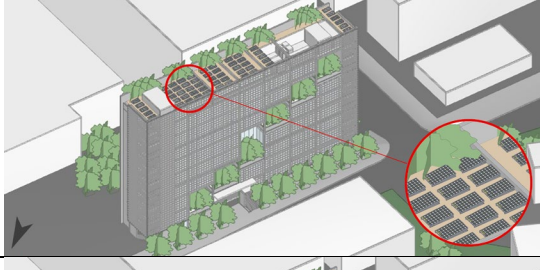
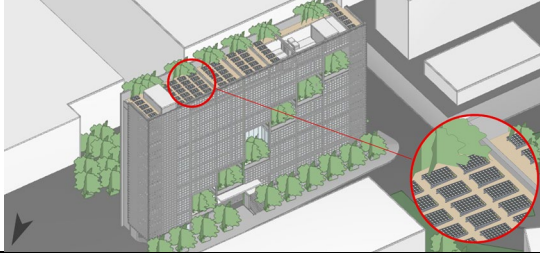
Figure 18. Matrix creation process. (a) Building B1. (b) Building B2.

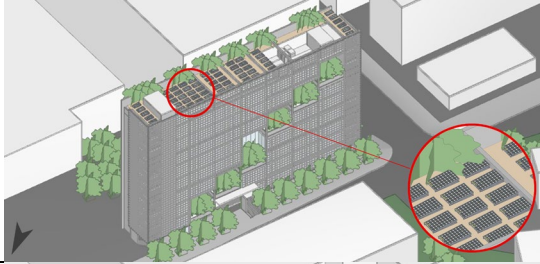
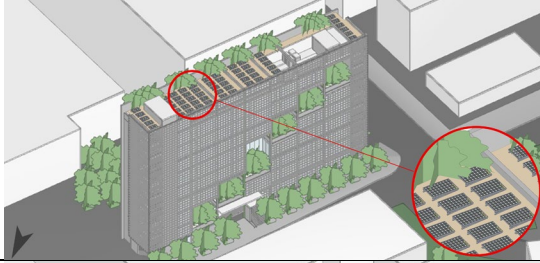
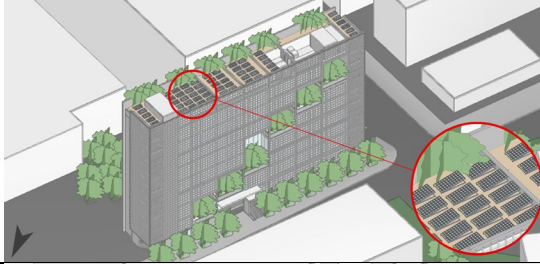
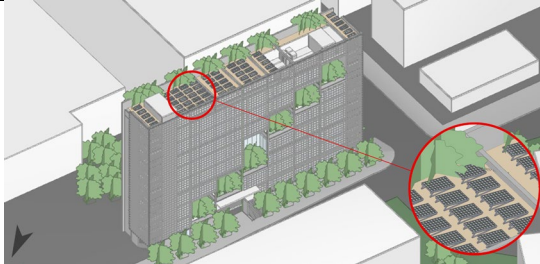
Remark 3. The parameters N , P , and D did not influence the number of matrices conceived since N and D are dependent on the other parameters and vary according to them, while the value of P is set regardless.

The totality of the “solution-matrices” designed, five for building B1 ($S_{1,B1}$, $S_{2,B1}$, $S_{3,B1}$, $S_{4,B1}$, $S_{5,B1}$), and eleven for B2 ($S_{1,B2}$, $S_{2,B2}$, $S_{3,B2}$, $S_{4,B2}$, $S_{5,B2}$, $S_{6,B2}$, $S_{7,B2}$, $S_{8,B2}$, $S_{9,B2}$, $S_{10,B2}$, $S_{11,B2}$), were modeled on ACCA’s BIM software, Solarius-PV, to simulate their energy production (Table 7).

Table 7. “Solution-matrices” and their modeling on Solarius-PV.

Solution		Matrix				
$S_{1,B1}$		$N_{220,1}$	$N_{192,2}$	$N_{245,3}$		
		$P_{375,1}$	$P_{375,2}$	$P_{375,3}$		
		$D_{0,1}$	$D_{0,2}$	$D_{0,3}$		
		$\Theta_{18,1}$	$\Theta_{0,2}$	$\Theta_{18,3}$		
		$\beta_{0,1}$	$\beta_{0,2}$	$\beta_{0,3}$		
		$T_{1,1}$	$T_{1,2}$	$T_{1,3}$		
$S_{2,B1}$		$N_{220,1}$	$N_{192,2}$	$N_{245,3}$		
		$P_{375,1}$	$P_{375,2}$	$P_{375,3}$		
		$D_{0,1}$	$D_{0,2}$	$D_{0,3}$		
		$\Theta_{18,1}$	$\Theta_{0,2}$	$\Theta_{18,3}$		
		$\beta_{0,1}$	$\beta_{0,2}$	$\beta_{0,3}$		
		$T_{2,1}$	$T_{2,2}$	$T_{2,3}$		
$S_{3,B1}$		$N_{131,1}$	$N_{120,2}$	$N_{151,3}$		
		$P_{375,1}$	$P_{375,2}$	$P_{375,3}$		
		$D_{50,1}$	$D_{50,2}$	$D_{50,3}$		
		$\Theta_{0,1}$	$\Theta_{0,2}$	$\Theta_{0,3}$		
		$\beta_{35,1}$	$\beta_{35,2}$	$\beta_{35,3}$		
		$T_{1,1}$	$T_{1,2}$	$T_{1,3}$		
$S_{4,B1}$		$N_{131,1}$	$N_{120,2}$	$N_{151,3}$		
		$P_{375,1}$	$P_{375,2}$	$P_{375,3}$		
		$D_{50,1}$	$D_{50,2}$	$D_{50,3}$		
		$\Theta_{0,1}$	$\Theta_{0,2}$	$\Theta_{0,3}$		
		$\beta_{35,1}$	$\beta_{35,2}$	$\beta_{35,3}$		
		$T_{2,1}$	$T_{2,2}$	$T_{2,3}$		
$S_{5,B1}$		$N_{131,1}$	$N_{120,2}$	$N_{151,3}$		
		$P_{375,1}$	$P_{375,2}$	$P_{375,3}$		
		$D_{50,1}$	$D_{50,2}$	$D_{50,3}$		
		$\Theta_{0,1}$	$\Theta_{0,2}$	$\Theta_{0,3}$		
		$\beta_{35,1}$	$\beta_{35,2}$	$\beta_{35,3}$		
		$T_{3,1}$	$T_{3,2}$	$T_{3,3}$		
$S_{1,B2}$		$N_{36,1}$	$N_{20,2}$	$N_{20,3}$	$N_{8,4}$	$N_{8,5}$
		$P_{375,1}$	$P_{375,2}$	$P_{375,3}$	$P_{375,4}$	$P_{375,5}$
		$D_{0,1}$	$D_{0,2}$	$D_{0,3}$	$D_{0,4}$	$D_{0,5}$
		$\Theta_{-51,1}$	$\Theta_{-51,2}$	$\Theta_{-51,3}$	$\Theta_{-51,4}$	$\Theta_{-51,5}$
		$\beta_{0,1}$	$\beta_{0,2}$	$\beta_{0,3}$	$\beta_{0,4}$	$\beta_{0,5}$
		$T_{1,1}$	$T_{1,2}$	$T_{1,3}$	$T_{1,4}$	$T_{1,5}$

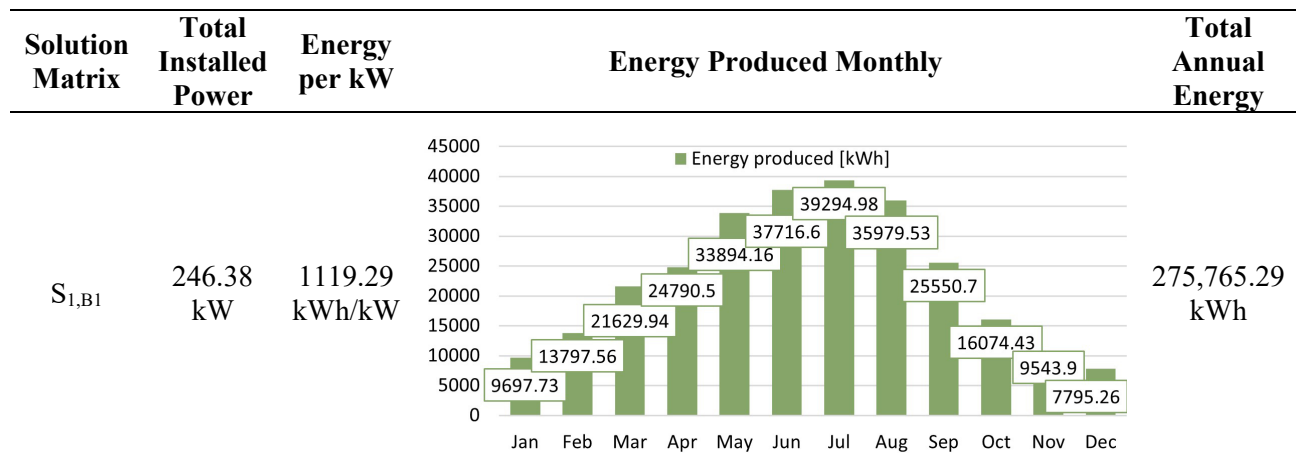
$S_{2,B2}$		$\begin{pmatrix} N_{36,1} & N_{20,2} & N_{20,3} & N_{8,4} & N_{8,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{0,1} & D_{0,2} & D_{0,3} & D_{0,4} & D_{0,5} \\ \Theta_{-51,1} & \Theta_{-51,2} & \Theta_{-51,3} & \Theta_{-51,4} & \Theta_{-51,5} \\ \beta_{0,1} & \beta_{0,2} & \beta_{0,3} & \beta_{0,4} & \beta_{0,5} \\ T_{2,1} & T_{2,2} & T_{2,3} & T_{2,4} & T_{2,5} \end{pmatrix}$
$S_{3,B2}$		$\begin{pmatrix} N_{24,1} & N_{12,2} & N_{12,3} & N_{6,4} & N_{8,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{-51,1} & \Theta_{-51,2} & \Theta_{-51,3} & \Theta_{-51,4} & \Theta_{-51,5} \\ \beta_{5,1} & \beta_{5,2} & \beta_{5,3} & \beta_{5,4} & \beta_{5,5} \\ T_{1,1} & T_{1,2} & T_{1,3} & T_{1,4} & T_{1,5} \end{pmatrix}$
$S_{4,B2}$		$\begin{pmatrix} N_{24,1} & N_{12,2} & N_{12,3} & N_{6,4} & N_{8,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{-51,1} & \Theta_{-51,2} & \Theta_{-51,3} & \Theta_{-51,4} & \Theta_{-51,5} \\ \beta_{5,1} & \beta_{5,2} & \beta_{5,3} & \beta_{5,4} & \beta_{5,5} \\ T_{2,1} & T_{2,2} & T_{2,3} & T_{2,4} & T_{2,5} \end{pmatrix}$
$S_{5,B2}$		$\begin{pmatrix} N_{24,1} & N_{12,2} & N_{12,3} & N_{6,4} & N_{8,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{-51,1} & \Theta_{-51,2} & \Theta_{-51,3} & \Theta_{-51,4} & \Theta_{-51,5} \\ \beta_{10,1} & \beta_{10,2} & \beta_{10,3} & \beta_{10,4} & \beta_{10,5} \\ T_{3,1} & T_{3,2} & T_{3,3} & T_{3,4} & T_{3,5} \end{pmatrix}$
$S_{6,B2}$		$\begin{pmatrix} N_{25,1} & N_{10,2} & N_{10,3} & N_{5,4} & N_{6,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{-141,1} & \Theta_{-141,2} & \Theta_{-141,3} & \Theta_{-141,4} & \Theta_{-141,5} \\ \beta_{5,1} & \beta_{5,2} & \beta_{5,3} & \beta_{5,4} & \beta_{5,5} \\ T_{1,1} & T_{1,2} & T_{1,3} & T_{1,4} & T_{1,5} \end{pmatrix}$
$S_{7,B2}$		$\begin{pmatrix} N_{25,1} & N_{10,2} & N_{10,3} & N_{5,4} & N_{6,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{39,1} & \Theta_{39,2} & \Theta_{39,3} & \Theta_{39,4} & \Theta_{39,5} \\ \beta_{5,1} & \beta_{5,2} & \beta_{5,3} & \beta_{5,4} & \beta_{5,5} \\ T_{1,1} & T_{1,2} & T_{1,3} & T_{1,4} & T_{1,5} \end{pmatrix}$

$S_{8,B2}$		$\begin{pmatrix} N_{25,1} & N_{10,2} & N_{10,3} & N_{5,4} & N_{6,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{-141,1} & \Theta_{-141,2} & \Theta_{-141,3} & \Theta_{-141,4} & \Theta_{-141,5} \\ \beta_{5,1} & \beta_{5,2} & \beta_{5,3} & \beta_{5,4} & \beta_{5,5} \\ T_{2,1} & T_{2,2} & T_{2,3} & T_{2,4} & T_{2,5} \end{pmatrix}$
$S_{9,B2}$		$\begin{pmatrix} N_{25,1} & N_{10,2} & N_{10,3} & N_{5,4} & N_{6,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{39,1} & \Theta_{39,2} & \Theta_{39,3} & \Theta_{39,4} & \Theta_{39,5} \\ \beta_{5,1} & \beta_{5,2} & \beta_{5,3} & \beta_{5,4} & \beta_{5,5} \\ T_{2,1} & T_{2,2} & T_{2,3} & T_{2,4} & T_{2,5} \end{pmatrix}$
$S_{10,B2}$		$\begin{pmatrix} N_{25,1} & N_{10,2} & N_{10,3} & N_{5,4} & N_{6,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{-141,1} & \Theta_{-141,2} & \Theta_{-141,3} & \Theta_{-141,4} & \Theta_{-141,5} \\ B_{10,1} & B_{10,2} & B_{10,3} & B_{10,4} & B_{10,5} \\ T_{3,1} & T_{3,2} & T_{3,3} & T_{3,4} & T_{3,5} \end{pmatrix}$
$S_{11,B2}$		$\begin{pmatrix} N_{25,1} & N_{10,2} & N_{10,3} & N_{5,4} & N_{6,5} \\ P_{375,1} & P_{375,2} & P_{375,3} & P_{375,4} & P_{375,5} \\ D_{50,1} & D_{50,2} & D_{50,3} & D_{50,4} & D_{50,5} \\ \Theta_{39,1} & \Theta_{39,2} & \Theta_{39,3} & \Theta_{39,4} & \Theta_{39,5} \\ B_{10,1} & B_{10,2} & B_{10,3} & B_{10,4} & B_{10,5} \\ T_{3,1} & T_{3,2} & T_{3,3} & T_{3,4} & T_{3,5} \end{pmatrix}$

Phase 5 - PV System Performance Analysis

Table 8 shows the data relating to the energy production of each “solution matrix” conceived, resulting from the annual simulation conducted on Solarius-PV.

Table 8. Energy simulation results.

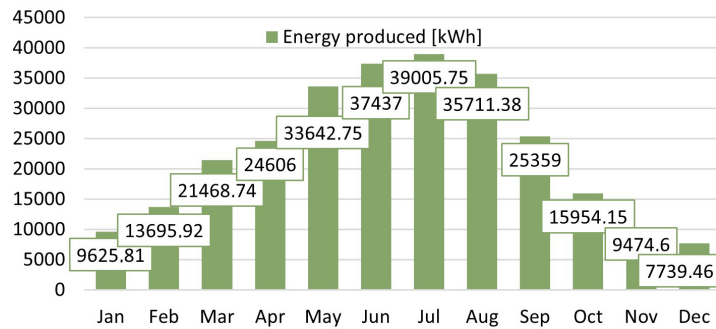


ENERGY EFFICIENCY IN BUILDINGS WITH A MULTISCALE APPROACH

S_{2,B1}

246.38
kW

1110.99
kWh/kW

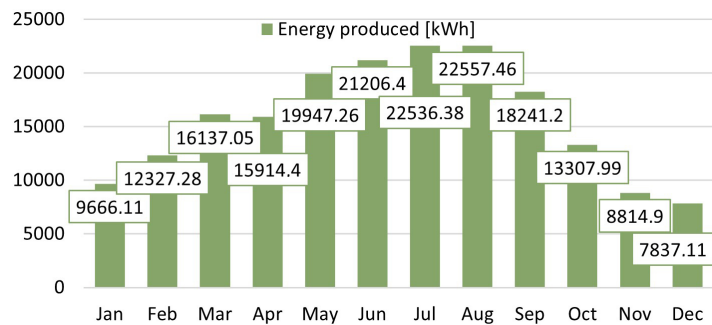


273,720.56
kWh

S_{3,B1}

150.75
kW

1250.37
kWh/kW

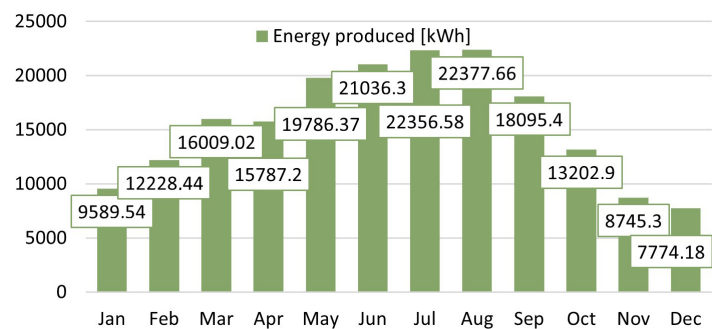


188,493.54
kWh

S_{4,B1}

150.75
kW

1240.39
kWh/kW

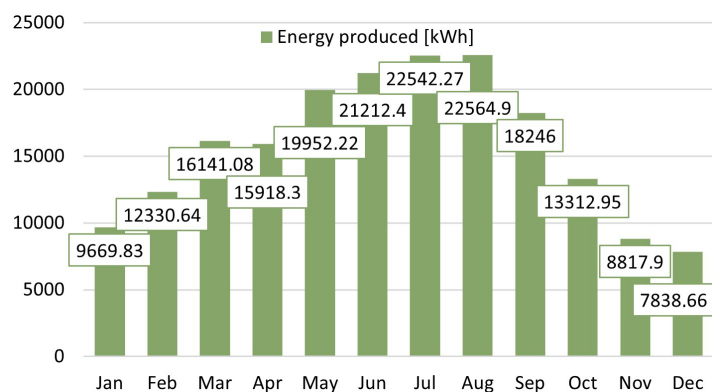


186,988.89
kWh

S_{5,B1}

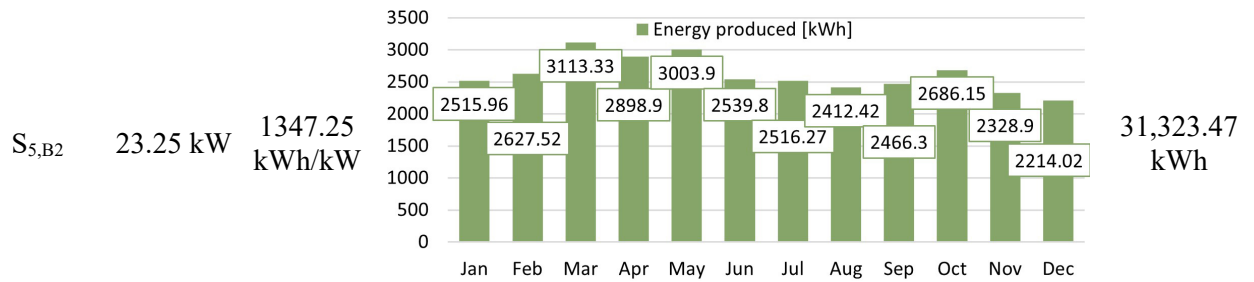
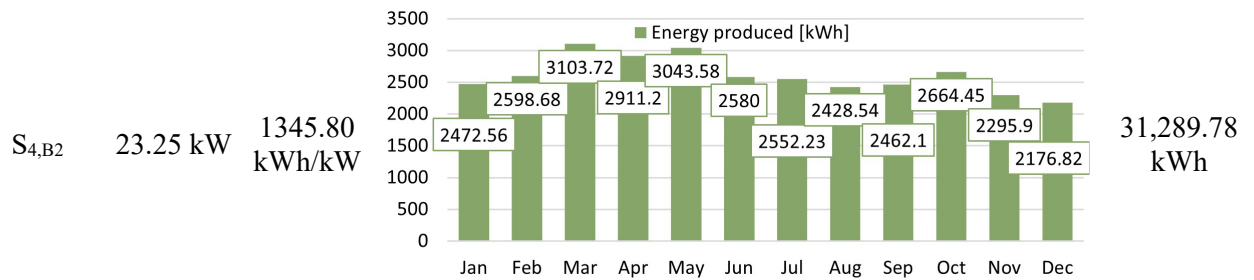
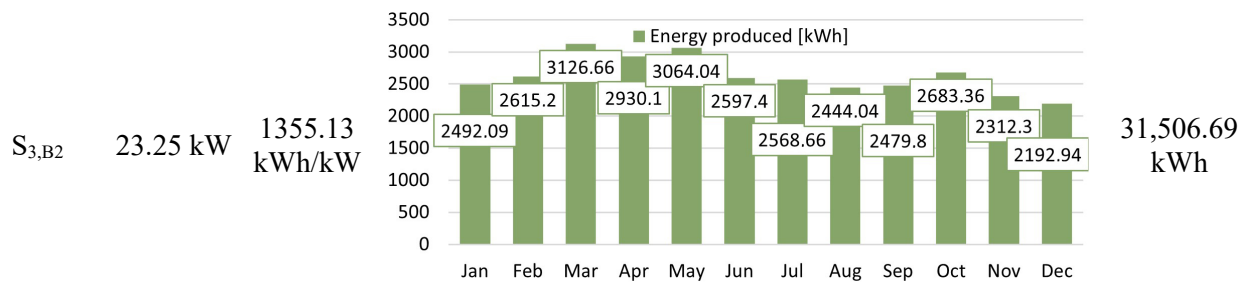
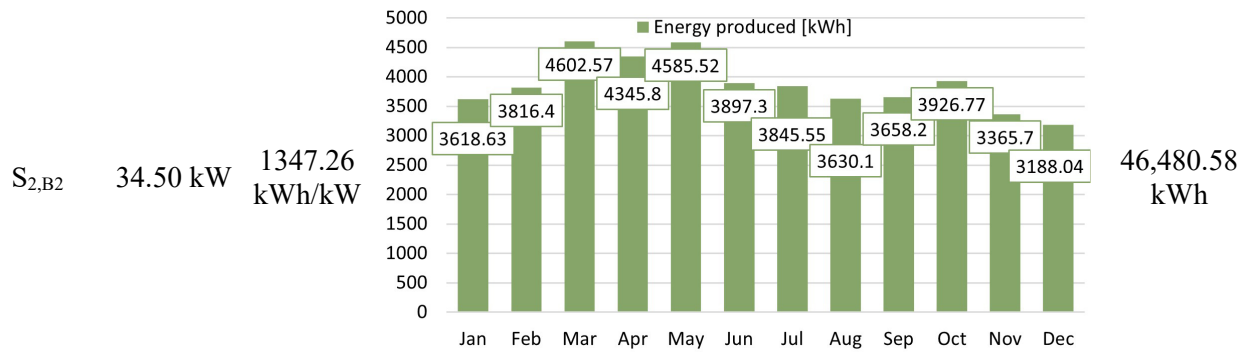
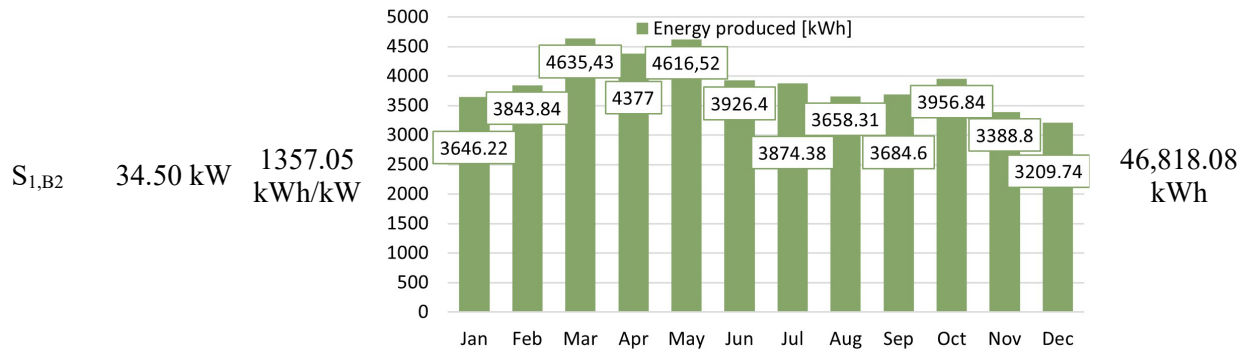
150.75
kW

1250.73
kWh/kW

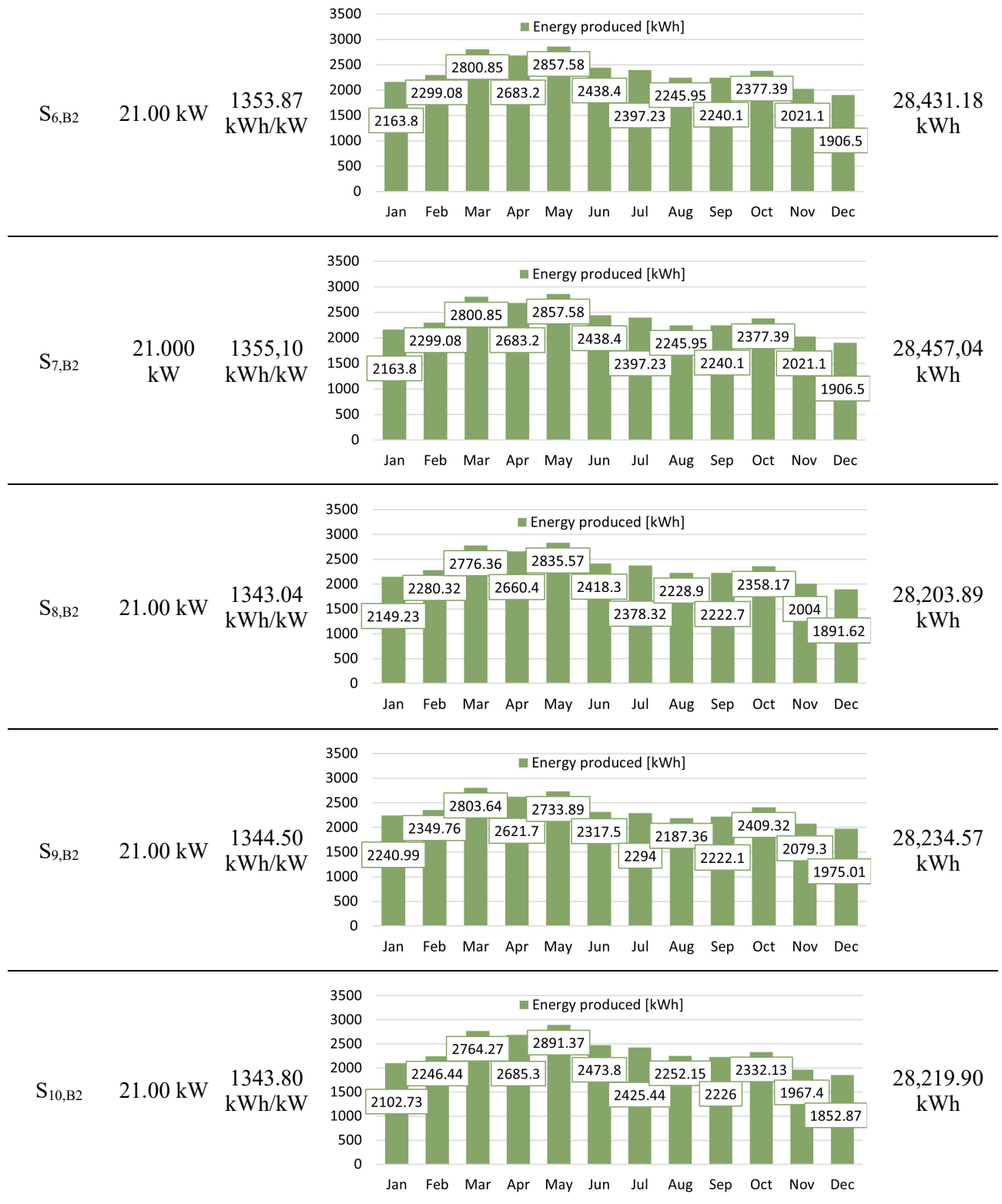


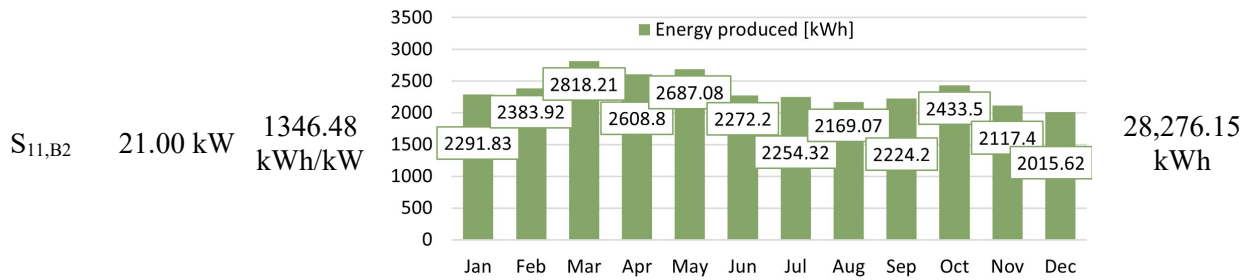
188,547.15
kWh

ENERGY EFFICIENCY IN BUILDINGS WITH A MULTISCALE APPROACH



ENERGY EFFICIENCY IN BUILDINGS WITH A MULTISCALE APPROACH





Phase 6 - Cost-Performance Analysis

From a literature analysis, the following costs for the technologies used emerged:

- 0.25 USD/Wp for HCC technology [49];
- 0.18 USD/Wp for PERC technology [50];
- 0.28 USD/Wp for Bifacial HCC technology [51].

Based on the data found, an embryonic cost-performance analysis of the various simulated solution matrices was performed following Equation (7).

$$\text{Cost per kWh of energy produced [USD/kWh]} = \frac{\text{Cost per kW [USD/kW]}}{\text{Energy produced per kW [kWh/kW]}} \quad (7)$$

The results of the analysis, useful for a preliminary design phase, are reported in Table 9.

Table 9. Cost-performance analysis of design strategies.

Solution Matrix	Energy Produced per kW [kWh/kW]	Cost per kW [USD/kW]	Cost per kWh of Energy Produced [USD/kWh]
S _{1,B1}	1119.29 kWh/kW	250 USD/kW	0.22 USD/kWh
S _{2,B1}	1110.99 kWh/kW	180 USD/kW	0.16 USD/kWh
S _{3,B1}	1250.37 kWh/kW	250 USD/kW	0.20 USD/kWh
S _{4,B1}	1240.39 kWh/kW	180 USD/kW	0.15 USD/kWh
S _{5,B1}	1250.73 kWh/kW	280 USD/kW	0.22 USD/kWh
S _{1,B2}	1357.05 kWh/kW	250 USD/kW	0.18 USD/kWh
S _{2,B2}	1347.26 kWh/kW	180 USD/kW	0.13 USD/kWh
S _{3,B2}	1355.13 kWh/kW	250 USD/kW	0.18 USD/kWh
S _{4,B2}	1345.80 kWh/kW	180 USD/kW	0.13 USD/kWh
S _{5,B2}	1347.25 kWh/kW	280 USD/kW	0.21 USD/kWh
S _{6,B2}	1353.87 kWh/kW	250 USD/kW	0.18 USD/kWh
S _{7,B2}	1355.10 kWh/kW	250 USD/kW	0.18 USD/kWh
S _{8,B2}	1343.04 kWh/kW	180 USD/kW	0.13 USD/kWh
S _{9,B2}	1344.50 kWh/kW	180 USD/kW	0.13 USD/kWh
S _{10,B2}	1343.80 kWh/kW	280 USD/kW	0.21 USD/kWh
S _{11,B2}	1346.48 kWh/kW	280 USD/kW	0.21 USD/kWh

6.2.4 Final Remarks

Based on Table 4, it is observed that the highest energy yield per kilowatt was achieved in Malaysia, specifically in configuration S_{1,B2}, at 1357.05 kWh/kW. This is followed by S_{3,B2} at 1355.13 kWh/kW using 375W HCC solar panels. The lowest performance was observed in S_{2,B1} at 1110.99 kWh/kW by using 375W PERC solar panels. This indicates Malaysia's geographical advantage in solar irradiance in comparison with Italy. In terms of energy yield, the highest annual energy output can be

achieved by $S_{1,B1}$, with 275,765.29 kWh using a total of 657 PV modules. It is worth noting that $S_{1,B2}$ generated a total of 46,818.08 kWh with only 92 PV modules. This indicates that the total module counts and installed capacity have a direct impact on energy production. Solution $S_{1,B1}$ demonstrated a higher annual energy yield than the others, both for the PV technology used (HCC) and for the fact that it allowed maximum coverage. However, it emerged that, with the same number of installed modules, an increase in yield of up to 10% can be achieved by optimizing the inclination of the panels, consequently bringing economic benefits. The simulations of case study B2 demonstrated that tilting the panels is not convenient because, with almost equal energy yield per kW, the solution with the modules coplanar to the roof allows the insertion of a greater number of panels, as it does not require distance between the panels for shading. For the Malaysian building, where it was not possible to orient the system completely to the south due to a non-optimal predisposition of the building, the most performing orientation among those simulated was south-west ($\Theta = -51^\circ$). From an economic point of view, PERC technology was found to be the most cost-effective for both case studies (Table 9). HCC modules presented a good balance between cost and energy output. On the contrary, Bifacial HCC modules have proven to be excessively expensive in relation to the energy benefits offered.

The study showed the effectiveness of the developed workflow. The latter, in fact, has enabled detailed analysis of the multitude of factors that influence the design of a PV system, following well-defined and logically linked steps, starting from a centralized BIM model. BIM, allowing highly accurate and realistic performance simulations, has facilitated multi-scenario analyses involving solar studies and panel performance assessments, ensuring design coherence and interdisciplinary coordination. The adoption of BIM represents a strategic tool to overcome regulatory obstacles in the integration of BIPV systems. At the international level, several governments actively promote its use through dedicated regulations, in some cases making it mandatory in public projects and incentivizing it in the private sector [52- 56]. Furthermore, the adoption of photovoltaic systems in public buildings is a topic of growing relevance in energy and environmental policies at the international level [52, 53, 57- 59]. In this context, having a unified and standardized protocol for BIM-based PV design could contribute to the current decarbonization and sustainability goals, keeping pace with the regulations in force in the field.

Currently, the main limitation of the proposed workflow lies in the balance between standardization and flexibility. The methodology has been designed to be highly structured and to help ensure quality and compliance in the design; at the same time, however, it must be sufficiently adaptable and updatable to respond to different design needs, continuous developments in the sector and the skills of various professionals. For this reason, a possible future development could be to validate the workflow by exploiting other BIM tools and different case studies, characterized by design needs distant from those pursued in this contribution.

6.2.5 Conclusions

To date, there are several software tools available for designing PV systems, each offering specific and distinct functionalities. However, these tools often lack proper integration, resulting in fragmented and disconnected workflows that hinder the development of a fully coherent and implementable project. The integration of the BIM methodology in the design of photovoltaic systems represents a significant advancement towards more efficient, coordinated, and sustainable management of the design process. The BIM approach allows for three-dimensional information modeling capable of integrating, in a shared environment, geometric, energy, economic, and temporal aspects of the system. The possibility of carrying out preliminary analyses on incident solar radiation, shading, and system performance guarantees greater accuracy and a substantial reduction in time to perform the calculations. BIM, therefore, unlike the current solutions offered by the market, allows

design to be carried out in a coherent, integrated, collaborative, and dynamic way. The workflow we propose, starting from a centralized BIM model, allows a smooth transition between BIM software without loss of information, ensuring design consistency and reducing the risk of errors. The workflow, conceived with the aim of developing a standardized and replicable procedure, is able to guide the professional in all project phases, starting from the most embryonic to the most detailed. The methodology has been tested on two case studies (B1 and B2) characterized by different architectural features and geographical locations. Thanks to BIM, it has been possible to evaluate various design strategies in a short time, taking into account a multiplicity of aspects that can hardly be accurately analyzed with manual design practice. The analyses conducted on the two case studies have shown how parameters such as orientation, inclination, photovoltaic technology, climate, etc., can have a great influence on the performance of the system.

In light of this, BIM has proven to be a fundamental tool for making strategic design choices, capable of optimizing the system and ensuring a good balance between energy production and costs. In a context where regulations on energy saving and reducing environmental impact are increasingly stringent, BIM could be a tool offering great support for the ecological transition.

A future development of the research could be to work on the flexibility of the workflow, testing it on other case studies, and foreseeing the use of BIM tools that are different from those employed in this contribution.

6.3 BIM-BASED DIGITAL TWIN FOR MONITORING AND OPTIMIZATION

Building Information Modeling (BIM)-based digital twin (DT) could play a fundamental role in overcoming the limitations of traditional monitoring methods by driving the digitalization of the construction sector. While existing studies on the topic have provided valuable insights, significant knowledge gaps remain, which continue to hinder the large-scale adoption of this approach. Moreover, to date, there is no standardized procedure available, able to guide the step-by-step creation of a DT. Another significant challenge concerns the choice of technologies able to integrate perfectly with each other throughout the process.

For these reasons, a workflow for creating a technical design for an existing building is proposed, while simultaneously experimenting with the "Living Lab" concept in an office building also used as an academic laboratory.

6.3.1 Workflow Equipment

Wireless Sensors Nodes (WSN)

In developing a DT, the foundation of the system is the data acquisition component, consisting of the nodes equipped with sensing elements. The sensor nodes have the possibility of being connected to computer networks and cloud infrastructures for analysis. Nowadays, the Internet of Things (IoT) paradigm represents the main methodology of connectivity structure for such devices [60]. Integrating IoT with BIM has demonstrated the potential to improve building management and operational efficiency. The IoT sensors offer real-time data on various environmental conditions, and when combined with BIM models, they enable more dynamic and responsive building management [61, 62]. Different technologies can be used for data exchange, and those are evaluated with respect to the particular implementation under consideration. Indoor applications that rely on sensor networks can be developed using technologies with short-range coverage, including Wi-Fi, Bluetooth, nearfield communication (NFC), and Zigbee [63, 64]. Other types of DT implementations can require a larger network coverage, so different technologies such as Low Power Wide Area Networks (LPWANs) are often employed [65]. In the case of this study, the sensor nodes allow the monitoring of internal environmental conditions by generating a stream of digitally encapsulated signals used for data collection. The network elements measure the following parameters: temperature and air humidity, which allow the behavior of the building to be scrupulously analyzed. The employed sensor network will be described in this paper.

BIM

BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition [66]. Unfortunately, the advantages of BIM in the operational phase have not yet been adequately analyzed due to the tool's inability to acquire and manage data in real time. In this context, digital twin technology is designed to fill the gaps in BIM and allow its use even during the operation phase.

Digital Twin

BIM models can simulate and predict future conditions, but their capacity for selflearning, autonomy, and external data processing is limited [67]. In contrast, the digital twin is capable of acquiring, communicating, and processing data in real time. A DT is a dynamic virtual copy of the real-world physical object, user, or activity in a digital world that is continuously updated through data and information collected in real time via smart sensors while maintaining historical data to make any predictions or decisions through simulations, machine learning, and reasoning [60]. A DT essentially has three components: the physical system, the virtual model, and the data acquired by the sensors [68]. BIM-based DT allows the user to visualize sensor data in a simple and intuitive way via a three-dimensional model of the building, supporting visual communication of the system [69]. DT has the potential to encourage transparency and collaboration between project stakeholders, reduce energy demand during the operational phase, support proactive building maintenance through instant anomaly detection, and help designers develop well-thought-out energy retrofit interventions, based on real data.

According to the Verdantix maturity model [70], there are five stages of digital twin evolution (Table 10). Essentially, the more mature the twin is, the more valuable it becomes.

Table 10. Stages of digital twin evolution.

Stages	Description
1. Descriptive twin	The twin accurately represents the building structure in the real world.
2. Informative twin	The twin is able to connect to IoT and sensors to communicate real data to the user.
3. Predictive twin	The digital twin uses its historical data to run analytics and predict trends.
4. Comprehensive twin	The digital twin, as it evolves, allows real-time simulation for future “what-if” scenarios.
5. Autonomous twin	The twin has the data and processes established to automatically take action based on the insights it delivers.

6.3.2 Workflow Application

This section explains in detail the work phases presented in the flow diagram reported in Figure 6 of Chapter 3.

Phase 1 - Physical Building Study

The case study chosen for the workflow application is the same as the one described in Section 6.1.1, i.e. the so-called "Solar House". Also in this case, only the top floor of the building (Figure 2) was considered for the experimentation, that is, the floor containing the offices of the Las.E.R Laboratory research group. A detailed description of the building is given in the Section 6.6.1.

Phase 2a—WSN Configuration

The monitoring, which lasted two weeks, involved four rooms, namely the hallway, the lighting laboratory, and offices one and two, each with different functional and occupational characteristics. The choice of rooms

is linked to specific reasons: the lighting laboratory is the room used for laboratory experiments, with non-constant occupancy; the hallway constitutes a passage space, where occupancy is variable; office one is a two-people cellular office, and office two is a one-person cellular office. Following the ISO 7726 standard [71], the sensors were positioned so that the thermal exchanges were more or less identical to those to which the room occupant was exposed. The location of the sensors is shown in Figure 19.



Figure 19. Areas affected by monitoring and indication of sensor nodes placement (red dots).

The block scheme of the monitoring system employed in this work is shown in Figure 20.

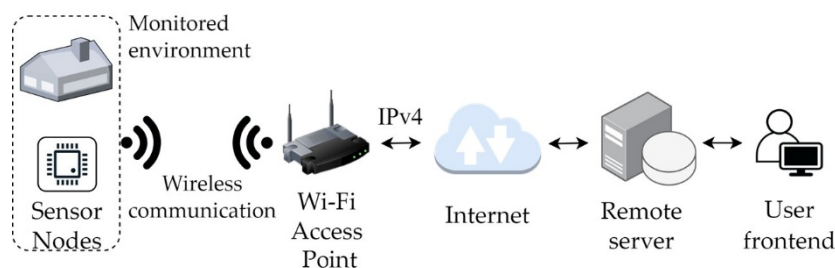


Figure 20. Block scheme of the IoT sensing system.

The sensor nodes are equipped with wireless communication using Wi-Fi. These elements are powered directly from the electrical grid by means of a Direct Current (DC) power supply. In this case, there is no need for batteries as the grid supply is always available. The same principles apply to scenarios where energy harvesting can be exploited in remote or non-electrically served environments [72]. The Wi-Fi network access for internet connection is the same one used for normal operation in the offices. Using HTTPS requests, the nodes forward the sensor measurements to the Tandem platform, which acts as a database. Then, the information can be accessed using the user front-end. The sensor nodes are structured as shown in Figure 21.

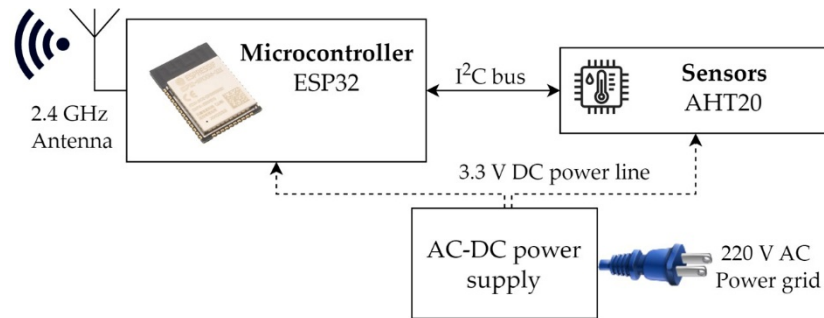


Figure 21. Block scheme of the sensor nodes.

A core ESP32 microcontroller [73], by Espressif, periodically retrieves information from the sensors, which are of the type AHT20 [74], from Asair. Data are encapsulated in JSON format and transmitted using POST requests. If the request is not successful, it is repeated after a guard time period. If the network connectivity is not available, the sensor nodes enter a sleep mode and the connection attempts loop. The sensors characteristics are reported in Table 11.

Table 11. Sensor characteristics.

Characteristic	Description
Type	Integrated circuit, resistive–capacitive sensing technology
Measuring Range	0 to 100% RH, −40 to +85 °C
Recommended range	0 to 80% RH, −20 to +60 °C
Accuracy (Typical)	Humidity: 0.024% RH, Temperature: 0.01 °C

A diagram of the functionality of the system is shown in Figure 22.

The sensor has a stable performance within the recommended working range, as the datasheet reports. Long-term exposure to conditions out of the normal range may cause a temporary signal drift. This is true especially when the humidity is >80%, where the datasheet reports a drift of +3% RH after 60 h. The sensor will slowly self-recover to the calibration state after returning to normal working conditions. This process can be executed in fast recovery by taking drying measures, as suggested by the sensor designers, by keeping it at 60–85 °C and <5%RH for 2–10 h.

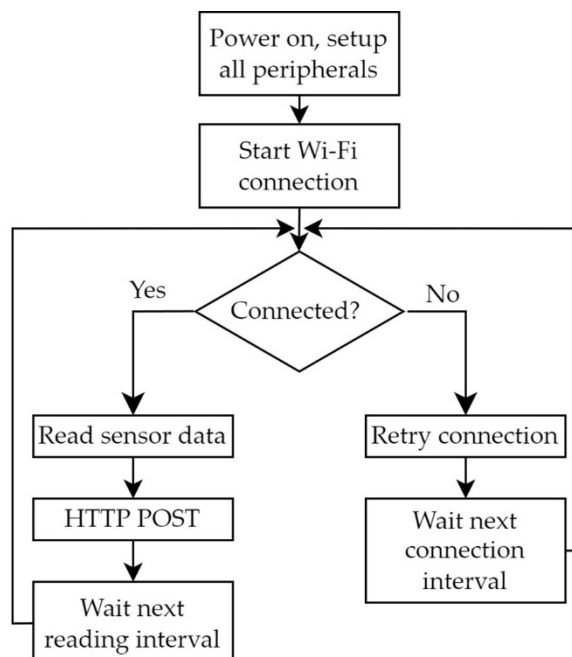


Figure 22. Functional diagram of the sensor nodes.

Figure 23 shows a picture of the experimental setup.

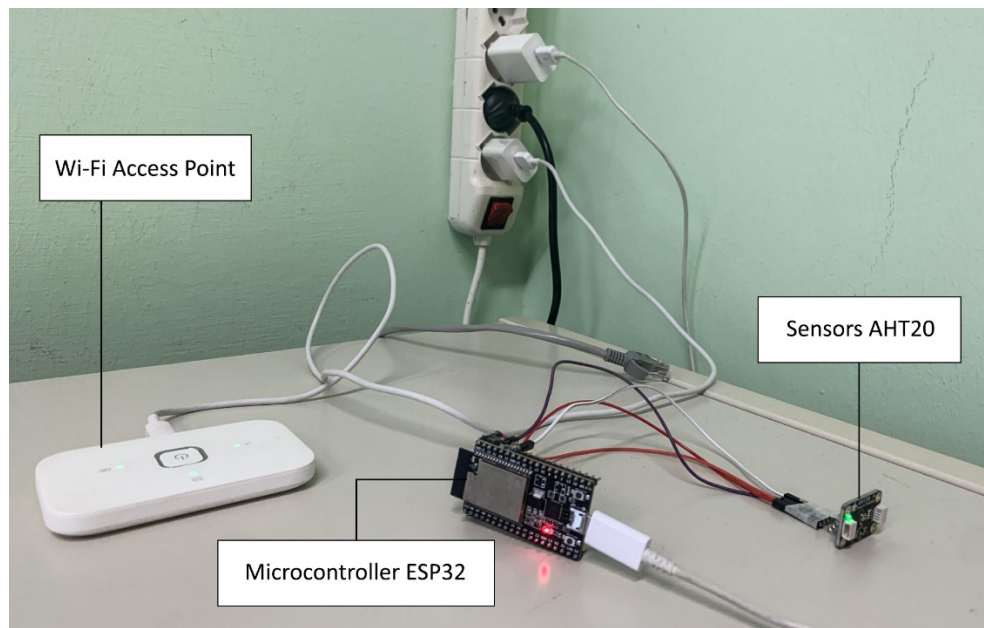


Figure 23. *Experimental setup.*

The electronic components used for the implementation of the WSN nodes in this study have been chosen following two main criteria. The Espressif ESP series microcontrollers are well documented by the producer both in terms of hardware and firmware development [75]. The configuration of the nodes is made easier using wireless interfaces that can be integrated using open-source documentation [76], allowing for the reduction of the overall complexity of the deployment of a research-grade system. The availability of the mentioned circuits in the market is the one motivation, as the selected node elements are widespread in the free market at competitive prices. The use of a Wi-Fi connection enables the portability of the sensor system to different locations, as the only gateway needed to access the internet is a Wi-Fi access point with a 2.4 GHz band. The integration of IoT–DT systems raises significant security and privacy concerns, especially regarding the protection of sensitive data transmitted and stored within these systems [77]. Huge efforts have been made in the search for solutions for the management of security data that provide accessibility, transparency, reliability, consistency, and traceability. Among these, a solution that seems to be very promising is the one that involves the use of blockchain technology for the reliable sharing of information between all the entities involved in a construction project [78].

Beyond the research currently underway, the basis for safeguarding data integrity and addressing privacy issues associated with real-time monitoring is certainly the implementation of robust security measures, such as encryption and access controls.

Encryption is fundamental for protecting data confidentiality in DT systems. Advanced encryption techniques ensure that data exchanged between the physical and virtual components of a DT remains secure from unauthorized access. Implementing end-to-end encryption protocols protects data both in transit and at rest. This approach ensures that even if data transmissions are intercepted, the information remains unintelligible without the proper decryption keys. In IoT-oriented systems, lightweight encryption algorithms are more suited as computational efficiency is critical. These algorithms provide a balance between security and performance, ensuring that encryption does not hinder the real-time capabilities of the DT system. Access control mechanisms ensure that only authorized personnel can access specific data and functionalities within DT systems. Role-Based Access Control (RBAC) models are widely used to assign permissions based on user roles and responsibilities, effectively limiting access to sensitive information. Access control is often coupled with Multi-Factor Authentication (MFA), which enhances security by requiring users to provide multiple forms of verification before accessing the system, including a password or a security token.

Real-time monitoring in DT systems involves continuous data collection and analysis, which may include sensitive operational and personal information. Addressing privacy concerns is crucial to complying with data

protection regulations like the General Data Protection Regulation (GDPR). Collecting only the data necessary for specific purposes reduces the risk of unauthorized exposure. Implementing data minimization strategies ensures that unnecessary or redundant data are not collected or stored, thereby limiting the potential impact of data breaches. Techniques that anonymize or pseudonymize personal data can prevent the identification of individuals from datasets. This involves altering or removing personal identifiers from the data, making it difficult to trace back to any individual while still retaining the usefulness of the data for analysis. Developing clear and transparent data policies that outline data collection, usage, storage, and sharing practices helps build trust with stakeholders. Ensuring that all parties are informed about how their data are handled and protected is essential for compliance and accountability.

Using encryption standards, such as Secure Sockets Layer (SSL) for data in transit, ensures that data are unreadable to unauthorized parties. In this work, the authors implemented the use of Hypertext Transfer Protocol Secure (HTTPS) for data exchange as a first layer security enabling solution. Its widespread adoption and standardization make it a practical choice for securing web-based communications within these systems. However, relying solely on HTTPS has limitations. Performance impacts due to encryption overhead, the complexity of certificate management, and its inapplicability to non-http protocols are notable drawbacks.

Phase 2b— BIM Modeling

The BIM model of the building was created with Autodesk Revit 2023. Revit was chosen due to its versatility in modeling various types of buildings and its adaptability to a wide range of studies [79]. Additionally, Revit offers a high level of interoperability compared to many other BIMs, providing greater flexibility when integrating with other software and other technologies for data exchange. The BIM environment has the advantage of being able to recreate the building at the required level of detail and accuracy. In our case, defining the internal partitions was crucial, as monitoring was conducted at the level of individual rooms (Figure 24).

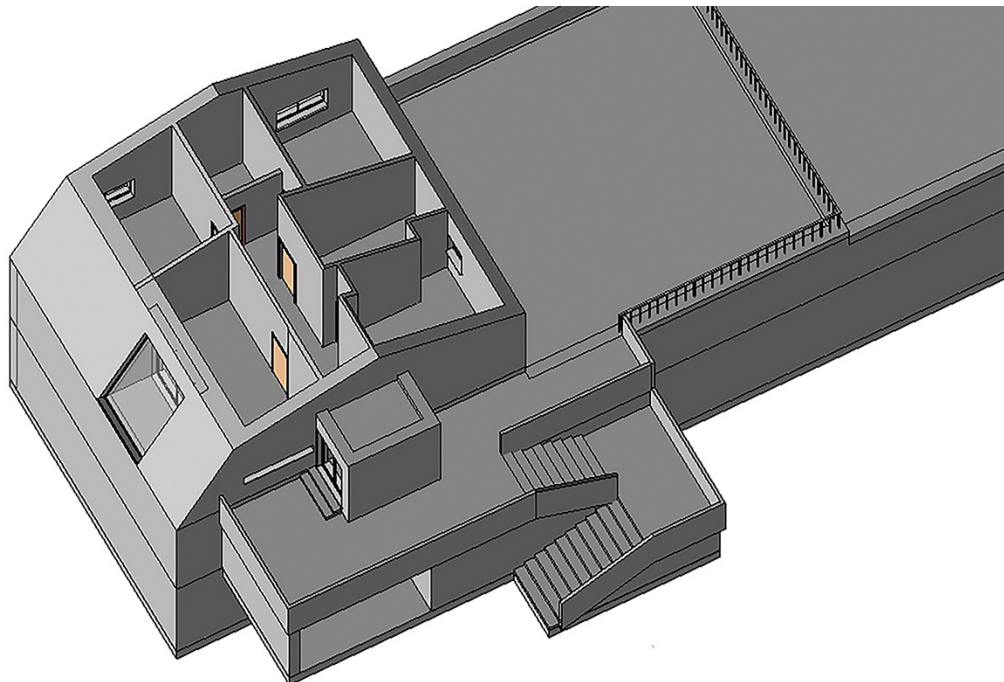


Figure 24. *Distribution of the internal spaces of the floor in question.*

The selected building has regular and standardized characteristics, fully aligned with a BIM approach. Therefore, from a semantic perspective, the model was mostly developed using existing families from the software libraries and, only in specific cases, by creating new custom families, such as for the sensors, which were placed in the model in the same positions as in reality and linked to the designated rooms within the model. Therefore, for monitoring purposes, the rooms constituting the “Solar House” were created within the model, enabling the integration of data from environmental sensors assigned to each room (Figure 25).

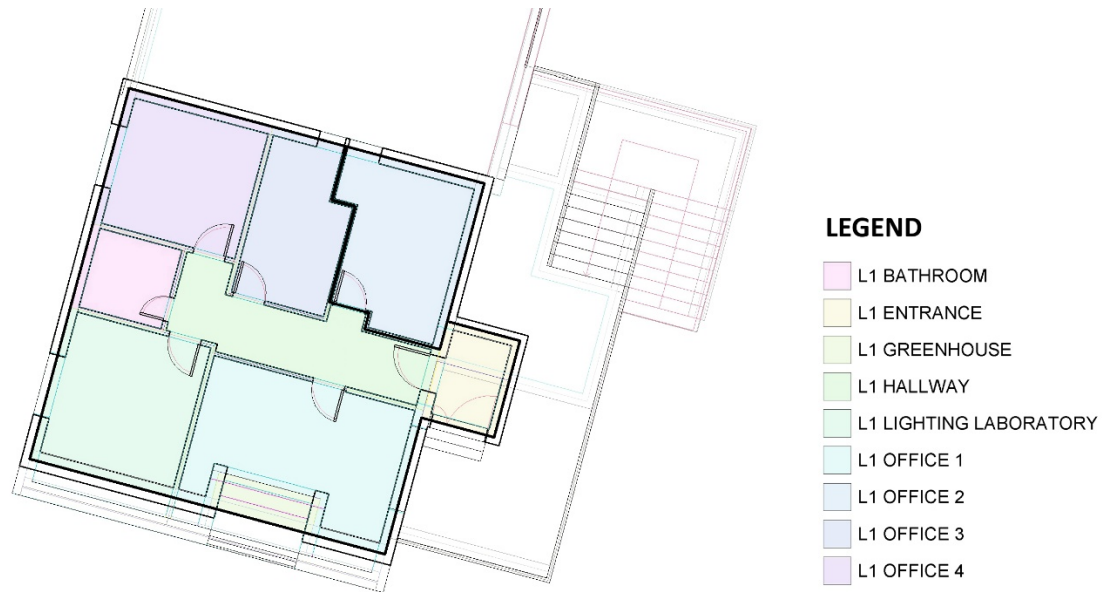


Figure 25. *Creation of analytical spaces.*

The DT was created based on the building's current characteristics with the aim of assessing its present features and performance to serve as a foundation for proposing future improvement interventions. Assigning each architectural component its thermophysical characteristics is important in order to create a digital twin capable of offering a holistic view of the building.

With all the data at hand, the user will be able to acquire an in-depth knowledge of the properties possessed by the building in question. Furthermore, a digital twin of the building rich in information can be subsequently imported into an energy simulation software in order to conduct more in-depth and accurate studies in view of any efficiency interventions.

Phase 3— Digital Twin Creation

Autodesk Tandem was used to create the digital twin of the building under investigation. The choice of middleware tool is linked to the fact that Tandem and Revit are released by the same software company, favoring the interoperability process and making Tandem able to read the BIM model correctly. Tandem is a cloud-based digital twin solution that enables collaboration in Architecture, Engineering, Construction and Operation (AECO). It consists of an online accessible platform that allows you to create an ecosystem in which all the resources, spaces, and systems of the building are related to each other. Therefore, Tandem can be seen as a middleware tool capable of connecting IoT systems to the BIM model of the building in a single environment, providing the end user with the key to control and interpret data easily and quickly from day zero. With the context of the robust 3D twin viewing and supporting charts and heatmaps, data insights are instantly visible. To use Tandem, you need to have an account. Since the twin is hosted in the cloud, the end users can access it from anywhere at any time, upon invitation from the account administrator. Based on their permission level, end users will be able to “Read”, “Edit” or “Manage” the digital twin. Tandem gives the possibility to analyze both real-time and historical data, allowing an accurate analysis of the structure's performance.

The first step to creating a digital twin on Tandem involves “create a new facility”. In this way, it is possible to import the BIM model of the building in “.rvt” or “.ifc” format onto the platform. To be able to send the data recorded by the sensors to Tandem, you need to create connections and assign them a classification. In Tandem, a connection is the digital representation of an IoT device or asset (for example, thermostats, air handling units, or occupancy sensors). Once you have created all the necessary connections, you need to

configure them. There are several ways to do this; in our case, the method used is HTTPS requests, using the provided endpoint. Each node in the DT platform has a unique endpoint that can be used to access the database. Tandem gives the possibility to assign the connection to a host, which can be any element or space. In our case, the various connections were assigned to the corresponding sensors, previously modeled on Revit using a custom family. This feature is very interesting, as it makes it possible to view instant data from each sensor simply by clicking on its virtual model, making monitoring much more direct and intuitive (Figure 26).

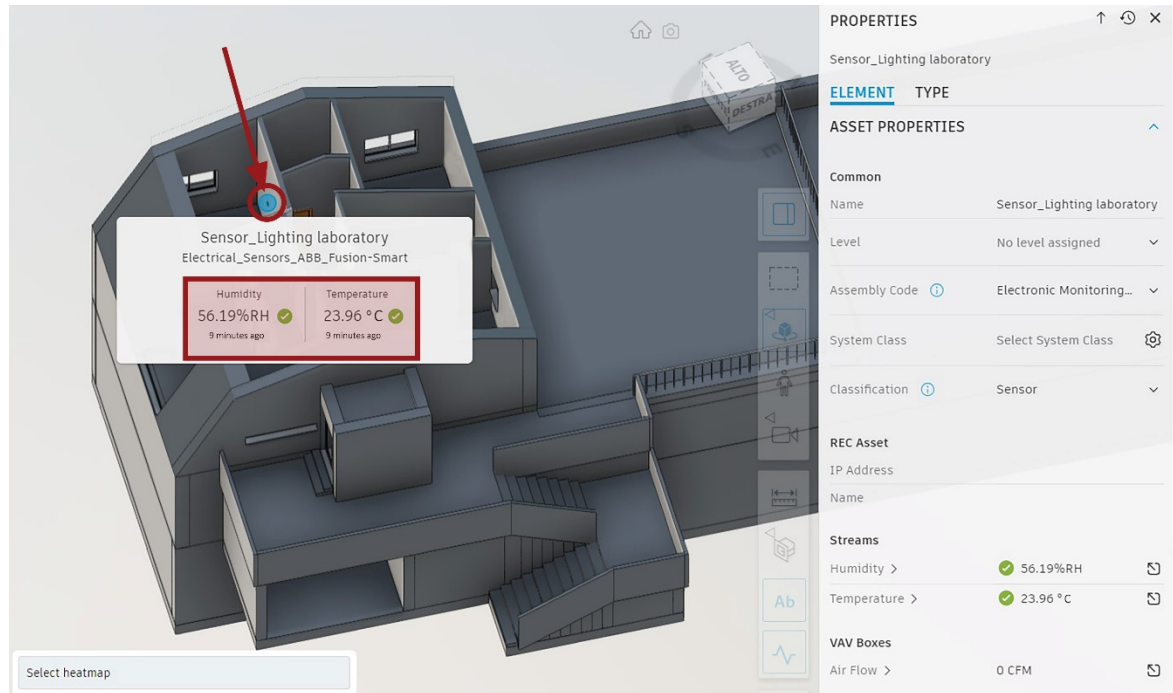


Figure 26. Example of instant data display for the lighting laboratory sensor.

In the “Streams” section it is possible to view the trend graphs of the various environmental parameters recorded over time, selecting the desired time interval. In Tandem it is possible to create thresholds, i.e., upper and lower limit values within which the environmental parameters should remain. When the values exceed the limits set by the user, the graphs signal it with red to facilitate the identification of critical issues. In our case, the limits were set in accordance with the criteria of the National Institute for Insurance of Accidents at Work (Inail), based on Legislative Decree 81/2008 [80]. According to the above criteria, in offices, it is advisable that the humidity remains between 40 and 60% and the temperature between 18 and 24 °C. Figure 27 shows the trends in humidity and temperature values for each room during three weeks of monitoring, from 30 May 2024 to 13 June 2024. The time intervals in which the parameters exceeded the imposed limits are highlighted in red.

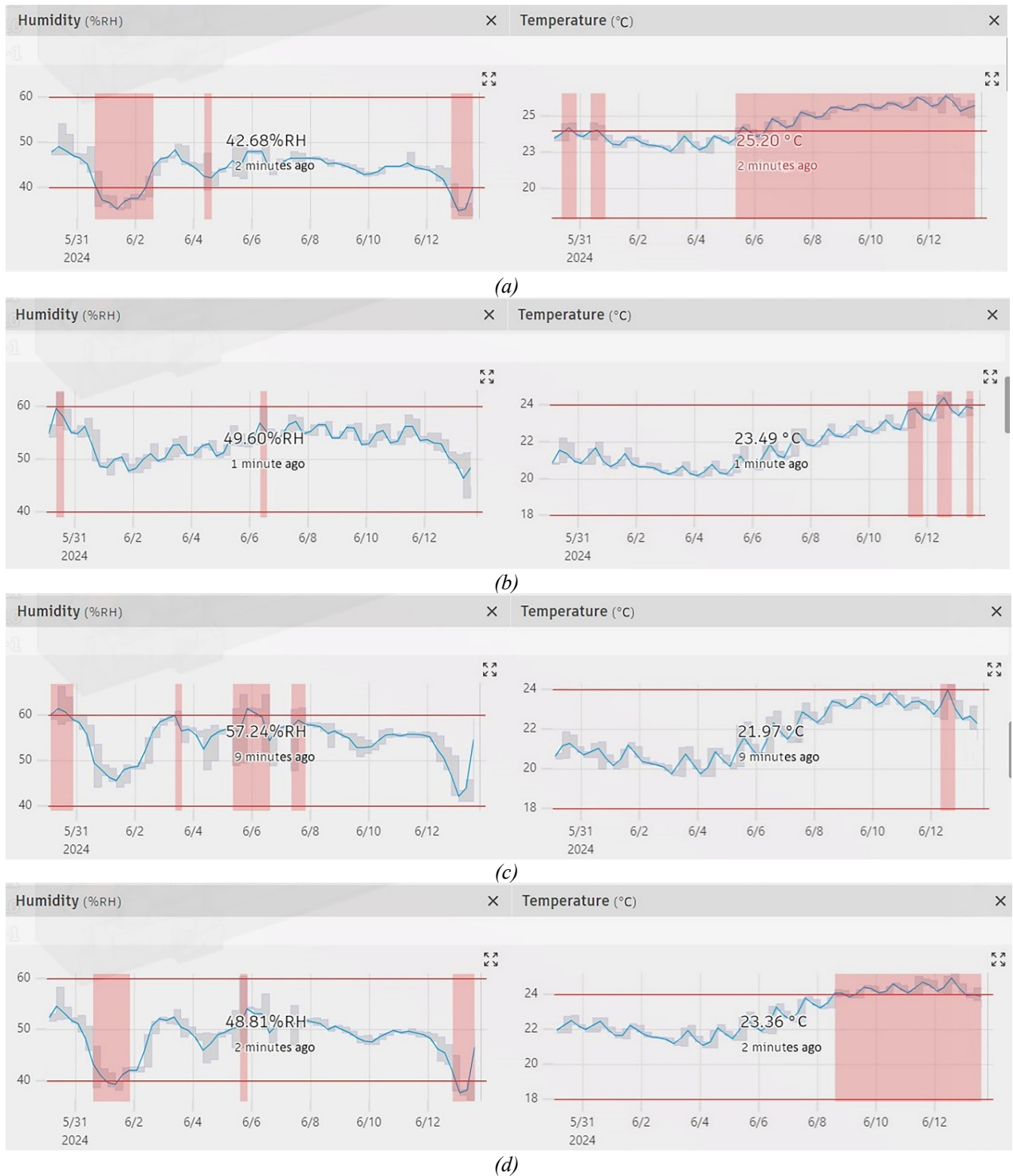


Figure 27. Humidity and temperature trend for each room. (a) Hallway. (b) Lighting laboratory. (c) Office 1. (d) Office 2. Horizontal axis: time; vertical axis: humidity or temperature value.

Autodesk Tandem provides the ability to configure and customize maps to reflect connected streams (Figure 28). The Heatmap widget shows the last set of data received for the streams of data as they are associated with spaces or assets within the digital twin.

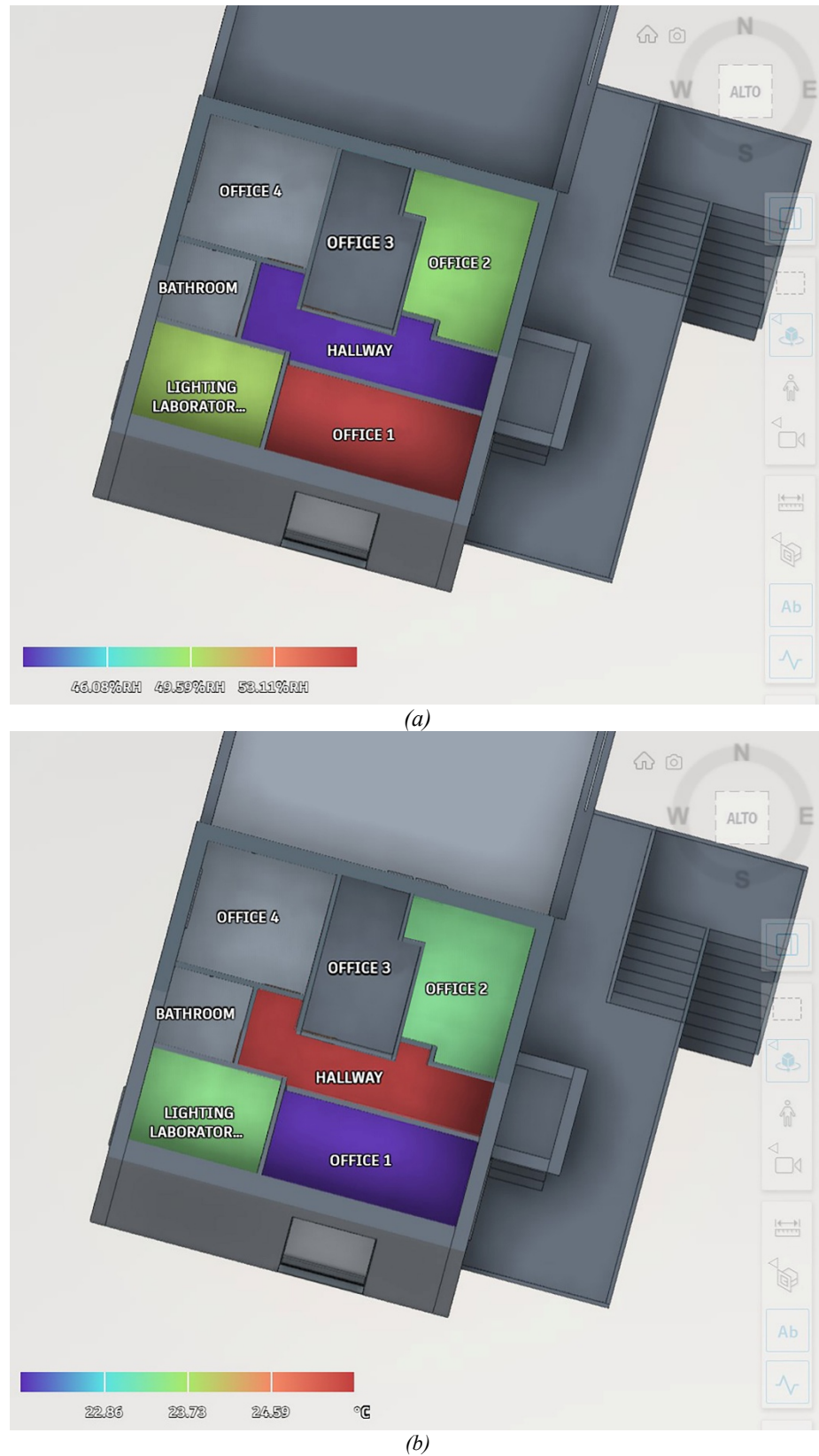
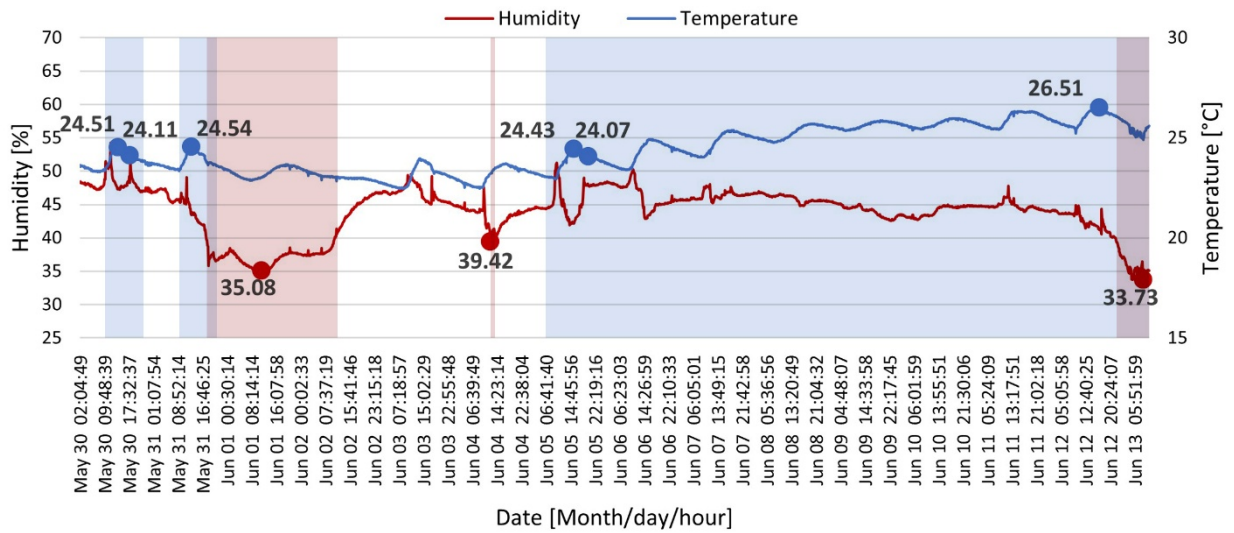


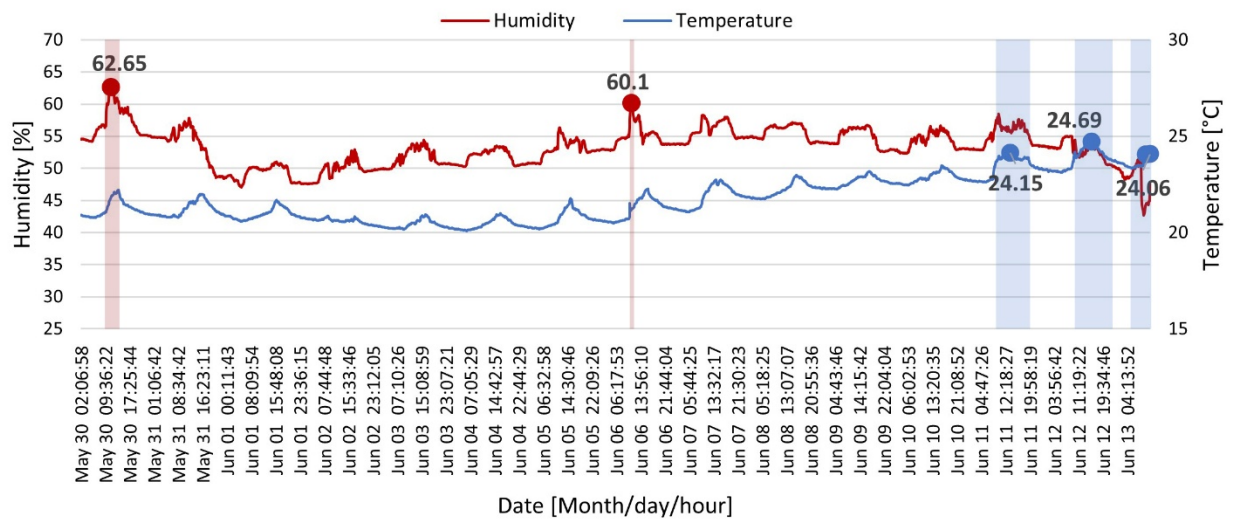
Figure 28. Mapping of average environmental parameters recorded during the monitoring period. (a) Humidity. (b) Temperature.

6.3.3 Results and discussion

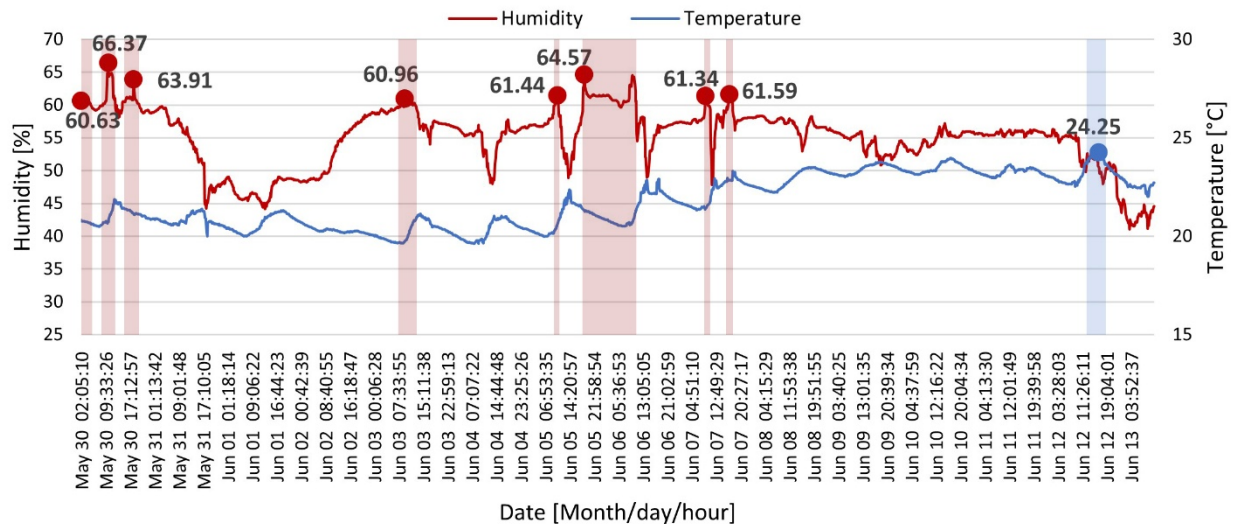
Figure 29 correlates the temperature and humidity values on the same graph, highlighting the peaks reached in the time intervals in which the values exceeded the limits imposed by the current decree.



(a)



(b)



(c)

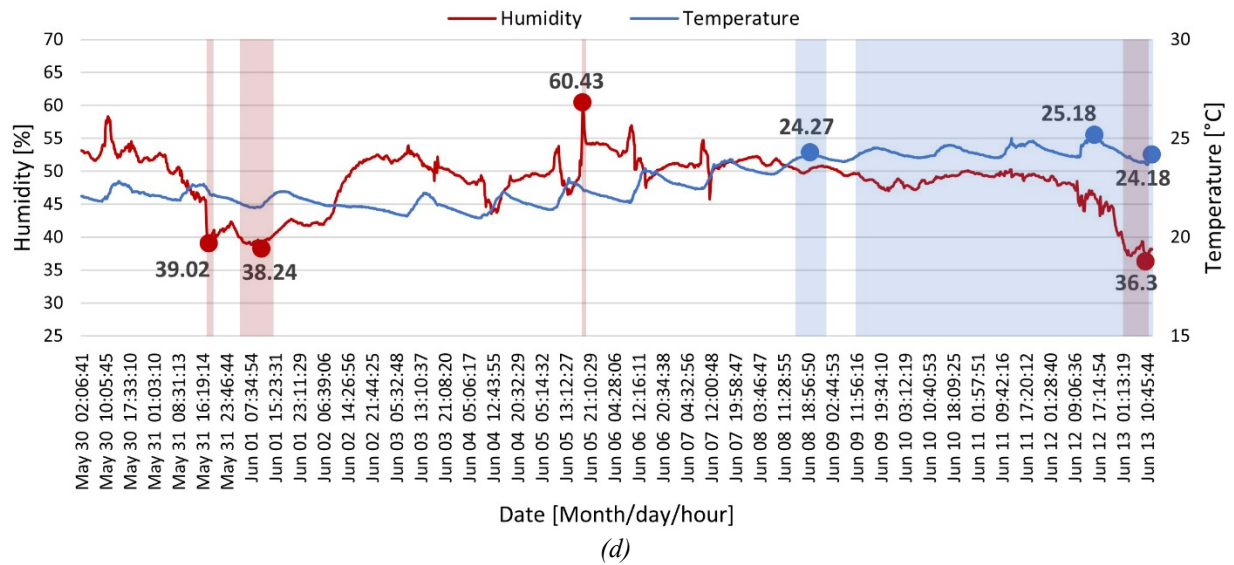


Figure 29. Monitoring results. (a) Hallway. (b) Lighting laboratory. (c) Office 1. (d) Office 2.

Table 12 reports the minimum, maximum and average values of humidity and temperature recorded during monitoring.

Table 12. Summary of monitoring results.

Room	RH _{min} [%]	RH _{max} [%]	RH _{ave} [%]	T _{min} [°C]	T _{max} [°C]	T _{ave} [°C]
Hallway	33.73	54.21	43.95	22.47	26.51	24.38
Lighting lab.	42.63	62.65	53.27	20.09	24.69	21.72
Office 1	41.07	66.37	54.99	19.61	24.25	21.73
Office 2	36.30	60.43	48.55	20.97	25.18	22.87

Table 12 shows some initial assessments, where the temperature of the monitored rooms varies from 19.61 °C to 26.51 °C, while the humidity is from 33.73% to 66.37%. The hallway has the lowest humidity and the highest temperature values. The high temperature is probably due to the fact that the hallway occupies a central position inside the building and, for this reason, is not affected by heat losses through the envelope. The dryness of the environment is a direct consequence of the high temperature found there. On the contrary, office one presented the highest humidity and lowest temperature values. This is linked to the presence of large glazing in the room, which favored heat dispersion in a period of the year when the external temperature was still relatively low. In any case, by averaging the humidity and temperature values recorded during the two weeks of monitoring for all the rooms under examination, it can be noted that the values recorded every 10 min fell within the limits imposed by the national decree in force, except in the case of the hallway, in which the average value of temperature exceeds the threshold of 0.38 °C. To have an even broader vision of the situation, it would be advisable to repeat the monitoring during the summer and winter periods.

Figure 30 shows the correlation matrix of the monitored parameters for the different rooms. Each off-diagonal subplot shows a scatterplot of a pair of variables, including a least-squares reference line, where the slope represents the displayed correlation coefficient. The diagonal subplots contain the distribution of a variable as a histogram. It is possible to assess that the temperature values of the different zones can be considered very close to each other, as expected in a building that does not present a big volume and room-dedicated air exchange systems. This can also be observed for the values of zone relative humidity. The correlation of temperatures and relative humidity values can be considered low, as the factors that rule the variation in humidity in each monitored room are various, and the interaction can be complex [81]. Furthermore, the relationships between internal temperature and humidity and the external climate are low; this can be due to a variety of factors, such as human activities, occupancy, and the behavior of the building envelope.

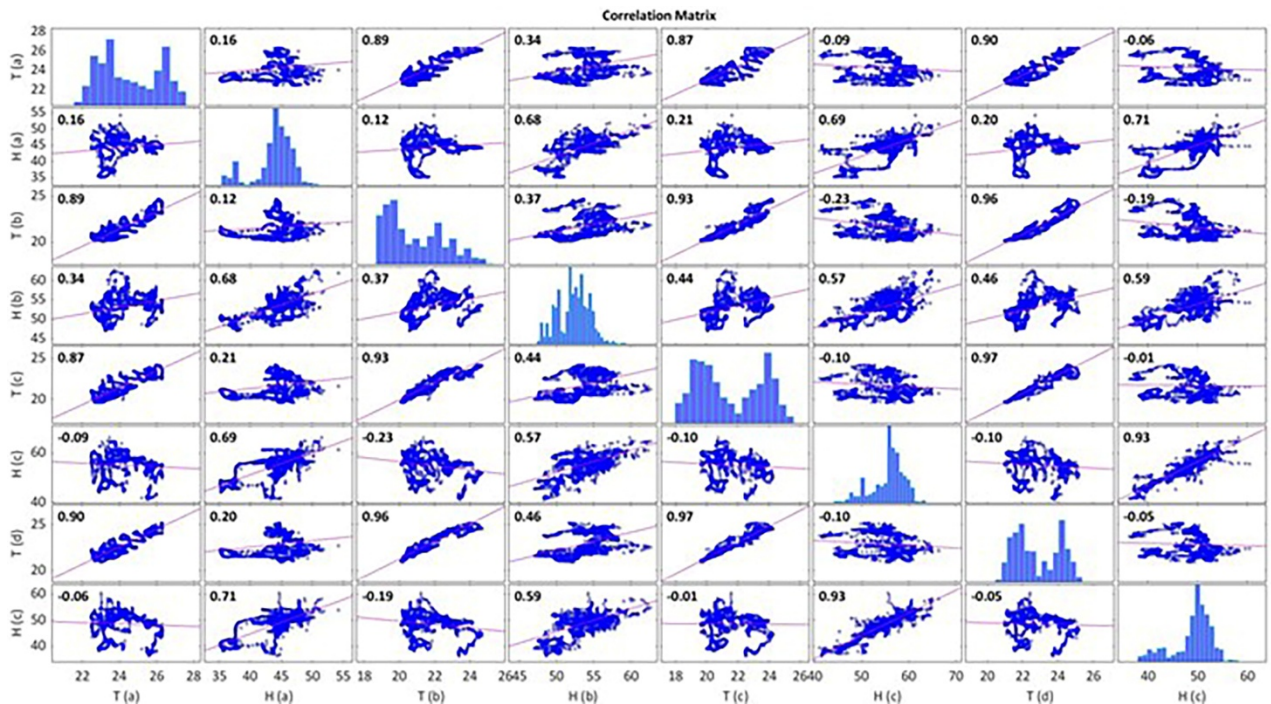


Figure 30. The correlation matrix of the monitored parameters for the rooms of interest. *T* stands for temperature, and *H* stands for relative humidity. (a) Hallway. (b) Lighting laboratory. (c) Office 1. (d) Office 2. (e) External environment.

During monitoring, the DT helped in the constant display of the parameters in a simple and quick way, allowing continuous updating on the thermo-hygrometric conditions of the different rooms at any time, even remotely. The developed DT lays the foundation for future implementations of the system capable of promoting both proactive and corrective maintenance interventions, guiding facility managers in identifying the most appropriate energy efficiency strategies. On the proactive maintenance level, for example, the DT allows for instant identification of the presence of anomalies, ensuring an immediate intervention by the facility managers in case of need.

In the context of corrective maintenance, the historical data collected during the monitoring period could be used to calibrate the thermal model of the building in order to obtain accurate and reliable energy analyses on which to base any energy efficiency interventions, simulating different design alternatives. Furthermore, the ability to update the digital twin in the event of changes to the real building would mean having a virtual model capable of providing continuously evolving data, which constantly reflects the conditions of the physical entity.

Given that the DT would bring several advantages within the life cycle of a single building, recent studies are considering the possibility of exploiting this technology in the field of urban planning [82–85]. According to Deng et al. [84], digital twins, along with the Internet of Things, fifth-generation wireless systems, blockchain, collaborative computing, simulation, and artificial intelligence technologies, could be the key to the transformation of the current urban governance paradigm toward smart cities. Taking inspiration from the work of Halimi et al. [86] that offers a methodological framework for the evaluation of the impact of transportation infrastructure on community connectivity, it would be interesting, in the future, to analyze the socio-economic benefits of DT at the community level, testing the applicability of our research on an urban scale.

The main aim of the paper was to present a detailed workflow for the practical application of creating a DT, seeking to provide a more comprehensive view by highlighting the workflow and methodological aspects involved.

From the application of the developed workflow, it emerged that for the creation of an efficient and functioning DT, it is important:

- to choose an appropriate BIM tool, which is capable of recreating the various building components in detail;

- to select suitable sensor devices capable of connecting to the appropriate network access point;
- to choose a reliable and efficient network connection that allows a fluid and constant flow of data;
- to identify a middleware tool capable of appropriately reading both the 3D model of the building and the data coming from the sensors;
- to ensure efficient synchronization between the BIM model and the IoT sensor devices by configuring the connection in the most appropriate way for the tools available.

Table 13 illustrates the technologies chosen for the creation of the DT, based on the needed interoperability requirements.

Table 13. Technologies chosen for the creation of the DT.

Technology	Interoperability Requirement	Selected Solution
Sensor	- possibility of physically connecting to the data acquisition device	AHT20
Data acquisition and exchange device	- wireless connection capability - capability of data exchange in the format required by the DT platform	Espressif ESP Microcontroller
BIM software	- capability to export the model in the format accepted by the DT platform	Autodesk Revit
DT platform	- ability to be accessible via the Internet - ability to import the model in the format supported by BIM - ability to receive data in the storage format supported by the data acquisition device - capability to support storage of the received data	Autodesk Tandem

A problem that could arise during the transition of the model from one platform to another could be the incorrect export of geometric data or the loss of information. If these critical issues emerge, it is appropriate to make changes to the three-dimensional model in most cases by proceeding with its geometric and semantic simplification [1]. The data exchange among internet-based services can be considered less critical due to a large spectrum of possible exchange protocols and methods [87]. Figure 31 summarizes the technologies, protocols, and exchange formats used to achieve efficient interoperability between the various tools involved in the process.

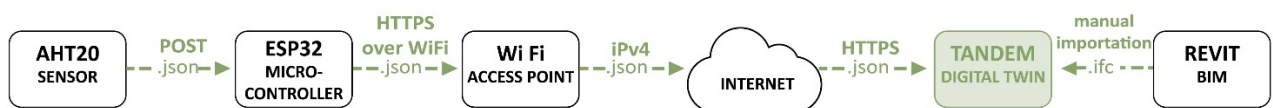


Figure 31. Schematic representation of interoperability between the tools involved in the creation of the digital twin.

Table 14 summarizes the main potentials and challenges in the application of BIM-based digital twin.

Table 14. *BIM-based digital twin potentials and challenges.*

Potentials	Challenges
• Digitalization of the construction sector • Integration between architecture and energy • Constant connection between physical and virtual entity • Real-time remote monitoring • Optimizing the data visualization and processing phase • User involvement in energy issues	• Lack of a standardized procedure for applying the technology • Use of technology still very limited • Absence of BIM models of historical or ancient buildings in the archive • Difficulty of interoperability between the different technologies and software involved in the application of DT.

6.3.4 Conclusions

For efficient energy management of buildings, it is crucial that energy use and the thermal environment are addressed simultaneously. Identifying a building's design criticalities can help choose the most appropriate energy optimization interventions, leading to a reduction in heat loss and, consequently, limiting the use of HVAC, with a consequent reduction in costs related to its consumption. Accurate diagnoses through comprehensive internal comfort monitoring campaigns are essential to identify the most efficient energy optimization strategies. With the rapid progress of urban modernization and construction industrialization, it is necessary to overcome the limitations of current environmental monitoring systems to promote the digital transformation of the construction sector. In this context, BIM-based DT technology can play a fundamental role. Nonetheless, despite the unquestionable potential of DT, there are still challenges and unresolved issues due to its relatively recent development. This study presents a detailed workflow for creating a DT, defining standard guidelines applicable to various case studies, also offering different solutions to optimize the integration of the various technologies necessary for the creation of an efficient DT. The developed workflow was tested on a singular building, an office building also used as an academic laboratory, with the aim of experimenting with the "Living Lab" concept. The system integrates real-time data collected through a WNS with a BIM-based 3D model that automatically combines the monitored data. The study confirms that DT offers several benefits for the construction industry, such as facilitating the integration of architecture and energy systems, accelerating the digitalization of the construction sector, and enabling the direct and continuous connection between physical and virtual entities. Additionally, it optimizes the data visualization and processing phase of monitoring, providing a user-friendly interface that is accessible to all users, in real time and remotely.

This work represents an initial exploration of digital twin (DT) technology, focusing on the second stage of DT evolution as outlined by the Verdantix maturity model. Future developments should involve conducting repeated monitoring at different times of the year also including other parameters influencing the IEQ index, in order to gain a broader understanding of the building performance.

Further advancements could consist of exploiting the DT for predictive analyses and real-time simulations, enhancing the accuracy and effectiveness of the decision-making process in energy requalification interventions and the overall quality of life for users.

From a future perspective, integrating monitoring sensors with digital technologies, such as BIM, DT, Internet of Things (IoT), and Artificial Intelligence (AI), could significantly advance the building automation field by encouraging the application of automated control systems, preserving energy efficiency, and ensuring a comfortable indoor environment throughout the building's lifespan [88].

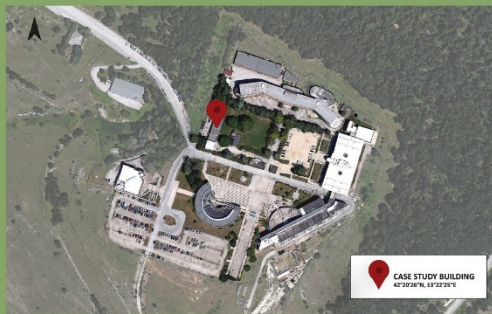
SUMMARY

6.1 BIM-BEM Interoperability

Two strategies have been investigated to bridge the gap between Building Information Modeling (BIM) and Building Energy Modeling (BEM): real-time connection (S1) and standardized exchange formats (S2). The validity of the BIM-to-BEM approach was verified by comparing it with the traditional approach, which involves the creation of the energy model directly in the BEM environment.

Phase 1 - Case study analysis

The case study chosen for experimentation is the “Solar House”, a building within the Engineering Campus of the University of L’Aquila, located in Monteluco di Roio. While the entire building was modeled, the energy analysis focused on the top floor, occupied by the offices of the Las.E.R and G. Parolini Laboratories.

*Phase 2 - Energy model creation*

The building’s energy model was developed using two distinct approaches: BIM-to-BEM (A1) and a widely-used EnergyPlus dynamic energy modeling (A2).

A1: BIM-to-BEM approach

The first step, common to both strategies, involved the BIM-based modeling of the “Solar House” with all its components, accurately replicated both geometrically and thermally. After finishing the BIM model, two interoperability strategies were tested to make the transition from BIM to BEM.

- Strategy 1 – Real-time connection

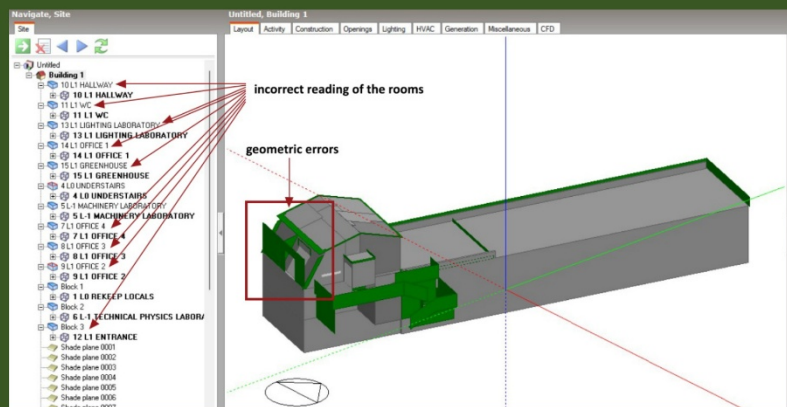
The “Real-time connection” strategy involves the creation of the energy model directly within the BIM environment through the installation of specific plug-ins equipped with BEM simulation engines. In this work, Autodesk Insight 360 was used for energy analysis, selected based on a literature review for its widespread use.

An obstacle to the application of the first interoperability strategy emerged during the definition of the energy settings.

- Standardized exchange formats

Following the second interoperability strategy, the architectural model, previously created in Revit, was exported to DesignBuilder, a BEM software, which uses EnergyPlus as its simulation engine.

The initial BIM-to-BEM import faced geometric errors and misinterpreted room definitions, which were resolved by simplifying geometry and combining rooms on the same floor into single zone. Thermal properties were successfully transferred, and the interoperability strategy proved particularly effective for HVAC modeling, as DesignBuilder allows extensive customization of system templates and operation schedules.



A2: Traditional BEM-based approach

Following the most common approach, the energy model was created within DesignBuilder from scratch. In the BIM-to-BEM approach, during the model import process in the BEM environment, the software automatically reduces the level of architectural detail, based on the needs required by an energy study. Using the traditional approach, instead, every geometric simplification necessary to build the model on the BEM was conducted manually, according to completely personal criteria.

Phase 3 - Energy analysis

Once the energy modeling was finished, the simulations were conducted with EnergyPlus, with the aim of obtaining the annual thermal consumption of the building in question.

Phase 4 - Models' calibration

The thermal models were calibrated using one month of real building energy consumption (March 15–April 15, 2023) following ASHRAE M&V guidelines with an hourly calibration approach. Calibration was considered successful when the Mean Bias Error (MBE) and Coefficient of Variation of the RMSE [CV(RMSE)] were within $\pm 10\%$ and 30% , respectively.

$$MBE (\%) = \frac{\sum_{Period} (S - M)_{Interval}}{\sum_{Period} M_{Interval}} \times 100 \quad (1) \quad CV(RMSE_{Period}) = \frac{RMSE_{Period}}{A_{Period}} \times 100 = \sqrt{\sum \frac{(S - M)_{Interval}^2}{N_{Interval}} \times \frac{1}{A_{Period}}} \times 100 \quad (2)$$

Where:

- M is the measured kilowatt-hours;
- S is the simulated kilowatt-hours;
- $N_{Interval}$ is the number of time intervals in the monitoring period;
- A_{Period} is the mean of the measured data for the period, calculated using Eq. (3). $A_{Period} = \frac{\sum_{Period} M_{Interval}}{N_{Interval}} \quad (3)$

Results and discussion

The calibrated models showed good agreement with measured data. The BIM-to-BEM approach had an MBE of -10% and a CV(RMSE) of 19% , while the traditional method had an MBE of -4% and a CV(RMSE) of 20% .

The results obtained so far demonstrated that the Real-time connection strategy (S1) may not be suitable due to limitations in customization options. Otherwise, the Standardized exchange formats strategy (S2) has proven to be able to perform accurate and reliable energy analyses, enabling informed decisions-making based on robust data. In the case in question, the results obtained using the BIM-to-BEM approach have proven to be consistent with those obtained using the traditional BEM-based approach, with a difference in annual thermal energy consumption of approximately 2% . In both cases, model calibration against real data demonstrated a high degree of accuracy, validating the effectiveness of both methodologies.

However, when considering a pre-existing BIM model, the BIM-to-BEM approach offers several significant advantages that could be less pronounced for simpler buildings like the 'Solar House', but increasingly valuable for complex and large-scale projects (Table 2).

Table 2. Pros and Cons of the BIM-to-BEM approach.

PROS	CONS
• creating a shared environment where the different professionals involved in the project can communicate and exchange data more easily • improved integration between architectural and energy design • reduced modeling time	• possibility of data loss or incorrect reading in the transition from BIM to BEM (more or less serious depending on the complexity of the model) • need for a partial knowledge of BIM software by the BEM user

Conclusions

Efficient BIM-BEM interoperability can enhance energy-aware design, but current workflows face communication challenges. Two strategies were compared: S1 (real-time connection) lacks customization, while S2 (standardized exchange formats) produces reliable results closely matching traditional BEM ($\sim 2\%$ difference). For pre-existing BIM models, the BIM-to-BEM approach offers key benefits: faster modeling, better integration of architectural and energy design, improved collaboration, and optimized building retrofit processes.

6.2. BIM for photovoltaic (PV) system design

A BIM-based workflow for photovoltaic system design is proposed and tested on two sample buildings with completely different architectural and climatic characteristics. In detail, the selected case studies are (i) B1: “Palazzo Silone”, in L’Aquila (IT), and (ii) B2: “Malaysian Institute of Architects”, in Kuala Lumpur (MY).

Remark. Since we are dealing with two public buildings, the design criterion chosen for the PV systems in question was the maximum exploitation of the available surface, thus providing the opportunity to evaluate the photovoltaic potential of the two case studies, without pre-established constraints.

Phase 1 – Study of the buildings characteristics

B1: “Palazzo Silone”, L’Aquila (IT)

The ground floor of the building occupies approximately 2714 m². The structure is characterized by three volumes with different heights and shapes, which make the roofing of the building extremely complex.

B2: “Malaysian Institute of Architects”, Kuala Lumpur (MY)

The building, appearing as a single parallelepiped with an area of about 525 m² and a uniform height of about 31 m, is configured as a volume with an extremely simple geometry.

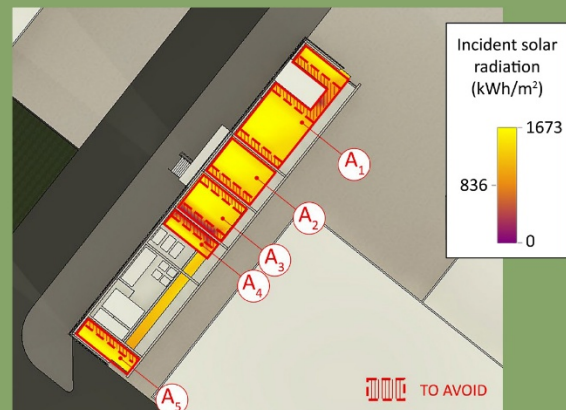
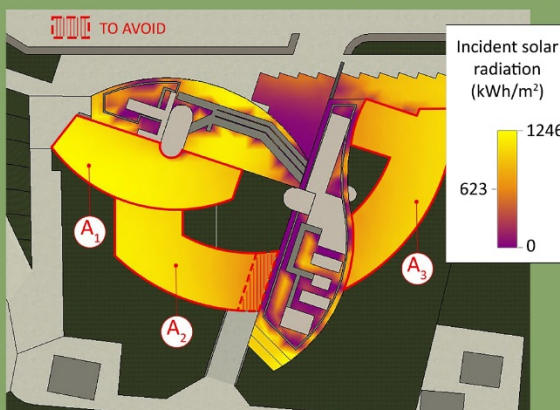
Phase 2 - BIM Modeling

BIM modeling of the two buildings (Figure 16) was performed using Autodesk Revit 2024.



Phase 3 – Solar Analyses

Regarding the Italian building, B1, areas A1, A2, and A3 were found to be the most favorable for the hypothetical installation of a photovoltaic system, with a maximum incident solar radiation of 1246 kWh/m² per year. As for the Malaysian building, B2, the analysis revealed an almost homogeneous photovoltaic potential on the roof, resulting in a maximum incident radiation value equal to 1673 kWh/m² per year.



Phase 4 – “Solution-Matrices” Creation

Different PV design solutions (S_n) were conceived, each characterized by a different choice of quantity, PV technology (T1: Half Cut Cells (HCC), T2: Passivated Emitter and Rear Cell (PERC), T3: Bifacial HCC), positioning, inclination (β), and orientation (θ) of the panels. The S_n were designed on the areas selected on the basis of previous solar analyses. The quantity of panels chosen for each S_n respects the criterion of maximum filling of the selected areas, as far as possible, also taking into account the distances between modules foreseen in some S_n .

The above matrices are composed of a series of elements $A_{i,j}$, where:

- A represents each analyzed parameter, i.e., N = number of panels, P = power of the panels (W), D = distance between panels (cm), Θ = azimuth of panels ($^\circ$), β = tilt of panels ($^\circ$), T = PV technology (1 = HCC, 2 = PERC, 3 = Bifacial HCC);
- i represents the value of the analyzed parameter;
- j indicates the area for installation of the panels, based on the solar analyses (3 for building B1, 5 for B2).

For example, “ $N_{10,1}$ ” indicates that there are 10 panels in area 1.

A total of five “solution-matrices” for building B1 ($S_{1,B1}$, $S_{2,B1}$, $S_{3,B1}$, $S_{4,B1}$, $S_{5,B1}$), and eleven for B2 ($S_{1,B2}$, $S_{2,B2}$, $S_{3,B2}$, $S_{4,B2}$, $S_{5,B2}$, $S_{6,B2}$, $S_{7,B2}$, $S_{8,B2}$, $S_{9,B2}$, $S_{10,B2}$, $S_{11,B2}$), were designed.

$$S_{1,B1} = \begin{pmatrix} N_{220,1} & N_{192,2} & N_{245,3} \\ P_{375,1} & P_{375,2} & P_{375,3} \\ D_{0,1} & D_{0,2} & D_{0,3} \\ \Theta_{18,1} & \Theta_{0,2} & \Theta_{18,3} \\ \beta_{0,1} & \beta_{0,2} & \beta_{0,3} \\ T_{1,1} & T_{1,2} & T_{1,3} \end{pmatrix} \quad S_{2,B1} = \begin{pmatrix} N_{220,1} & N_{192,2} & N_{245,3} \\ P_{375,1} & P_{375,2} & P_{375,3} \\ D_{0,1} & D_{0,2} & D_{0,3} \\ \Theta_{18,1} & \Theta_{0,2} & \Theta_{18,3} \\ \beta_{0,1} & \beta_{0,2} & \beta_{0,3} \\ T_{2,1} & T_{2,2} & T_{2,3} \end{pmatrix} \quad S_{3,B1} = \begin{pmatrix} N_{131,1} & N_{120,2} & N_{151,3} \\ P_{375,1} & P_{375,2} & P_{375,3} \\ D_{50,1} & D_{50,2} & D_{50,3} \\ \Theta_{0,1} & \Theta_{0,2} & \Theta_{0,3} \\ \beta_{35,1} & \beta_{35,2} & \beta_{35,3} \\ T_{1,1} & T_{1,2} & T_{1,3} \end{pmatrix} \quad S_{4,B1} = \begin{pmatrix} N_{131,1} & N_{120,2} & N_{151,3} \\ P_{375,1} & P_{375,2} & P_{375,3} \\ D_{50,1} & D_{50,2} & D_{50,3} \\ \Theta_{0,1} & \Theta_{0,2} & \Theta_{0,3} \\ \beta_{35,1} & \beta_{35,2} & \beta_{35,3} \\ T_{2,1} & T_{2,2} & T_{2,3} \end{pmatrix} \quad \dots *$$

*The complete list of “solution-matrices” is given in section 6.2.6. of Chapter 6.

Phase 5 – PV System Performance Analysis / Phase 6 – Cost-Performance Analysis

The totality of the “solution-matrices” designed were modeled on ACCA’s BIM software, Solaris-PV, to simulate their energy production (Table 3). Subsequently, an embryonic cost-performance analysis of the various simulated solution matrices was performed, based on the costs of the technologies available in the literature (Table 3).

Table 3. Energy simulation results and cost analysis.

Solution Matrix	Total Installed Power	Energy per kW	Total Annual Energy	Cost per kWh of Energy Produced [USD/kWh]
$S_{1,B1}$	246.38 kW	1119.29 kWh/kW	275,765.29 kWh	0.22 USD/kWh
$S_{2,B1}$	246.38 kW	1110.99 kWh/kW	273,720.56 kWh	0.16 USD/kWh
$S_{3,B1}$	150.75 kW	1250.37 kWh/kW	188,493.54 kWh	0.20 USD/kWh
$S_{4,B1}$	150.75 kW	1240.39 kWh/kW	186,988.89 kWh	0.15 USD/kWh
$S_{5,B1}$	150.75 kW	1250.73 kWh/kW	188,547.15 kWh	0.22 USD/kWh
$S_{1,B2}$	34.50 kW	1357.05 kWh/kW	46,818.08 kWh	0.18 USD/kWh
$S_{2,B2}$	34.50 kW	1347.26 kWh/kW	46,480.58 kWh	0.13 USD/kWh
$S_{3,B2}$	23.25 kW	1355.13 kWh/kW	31,506.69 kWh	0.18 USD/kWh
$S_{4,B2}$	23.25 kW	1345.80 kWh/kW	31,289.78 kWh	0.13 USD/kWh
$S_{5,B2}$	23.25 kW	1347.25 kWh/kW	31,323.47 kWh	0.21 USD/kWh
$S_{6,B2}$	21.00 kW	1353.87 kWh/kW	28,431.18 kWh	0.18 USD/kWh
$S_{7,B2}$	21.000 kW	1355.10 kWh/kW	28,457.04 kWh	0.18 USD/kWh
$S_{8,B2}$	21.00 kW	1343.04 kWh/kW	28,203.89 kWh	0.13 USD/kWh
$S_{9,B2}$	21.00 kW	1344.50 kWh/kW	28,234.57 kWh	0.13 USD/kWh
$S_{10,B2}$	21.00 kW	1343.80 kWh/kW	28,219.90 kWh	0.21 USD/kWh
$S_{11,B2}$	21.00 kW	1346.48 kWh/kW	28,276.15 kWh	0.21 USD/kWh

Conclusions

The proposed workflow establishes a standardized, repeatable process that supports professionals through every project phase, from initial concept to detailed design. Tested on two architecturally and geographically distinct case studies (B1 and B2), the methodology demonstrates that BIM is capable of rapidly assessing multiple design strategies that would be difficult to evaluate manually. The results show that factors such as orientation, inclination, photovoltaic technology, and climate significantly affect system performance. In light of this, BIM has proven to be a fundamental tool for making strategic design choices, capable of optimizing the system and ensuring a good balance between energy production and costs. In a context where regulations on energy saving and reducing environmental impact are increasingly stringent, BIM could be a tool offering great support for the ecological transition.

A future development of the research could be to work on the flexibility of the workflow, testing it on other case studies, and foreseeing the use of BIM tools that are different from those employed in this contribution.

6.3. BIM-based Digital Twin for monitoring and optimization

A workflow for creating a Digital Twin of an existing building is proposed, while simultaneously experimenting with the "Living Lab" concept in an office building also used as an academic laboratory.

Phase 1 - Physical Building study

The case study chosen for experimentation is the "Solar House", a building already described in section 6.1.

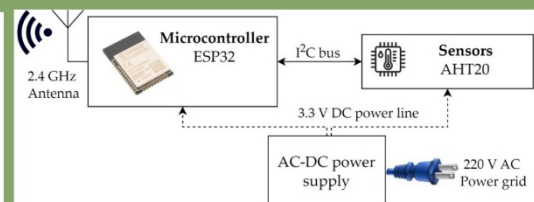
Phase 2a - Wireless Sensors Nodes (WSN) configuration

A two-week monitoring campaign was conducted in four spaces—the hallway, lighting laboratory, and two offices—each with different uses and occupancy patterns. In accordance with ISO 7726 [71], sensors were placed to reflect the same thermal conditions experienced by occupants. The block scheme of the monitoring system employed in this work is shown below on the left.

The monitoring system uses Wi-Fi-enabled sensor nodes powered by the electrical grid via DC supplies, eliminating the need for batteries. Sensor data are transmitted over the existing office Wi-Fi network via HTTPS to the Tandem platform, which serves as a database and provides access through a user front-end. The sensor nodes are structured as shown below on the right.



SCHEME OF THE MONITORING SYSTEM



STRUCTURE OF SENSOR NODES

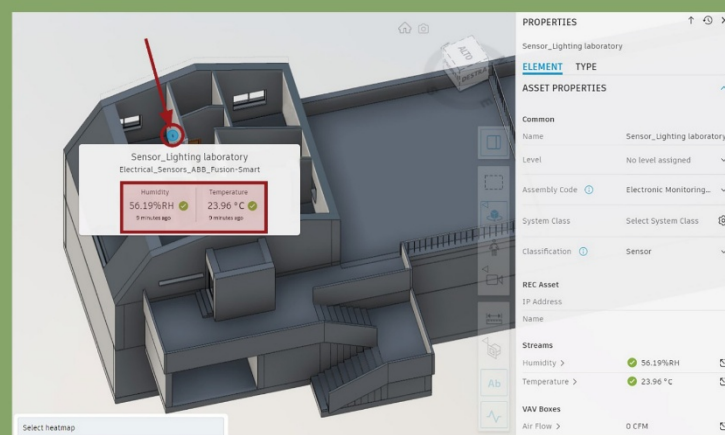
A core ESP32 microcontroller [73], by Espressif, periodically retrieves information from the sensors, which are of the type AHT20 [74], from Asair. Data are encapsulated in JSON format and transmitted using POST requests. If the request is not successful, it is repeated after a guard time period. If the network connectivity is not available, the sensor nodes enter a sleep mode and the connection attempts loop.

Phase 2b - BIM modeling

The BIM model of the building was created with Autodesk Revit 2023, chosen due to its versatility in modeling various types of buildings and its adaptability to a wide range of studies [79].

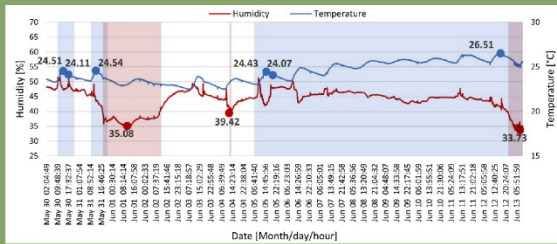
Phase 3 - Digital Twin Creation

Autodesk Tandem was used to create the digital twin of the building under investigation. The choice of middleware tool is linked to the fact that Tandem and Revit are released by the same software company, which favors the interoperability process and makes Tandem able to read the BIM model correctly. Tandem consists of an online accessible platform that allows you to create an ecosystem in which all the resources, spaces, and systems of the building are related to each other.

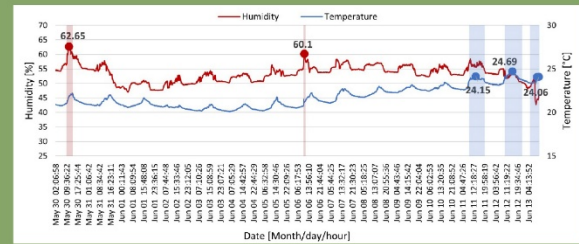


Results and Discussion

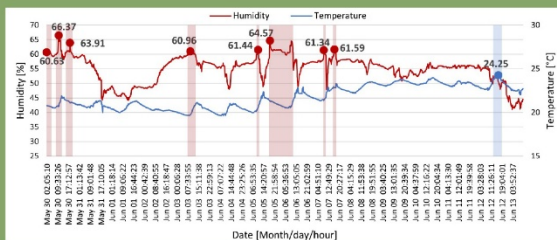
Below is a correlation between the recorded temperature and humidity data, highlighting the peaks reached in the time intervals in which the values exceeded the limits imposed by the current decree.



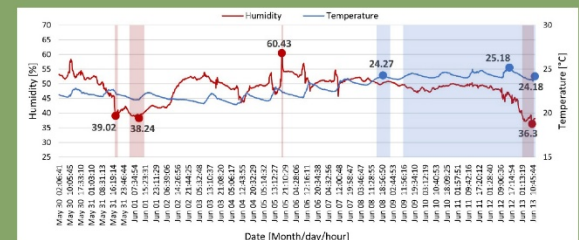
HALLWAY



LIGHTING LABORATORY



OFFICE 1



OFFICE 2

The study revealed the following.:

- The hallway has the lowest humidity and the highest temperature values. The high temperature is probably due to the fact that the hallway occupies a central position inside the building and, for this reason, is not affected by heat losses through the envelope. The dryness of the environment is a direct consequence of the high temperature found there.
- On the contrary, office 1 presented the highest humidity and lowest temperature values. This is linked to the presence of large glazing in the room, which favored heat dispersion in a period of the year when the external temperature was still relatively low.
- In any case, by averaging the humidity and temperature values recorded during the two weeks of monitoring for all the rooms under examination, it can be noted that the values recorded every 10 min fell within the limits imposed by the national decree in force, except in the case of the hallway, in which the average value of temperature exceeds the threshold of 0.38 °C. To have an even broader vision of the situation, it would be advisable to repeat the monitoring during the summer and winter periods.

During monitoring, the DT helped in the constant display of the parameters in a simple and quick way, allowing continuous updating on the thermo-hygrometric condition of the different rooms at any time, even remotely. The developed DT lays the foundation for future implementations of the system capable of promoting both proactive and corrective maintenance interventions, guiding facility managers in identifying the most appropriate energy efficiency strategies. On the proactive maintenance level, for example, the DT allows to instantly identify the presence of anomalies ensuring an immediate intervention by the facility managers in case of need.

Conclusions

Efficient building energy management requires jointly assessing energy use and indoor thermal conditions. This study proposes a standardized workflow for creating a BIM-based Digital Twin (DT) that integrates real-time monitoring data to identify design weaknesses, reduce heat loss, and optimize energy performance. Tested on an office “Living Lab,” the system enhances data visualization, supports digitalization of the construction sector, and strengthens the link between physical and virtual environments.

Future developments should involve conducting repeated monitoring at different times of the year also including other parameters influencing the IEQ index, in order to gain a broader understanding of the building performance.

Further advancements could consist of exploiting the DT for predictive analyses and real-time simulations, integrating monitoring sensors with digital technologies, such as BIM, DT, Internet of Things (IoT), and Artificial Intelligence (AI).

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7. INTEGRATED MULTISCALE DISCUSSION

7.1 INTERACTIONS BETWEEN COMPONENT, WALL, AND BUILDING SCALES

This research adopts a multiscale approach that demonstrates how analyses conducted at each level (component, wall, and building) are fundamentally interdependent in determining overall building energy performance. Localized design choices propagate upward through the system, influencing the thermal behavior of wall assemblies and, ultimately, the energy efficiency of the entire building. At the same time, building-level performance requirements and modeling outcomes feed back into lower-scale decision-making, guiding the optimization of components and construction strategies. The result is a continuous, bidirectional chain of cause-and-effect relationships, in which each scale shapes and is shaped by the others, reinforcing the need for an integrated perspective in the pursuit of high-performance, energy-efficient architecture.

At the component-level, additive manufacturing experiments reveal how the internal geometry and filler materials of 3D-printed blocks influence their thermal behavior. The finding that honeycomb-inspired geometries and natural fillers significantly reduce U-values is not only relevant for building block optimization but also crucial for larger scales. These component-level improvements directly influence the thermal behavior of wall assemblies, meaning that even small geometric refinements at the micro level can lead to measurable differences at the meso level. Furthermore, limitations encountered at the building level, such as the failure to achieve high-performance envelope standards, provide an important basis for guiding future component development.

Moving to the wall-scale, the study evaluates the thermal behavior of the building envelope and the degree of accuracy with which this behavior can be measured. A comparison of HFM and IRT methods shows that accurate thermal characterization depends on the ability to capture the true effects of the stratigraphic package that constitutes the wall (in terms of geometry and materials). This reinforces the need for tight integration between scales: wall-scale assessments must be sensitive enough to validate component-level advances and provide reliable input for building-scale energy modeling.

At the building-scale, the importance of this integration becomes even more evident. The reliability of entire building simulations depends on the accuracy of wall-scale measurements, which in turn depends on the thermal behavior of the components. Conversely, building-scale modeling provides critical information at lower scales: design constraints, energy objectives, and retrofit priorities help guide future component research toward geometries and materials that meet building-level performance objectives.

Across all phases, the research shows that no scale can be optimized in isolation. The multiscale integration establishes a continuous, iterative workflow where improvements at one scale amplify those at the others, ultimately enabling the development of smarter, more efficient, and more resilient buildings.

7.2 PRACTICAL IMPLICATIONS AND TECHNOLOGICAL TRANSFER

The findings of this research have significant practical implications, demonstrating how innovations at the component, wall, and building levels can be translated into the construction industry.

At the component-level, additive manufacturing represents a flexible method for producing thermally optimized building elements. The experimental results obtained at this scale can guide the prefabrication of customized envelope components, enabling designers and manufacturers to meet specific energy performance requirements while simultaneously reducing the building system's environmental impact.

At the wall-level, the study emphasizes the crucial importance of accurate and reliable thermal assessment. Each method studied has advantages and disadvantages, and therefore, the choice of approach should be guided by the intended application, required accuracy, and environmental controllability.

At the building-scale, research highlights the key role of BIM in the energy transition in buildings, as a tool capable of providing support throughout a building's entire life cycle, from design to demolition or renovation. Potential BIM-BEM interoperability allows for energy considerations to be integrated right from the conceptual design stage, facilitating the designer's evaluation of design alternatives that best integrate energy and architectural aspects, thus complying with current regulatory requirements. Furthermore, the definition of BIM-based workflows for the design of PV systems or for the creation of digital twins for environmental monitoring can offer standardized procedures capable of promoting the use of the tool in the professional field and encouraging the digitalization of the construction sector.

7.3 RELEVANCE FOR INDUSTRY AND MARKET

As regards the findings of the studies conducted at the scale of the building component, they have implications for the construction and building materials industry, particularly at a time when the market is actively seeking sustainable, high-performance, and customizable solutions. By showing that additive manufacturing can be used to create building blocks with complex internal geometries, the work opens up new possibilities for the production of insulation components that would be difficult or too expensive to produce using traditional methods. This positions 3D printing not only as a prototyping tool, but as a realistic production path for customized, high-performance building envelope systems. An important aspect of this research is the demonstration that significant improvements in the thermal performance of building components can be achieved through geometric optimization. Refined and biomimetic designs improved thermal behavior without increasing the amount of material required. For industry, this is particularly valuable because it means manufacturers can improve product performance while keeping material costs low and reducing environmental impact: two priorities that align well with the growing focus on eco-design and resource-efficient construction. The integration of natural waste materials as insulating fillers adds another dimension of market relevance. Materials such as sawdust, hemp, and sheep's wool have significantly improved the thermal performance of engineered building blocks, in some cases reducing their thermal transmittance by more than half. Because these materials are affordable, abundant, and environmentally friendly, they align with the construction industry's transition to circular economy practices and low-carbon building products. The results achieved with sheep's wool, in particular, highlight the potential for high-quality, bio-based insulation solutions that also deliver high performance. More generally, the study addresses several key trends shaping today's construction market: the demand for energy-efficient buildings, the need for customizable solutions, and the push toward automated, low-waste production. The ability to optimize a component's thermal performance simply by modifying its internal geometry offers manufacturers a powerful and scalable design strategy that directly addresses these trends. The work also opens up practical opportunities for the development of new commercial products. The concept of 3D-printed insulation blocks, either hollow or filled with natural fibers, could lead to factory-produced components tailored to local climate requirements. While current prototypes require further development before they can be used structurally on a large scale, the study provides a solid technical foundation for future innovation, especially with the continued growth of large-format 3D printing in construction. In summary, this work demonstrates that additive manufacturing, combined with careful design and sustainable insulation materials, can produce a new generation of thermally optimized and environmentally friendly building components. This makes the research directly relevant to ongoing industrial efforts to modernize construction methods, reduce carbon footprints, and meet evolving energy efficiency standards.

Moving on to the wall scale, the study conducted has practical relevance for the building and construction industry because it deals with a key issue that affects energy performance, regulatory compliance, and the overall sustainability of buildings: accurately determining the thermal transmittance, or U-value, of building components. As energy efficiency standards become stricter around the world, manufacturers, designers, energy auditors, and regulatory bodies all need dependable ways to measure and verify how well walls and building envelopes perform. The more reliable these measurement methods are, the easier it is for companies to certify their products, optimize new materials, and demonstrate compliance with increasingly demanding regulations such as Nearly Zero Energy Building (NZEB), Energy Performance of Buildings Directive (EPBD) directives, and national energy codes. The study's comparison of two different experimental techniques—

HFM and IRT—directly addresses this industrial need. Each method comes with different costs, levels of invasiveness, speed, and accuracy. Understanding their strengths and limitations helps companies select the right technique for their specific context. For example, the HFM method proved to be the most accurate and robust, making it suitable for manufacturers who require high-precision laboratory testing when validating new wall assemblies or insulation systems. The Q-IRT method, although less precise due to the accuracy limitations of the camera, still showed promising results under controlled conditions. This is valuable for industry because thermography offers a quick, non-invasive way to evaluate buildings without cutting into walls or disturbing occupants. Its ability to provide rapid, contactless assessments makes Q-IRT attractive for building diagnostics, quality control during construction, and large-scale energy audits—including those required for public buildings or refurbishment projects. As thermographic technology continues to improve, companies and energy service providers may increasingly rely on it for routine U-value verification, especially when time or accessibility issues make traditional HFM measurements impractical. Finally, the study is particularly relevant to the growing segment of the market focused on sustainable and bio-based construction. For these manufacturers, demonstrating the real thermal performance of their assemblies is essential for gaining market credibility, satisfying certification schemes like Passivhaus or Leadership in Energy and Environmental Design (LEED), and supporting consumer trust in natural, low-carbon materials. By providing a full-scale, controlled comparison of measurement methods, the research helps ensure that the industry can evaluate such products accurately, consistently, and transparently.

Finally, the relevance of the building-scale study to the construction industry is quite significant, especially as the sector continues to shift toward digitalization, energy efficiency, and integrated project delivery. BIM has already become a standard tool in architecture and construction because of its ability to organize information and streamline collaboration, but its actual potential in the energy-design market is far from fully exploited. What this research shows is that a more seamless link between BIM and Building Energy Modeling could transform the way buildings are designed, analyzed, renovated, and even managed throughout their life cycle. To date, energy modeling is often treated as a separate task carried out late in the design process or even after construction, which makes it harder to adjust architectural decisions based on performance outcomes. By exploring how BIM can form a solid foundation for BEM modeling, the study highlights a pathway for the industry to move toward a truly integrated design workflow—one where energy considerations can influence design choices from the very beginning. This is increasingly important for markets under pressure from stricter energy regulations, carbon-reduction goals, and certification schemes like LEED and national NZEB directives. What gives this work relevance is its focus on the practical challenges of interoperability.

Furthermore, the study on the integration of BIM in photovoltaic (PV) system design represents an advancement for both the construction and renewable energy sectors. As energy efficiency and decarbonization targets become increasingly stringent globally, public and private stakeholders require tools that ensure precise, cost-effective, and sustainable PV deployment. The BIM-based workflow presented in this study addresses these needs by providing a standardized, replicable approach that bridges architectural design, energy modeling, and economic evaluation. From an industry perspective, the workflow enables faster design iterations and multi-scenario analyses, supporting developers, engineers, and policymakers in identifying the most effective intervention strategy. At the policy level, BIM-facilitated PV design aligns with international energy and environmental strategies, enabling compliance with regulations, accelerating renewable energy adoption, and supporting national decarbonization goals. In summary, the BIM-based PV design workflow offers a comprehensive solution for the evolving market needs of the renewable energy sector, combining technical accuracy, economic viability, and policy compliance. Its adoption can accelerate the deployment of photovoltaic systems in public and private buildings, contributing to sustainable energy targets and supporting the transition toward a low-carbon built environment.

Finally, the development of a methodology for the creation of a Digital Twin (DT) based on BIM is interesting for the construction and building management sectors. Traditional building monitoring methods are often fragmented, labor-intensive, and limited to static assessments. In contrast, the integration of BIM, DT, and IoT technologies enables real-time monitoring, predictive analytics, and data-driven decision-making, significantly enhancing operational efficiency and energy performance. By providing a continuous digital representation of

a physical building, DTs allow facility managers, designers, and engineers to optimize energy use, identify anomalies, and plan maintenance proactively. By combining WSN sensors, BIM modeling, and cloud-based platforms, the workflow ensures seamless data acquisition, visualization, and management. This approach reduces errors, accelerates project timelines, and supports compliance with energy efficiency and occupational comfort standards, making it highly relevant for public, commercial, and research-oriented building projects. Moreover, the experimental application of the workflow in an office building demonstrates its practical value in implementing the “Living Lab” concept, where real-time building data can inform iterative improvements and energy retrofit interventions. Beyond individual buildings, DTs hold potential for urban-scale applications, enabling smart city initiatives through integrated monitoring, predictive simulations, and AI-driven analysis. The adoption of DTs is expected to accelerate the digitalization of the construction sector, improve collaboration among stakeholders, and optimize the lifecycle management of buildings, aligning with global sustainability targets and the growing demand for intelligent, responsive infrastructure.

7.4 FUTURE PERSPECTIVES IN MULTISCALE BUILDING DESIGN

The multiscale framework explored in this research opens a number of future directions that can advance both scientific research and industrial practice. One of the most promising developments lies in strengthening the continuity between component-level design, wall-level characterization, and building-level modeling. Today, these scales often remain partially disconnected, with data and decisions flowing in only one direction. In the coming years, the emphasis will likely shift toward the creation of fully integrated digital workflows, where the properties of building components and architectural elements flow seamlessly upward into whole-building simulations, and where building-level performance objectives, in turn, guide microscale design choices. This two-way exchange of information could enable a more iterative and predictive design process, where each scale is continually recalibrated based on the evolving requirements of the others.

Additive manufacturing will play an important role in this evolution. As large-scale 3D printing technologies advance, it will become possible to manufacture components whose internal structure varies based on local heat transfer requirements, or even to integrate sensors directly into the printed elements. This could lead to the development of intelligent and adaptive building components capable of monitoring their own thermal behavior and communicating directly with digital models at higher scales.

At the wall level, future research will benefit from improved thermal characterization tools. The analysis presented in this article highlights both the strengths and limitations of current nondestructive methods. In the future, hybrid techniques that combine the low invasiveness of IRT with the precision of contact systems such as HFM could offer an excellent alternative to traditional analysis systems.

Building-scale modeling, already undergoing rapid digital transformation, will continue to evolve toward more interoperable, automated, and data-rich environments.

Photovoltaic system integration is another area where future advances are expected. BIM-based photovoltaic modeling will expand from building-specific analyses to city-scale solar assessments, connecting BIM, Geographic Information System (GIS), and real-time monitoring platforms

Perhaps the most transformative future direction concerns the evolution of BIM-based digital twins. As sensing technologies become cheaper and more pervasive, digital twins will shift from static dashboards to dynamic, predictive systems capable of optimizing building performance autonomously, through the use of technologies such as machine learning.

Overall, these prospects suggest that the next major advances in building design will not come from isolated innovations, but from the convergence of thermal analysis at the component and architectural element scale, digital modeling, sensing technologies, and multiscale reasoning. As these sectors become more interconnected, buildings will be conceived, constructed, and operated within a much more integrated digital ecosystem, enabling higher performance, lower environmental impact, and a more resilient and intelligent built environment.

SUMMARY

7.1. Interactions between component, wall, and building scales

This research highlights a multiscale approach to building energy performance, demonstrating that component-, wall-, and building-level analyses are closely interdependent. Component-level innovations, such as 3D-printed blocks with optimized geometries and natural fillers, directly improve the thermal behavior of walls, which in turn impacts the overall building efficiency. Accurate wall-level measurements are essential to validate these component improvements and provide reliable building-level simulations. Conversely, building-level modeling provides feedback that guides the design of wall components and assemblies to achieve energy performance objectives. The study demonstrates that no scale can be optimized in isolation; instead, a continuous, iterative workflow across scales is necessary to develop smarter, more efficient, and more resilient buildings.

7.2. Practical implications and technological transfer

This research demonstrates clear practical implications for the construction industry. At the component-level, 3DP enables the creation of thermally optimized elements, with honeycomb-inspired geometries and sustainable fillers like wood, sheep's wool, or hemp, significantly reducing thermal transmittance and supporting customized, eco-friendly prefabrication. At the wall level, accurate, non-destructive thermal assessment methods—HFM and IRT—are essential for validating component performance and ensuring reliable integration into full-scale assemblies. At the building scale, BIM facilitates energy-efficient design throughout a building's life cycle, with BIM-BEM interoperability supporting early-stage energy optimization, PV system design, and Digital Twin-based monitoring. Together, these findings provide a practical framework for translating multiscale research into energy-efficient, sustainable, and digitally integrated building practices, offering a pathway for technological transfer and innovation in the construction sector.

7.3. Relevance for industry and market

The studies conducted have a significant impact on the world of industry and the market.

Component Level

- 3D printing, allowing the creation of complex shapes, is positioned not only as a prototyping tool, but also as a realistic production path for customized, high-performance building envelope systems.
- The use of natural fillers (such as sawdust, hemp, sheep's wool) can significantly reduce the thermal transmittance of the building envelope, while minimizing the environmental impact and promoting circular economy practices.
- The ability to optimize a component's thermal performance simply by modifying its internal geometry offers manufacturers a powerful and scalable design strategy that directly addresses these trends.

Wall Level

- Accurate U-value measurements are essential for regulatory compliance, energy certification, and market credibility.
- Comparing measurement methods helps manufacturers, companies, and professional firms choose the most appropriate approach for their circumstances.
- Knowing the limits of the approaches can help companies avoid errors in certification processes and push for improved or updated versions of the method.

Building Level

- BIM is a key tool for the digitalization of the construction sector.
- BIM-BEM interoperability allows energy considerations to be integrated early in the design process, improving performance-driven decisions.
- Standardized BIM workflows support efficient PV system design, multi-scenario energy modeling, and cost-performance optimization.
- BIM-based Digital Twins enable real-time monitoring, predictive analytics, and data-driven building management.
- BIM supports lifecycle management, retrofit planning, and compliance with energy efficiency and sustainability standards.

7.4. Relevance for industry and market

The research points to future progress through stronger integration across component, wall, and building scales via fully connected digital workflows. Advances in additive manufacturing, improved thermal characterization methods, interoperable building-scale models, BIM-based photovoltaic analysis, and dynamic digital twins are expected to support more predictive, data-driven design and operation. Overall, the convergence of multiscale thermal analysis, digital modeling, and sensing technologies is likely to enable more efficient, intelligent, and environmentally resilient buildings.

8. CONCLUSIONS

Across the three scales analyzed—component, wall, and building—this research demonstrates how energy-conscious design, experimental validation, and digital modeling can provide a coherent path toward more efficient and intelligent building design. From an energetic perspective, the work highlights how improvements at the micro-scale can propagate measurable benefits at the macro-scale in terms of operational energy use, peak load reduction, and long-term sustainability.

At the component scale, the study confirms the significant potential of additive manufacturing for the production of thermally efficient building elements with direct implications for energy demand reduction. By experimentally testing different internal geometries and natural insulating fillers, it was demonstrated that geometric refinement strongly influences thermal behavior: complex honeycomb-inspired structures achieved significantly lower U-values than simpler configurations, thereby reducing heat losses through the envelope. The benefits were further amplified when the cavities of the 3D-printed blocks were filled with bio-based insulation, with sheep's wool reducing thermal transmittance by more than half compared to the same unfilled prototype. These improvements can be associated with a substantial decrease in operational energy demand and, consequently, with a meaningful reduction of operational carbon emissions over the building life cycle. From an energy perspective, these reductions translate into lower heating and cooling loads, improved internal thermal stability, and potential downsizing of HVAC systems. In addition, the adoption of bio-based fillers supports a further decrease in embodied emissions, strengthening the overall carbon mitigation potential of the component. While these results do not yet match the performance of high-performance envelope systems, they validate theoretical predictions regarding the relationship between thermal resistance, cell morphology, and material selection. Furthermore, the use of bio-based fillers introduces additional energy benefits in terms of embodied energy and lifecycle performance, indicating a promising direction for future 3D-printed building components. Future research should focus on developing new geometries, exploring alternative sustainable fillers and printing materials, and evaluating the mechanical performance of the blocks under real operating conditions to test the real applicability of 3D printing in the building sector.

At the wall scale, the study provided experimental benchmarking of two techniques for assessing thermal transmittance under controlled laboratory conditions, a critical step for ensuring energy reliability in building design. Accurate U-value measurement is essential for calibrating simulation models, predicting building energy consumption, and verifying compliance with energy performance regulations. The Heat Flux Meter (HFM) method emerged as the most reliable, offering the closest agreement with theoretical values, while infrared thermography (IRT) provided comparable results but with greater uncertainty. These findings underline the importance of robust diagnostic methods for minimizing the performance gap between design-stage energy predictions and real operational behavior. Reliable wall-scale measurements ensure that innovative components effectively deliver the expected reductions in heat loss and energy demand when integrated into full envelope assemblies. By reducing the gap between predicted and actual performance, accurate U-value assessment indirectly contributes to avoiding unnecessary energy use and the associated carbon emissions during building operation.

At the building level, the research evaluated digital methodologies essential for contemporary energy design: BIM-BEM interoperability, BIM-based photovoltaic (PV) system modeling, and BIM-enabled Digital Twins (DT). The interoperability study clearly demonstrated that standardized exchange formats (IFC, gbXML) provide a robust and accurate strategy for transferring geometric and thermal information between architectural and energy simulation environments when dealing with buildings with simple geometry. Compared to traditional modeling, the BIM-derived energy model produced nearly identical annual energy consumption results, while also reducing modeling time and improving coordination between architectural and energy aspects. More reliable and consistent energy modeling enables early identification of low-carbon design strategies and supports systematic reductions in operational emissions across the building life cycle. Future research will investigate the applicability of the "BIM to BEM" approach to more complex building geometries and seek to optimize the real-time connection strategy to integrate the architectural and energy models into a

single environment. Similarly, the BIM-based workflow developed for photovoltaic system design enabled integrated assessments of climate, orientation, tilt, and technology, supporting energy strategies aimed at on-site renewable generation, self-consumption maximization, and reduction of grid dependency. This directly translates into avoided carbon emissions by replacing grid-supplied electricity with on-site renewable energy. Tests on two case studies confirmed that BIM offers a level of consistency and adaptability unreachable with conventional and fragmented photovoltaic design tools. In the future, BIM-based photovoltaic modeling will expand from building-specific analyses to city-scale solar assessments, integrating BIM, Geographic Information System (GIS), and real-time monitoring platforms into a single workflow. The Digital Twin experiment further expanded building-level analysis by integrating real-time monitoring with a BIM model to create a dynamic representation of a living laboratory building. This system not only supported the continuous assessment of indoor environmental conditions but also demonstrated the potential of digital twins to simplify data interpretation, improve user accessibility, and lay the foundation for predictive and automated energy management. This approach lays the foundation for dynamic energy optimization, fault detection, and predictive control strategies that can reduce energy waste, smooth out peak loads, and improve occupant comfort. Such capabilities are strongly linked to continuous operational emission reductions through more efficient and adaptive building management. While still in the early stages of digital twin maturity, the findings highlight the transformative impact that sensor networks, BIM, Internet of Things (IoT), and Artificial Intelligence (AI) could collectively have on optimizing building performance.

Taken together, the findings across all three scales underline a common trajectory: from the micro-scale optimization of 3D-printed geometries, to the meso-scale verification of thermal behavior, and finally to the macro-scale integration of comprehensive digital tools, each level reinforces the next. The component-scale innovations require accurate wall-scale measurement for validation, and both are essential inputs for reliable building-scale digital modeling. At the same time, building-scale modeling provides critical information at lower scales: design constraints, energy objectives, and retrofit priorities help guide future component research toward geometries and materials that meet building-level performance objectives. Ultimately, this multiscale approach demonstrates that advancing energy-efficient construction requires not isolated improvements, but a continuous energy-driven chain of innovation—linking materials, measurements, and digital intelligence into a unified and interoperable workflow capable of supporting low-energy, low-carbon, and intelligent buildings of the future.

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