Politecnico di Torino

Master's Degree in Building Engineering
A.y. 2024/2025
March 2025

Implementing Building Information Modeling Solutions for Sustainable Development in Mountainous Regions

The case study of Valle Cervo

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Abstract

This thesis explores the application of Building Information Modeling (BIM) to foster sustainable development in mountainous regions, focusing on the historic town of Rosazza in Valle Cervo, Italy. It investigates how BIM enhances energy efficiency, architectural preservation, and community involvement within challenging geographic and climatic contexts.

By integrating BIM with Geographic Information Systems (GIS) and advanced simulation techniques, the research highlights BIM's dual role in optimizing building performance and supporting cultural heritage preservation. The proposed methodological framework combines energy modeling, structural analysis, and visualization of conservation interventions, offering an innovative renovation strategy for managing building lifecycles in remote areas.

The study addresses the unique challenges posed by Rosazza's rugged terrain and historical infrastructure, demonstrating how BIM minimizes energy consumption through thermal dynamics modeling and renewable energy integration. It emphasizes how BIM-driven projects foster local engagement and collective sustainability efforts.

Rosazza serves as a model for similar communities, showing how BIM supports heritage preservation while promoting green building practices. The different data domains developed in this thesis are integrated into an ontology to improve data management and interoperability. This work lays the foundation for future research, representing a first step towards the development of an urban digital twin.

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1. Introduction

Building Information Modelling (BIM) is now a global digital technology which is widely believed to have the potential to revolutionize the construction industry. This has been mainly a result of worldwide government initiatives promoting BIM uptake to improve efficiency and quality in delivering construction projects. This push has been accompanied by the release of a tremendous amount of BIM software systems which are now available in the market [1]. This master's thesis delves into the multifaceted implications and applications of BIM in fostering sustainable development within the unique environmental and socio-cultural landscape of mountainous regions, focusing specifically on the historic town of Rosazza, located in the Piedmont region of Italy. This study meticulously illustrates how BIM serves not only as a cornerstone technology that revolutionizes traditional building practices, addressing contemporary environmental challenges but also preserving cultural heritage. BIM adoption has the potential to improve building design, construction coordination, productivity, facility management, cost estimate accuracy while reducing clashes (up to 10%), omissions, construction time (up to 7%) and overall project cost [2].

Mountainous regions such as Rosazza present distinctive challenges and opportunities for sustainable development. The rugged terrain, variable climates, and often remote locations require innovative approaches to design and construction that can adapt to intense environmental conditions while respecting the delicate ecological balance. Additionally, these regions often harbor communities with rich historical backgrounds and architectural legacies that necessitate sensitive approaches to modernization and energy efficiency. In addressing these challenges, BIM emerges as a pivotal tool, offering precise modeling capabilities, real-time data integration, and collaborative project management functionalities that enhance both the efficiency and sustainability of construction projects.

At the forefront of architectural innovation, BIM extends beyond mere modeling to encapsulate a comprehensive management tool that supports the entire lifecycle of a building, from initial design through to construction, maintenance, and eventual decommissioning. The core strength of BIM lies in its ability to integrate multidimensional data—spanning geometric, temporal, and cost analyses—into a cohesive model that stakeholders across various disciplines can utilize to make informed decisions. This integrative approach facilitates a deep understanding of a building's performance, including its energy consumption, structural integrity, and environmental impact, which is crucial for achieving sustainability in challenging environments.

Rosazza provides a compelling case study due to its historical significance and challenging geographic location. The town is characterized by its historic buildings and infrastructure, which are integrated into a landscape that poses both climatic and logistical challenges for modern engineering. The application of BIM in Rosazza demonstrates its capacity to enhance architectural preservation, improve energy efficiency, and foster community engagement in sustainable practices. Through detailed simulations and analyses, BIM enables the identification of optimal retrofitting strategies that align with both conservation goals and modern energy standards, presenting a balanced approach to enhancing building performance while maintaining architectural integrity.

This thesis adopts a mixed-methods approach, employing both qualitative assessments and quantitative BIM simulations to explore the effectiveness of BIM technologies in mountainous, historic settings. The methodology encompasses a detailed examination of BIM's capabilities in energy modeling, structural analysis, and heritage conservation, supported by case studies and primary data collected from Rosazza. By integrating BIM with Geographic Information Systems (GIS) and other digital tools, the research provides a nuanced understanding of how advanced technologies can be harmoniously woven into the fabric of historical preservation and environmental stewardship.

The findings of this research are expected to contribute significantly to the discourse on sustainable development in mountainous regions, offering practical insights and methodologies that can be applied in similar contexts worldwide. The thesis not only underscores the adaptability and utility of BIM in managing complex construction projects but also highlights its role in promoting collaborative and informed decision-making among stakeholders. Ultimately, this study aims to pave the way for future research and implementation of BIM in heritage conservation and sustainable urban planning, providing a robust framework that other regions can adapt to reconcile the demands of modernity with the imperatives of conservation and sustainability.

By situating the discussion within the context of Rosazza, the research addresses specific local challenges and contributes to a broader understanding of how BIM can be effectively utilized to meet the diverse needs of mountainous regions, ensuring that development is both sustainable and respectful of historical and cultural legacies. This comprehensive exploration of BIM as a transformative technology in the field of sustainable construction and heritage conservation sets a benchmark for future initiatives in similar environments.

2.Background

During the last decades, society has increasingly moved towards the adoption of digital solutions in almost every aspect of people's lives with the aim of enhancing daily activities. At the same time, the environmental impact of the built environment has attracted the attention of public opinion that is gradually perceiving the necessity of limiting its negative effects in order to safeguard the Earth and people's wellbeing [7]. Building Information Modeling (BIM) is revolutionizing the architecture, engineering, and construction (AEC) industries by integrating digital technologies into the entire building lifecycle. More than just a 3D modeling tool, BIM serves as a collaborative methodology that enhances efficiency, reduces errors, and improves decision-making from initial design through construction and facility management.

This chapter explores the definition and evolution of BIM, tracing its journey from early CAD-based systems to today's data-driven, multi-dimensional models. It also delves into the key components and technologies that form the backbone of BIM, including parametric modeling, data centralization, and real-time collaboration.

Furthermore, the chapter highlights BIM's role in sustainable development, emphasizing its impact on energy efficiency, heritage conservation, and infrastructure optimization. By integrating BIM with emerging technologies like digital twins, AI, and IoT, the construction industry is advancing toward smarter, more sustainable built environments.

This overview sets the stage for a deeper understanding of BIM's transformative capabilities and its growing importance in shaping the future of the built environment.

2.1 Definition and Evolution of BIM

Definition of BIM

Building Information Modeling (BIM) is more than just a digital representation of a physical building; it is a transformative methodology that encompasses the entire lifecycle of a building, from conceptual design through construction, operations, and even demolition or repurposing. BIM leverages 3D models as the core of its process, but it also incorporates multiple dimensions of data (4D time, 5D cost, and beyond) to facilitate efficient planning, design, construction, and management of buildings and infrastructure. This enables stakeholders across various disciplines—such as architects, structural engineers, mechanical engineers, contractors, and facility managers—to work collaboratively on a unified model that serves as a central repository of information. Building Information Modelling (BIM) can help to perform LCA during the design process. Current BIM-LCA approaches follow two trends. Either they use complex models in detailed design phases, when it is late for major changes, or they are based on simplified approaches only applicable in early design stages. [3].

Figure 1 illustrates how BIM integrates various aspects of construction, management, and operations, highlighting its role in improving collaboration and efficiency across disciplines.

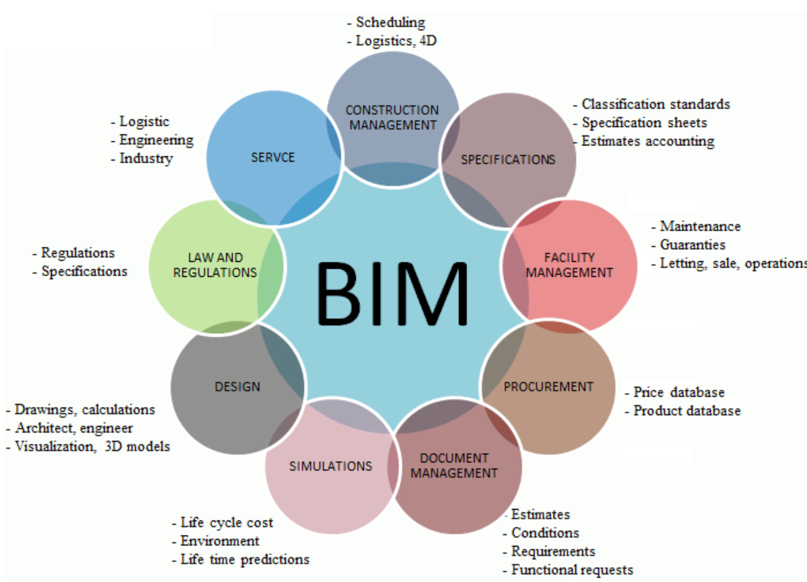


Figure 1:BIM framework [15].

The core philosophy of BIM is integration: it ties together architectural design, structural analysis, material performance, and energy use in a single digital environment. To the theoretical aspects, new BIM tools need to be developed for assessing related sustainability criteria throughout the project's life cycle, including the materials used and energy-consumption aspects [4]. BIM models do not just represent the geometric aspects of a building but also capture its spatial, structural, and functional details. BIM software tools can be used for modeling building elements and carrying out energy optimization techniques. BIM-based building geometry data can also be used to visualize simulation models and results in building performance simulation (BPS) tools[5]. These models are parametric—meaning they are driven by parameters that describe their geometry and behavior. For example, a window is not just a shape; it has information about its material, insulation values, manufacturer details, and even its cost. If one aspect of the design changes, such as the window size, all related data (including adjacent walls and mechanical systems) update automatically. The key factors identified in the process of retrofitting buildings should be considered regarding their condition [5].

This shared resource enables better decision-making, minimizes errors, and facilitates coordination, which reduces delays and project costs. Traditional 2D CAD systems, while useful for drafting, do not offer this level of information integration or real-time collaboration. In contrast, BIM's strength lies in how it ties every design element to pertinent data that can be accessed throughout the building's lifecycle—from conceptual design through to facility management. BIM is also inherently collaborative, providing a platform for multiple stakeholders to contribute to and access information simultaneously[5].

Moreover, BIM serves as a foundation for emerging technologies like digital twins and smart cities. As buildings and infrastructure systems become increasingly complex, BIM plays a crucial role in enabling real-time data integration, making it a key player in the shift toward more sustainable and intelligent environments. The benefits of BIM, such as effective decision-making, improved analysis, easier access to information, and simpler green building certification, provide an optimized solution for sustainable design and construction [6].

Evolution of BIM

1960s–1980s: Pre-BIM Era (The Foundation of CAD and Parametric Design)

Before the formalization of BIM, the building industry relied heavily on manual drafting techniques, using paper-based blueprints that were difficult to modify and often prone to errors. This manual process was slow and costly, particularly when design changes required revisions across multiple drawings. The advent of Computer-Aided Design (CAD) in the 1960s and 1970s revolutionized this process by allowing architects and engineers to create 2D and later 3D models of buildings. CAD was primarily a tool for drafting, focusing on the geometric aspects of design without integrating much additional information, such as materials or costs. [8].

The transition to object-oriented, parametric design in the 1980s was the precursor to BIM. Early systems like ArchiCAD and MicroStation began to offer tools that allowed objects in a model to carry data beyond geometry, though this was still limited. These objects, such as walls or doors, could retain certain properties, but the full potential of data-rich models was not yet realized [8]. Many of the costs of design, constructipn,and building operation deriVe from the reliance on drawings as the deScription of record of the building. This paper outlines as a replacement the design of a computer system useful for storing and manipulating design.information at a detail allowing design, construction, and operational analysis[11].

1990s: Early Concepts of BIM (The Birth of Parametric Design and Object-Based Modeling)

The 1990s were a transformative period in the development of BIM, as parametric modeling emerged as a key concept Parametric modeling allows the elements in a design to be interrelated and automatically adjusted based on changes to parameters like dimensions or material properties [8]. **Figure 2** illustrates the parallel evolution of BIM and sustainability initiatives over time, highlighting key technological advancements such as the introduction of IFC standards and government mandates, alongside major global sustainability efforts like the Kyoto Protocol and COP21.

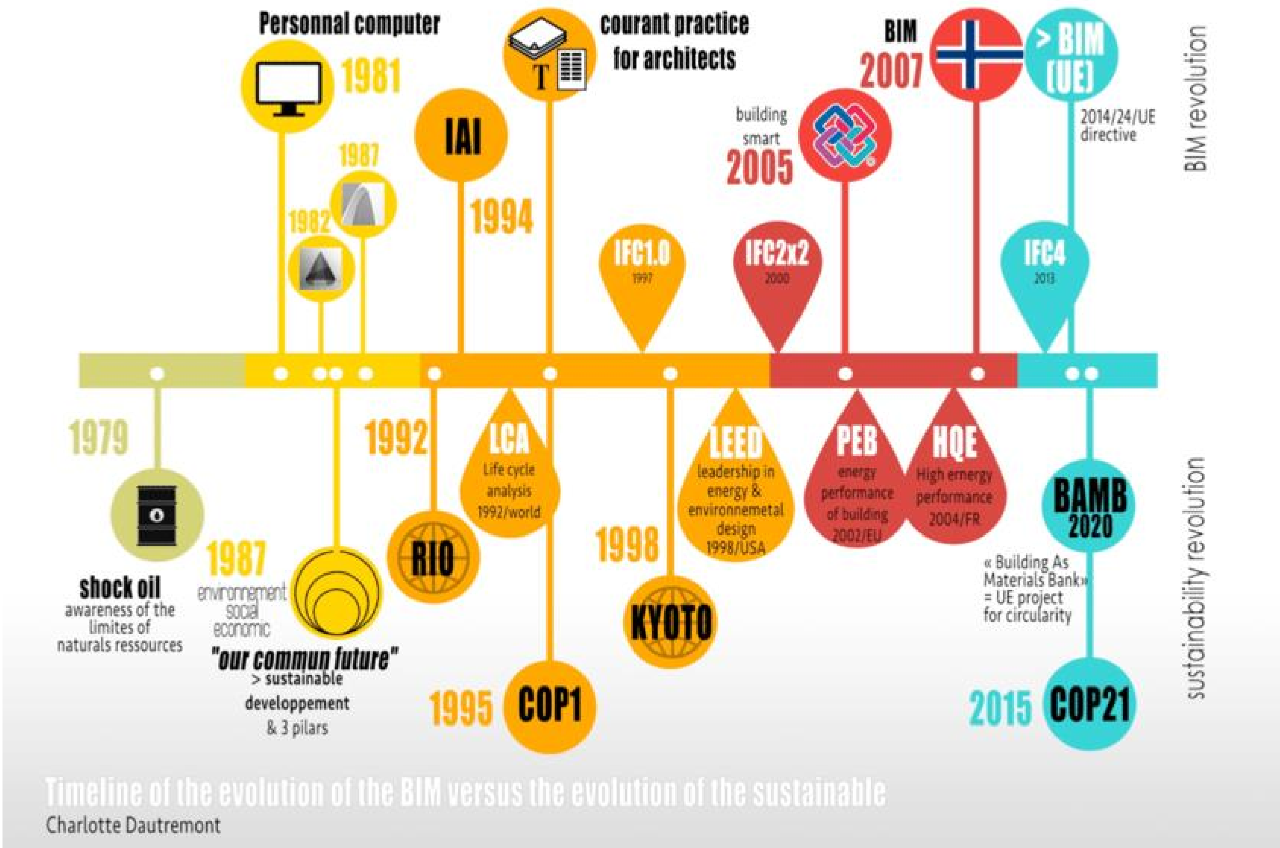


Figure 2: Evolution of BIM [16].

This development was a significant leap forward from earlier CAD tools because it introduced object-based modeling, where individual components (like doors, windows, or walls) could contain embedded data, including physical properties, material specifications, and functional behavior. These objects were no longer isolated geometric entities but were interconnected parts of a dynamic model [8].

Software like ArchiCAD and Bentley Systems introduced some of the first true BIM concepts during this decade, but it was the launch of Autodesk Revit in 2002 that signaled a major turning point. Revit was built from the ground up as a BIM tool, designed to manage and manipulate data-rich, parametric models of buildings. Unlike earlier programs that adapted to BIM methodologies later, Revit incorporated multi-discipline collaboration from the start, allowing various teams (architects, engineers, contractors) to work together on a single shared model [9].

2000s: Formalization of BIM (BIM as an Industry Standard and the Introduction of Dimensions Beyond 3D)

The early 2000s saw the formal recognition of Building Information Modeling as a distinct methodology and industry standard. This era was characterized by growing adoption of BIM in both public and private sectors, particularly as governments began to recognize its benefits in terms of cost savings, efficiency, and improved collaboration. In 2007, the UK government became one of the earliest advocates of BIM, announcing its intention to mandate BIM on public projects by 2016. This move set a precedent for the global construction industry, prompting other countries to follow suit [10].

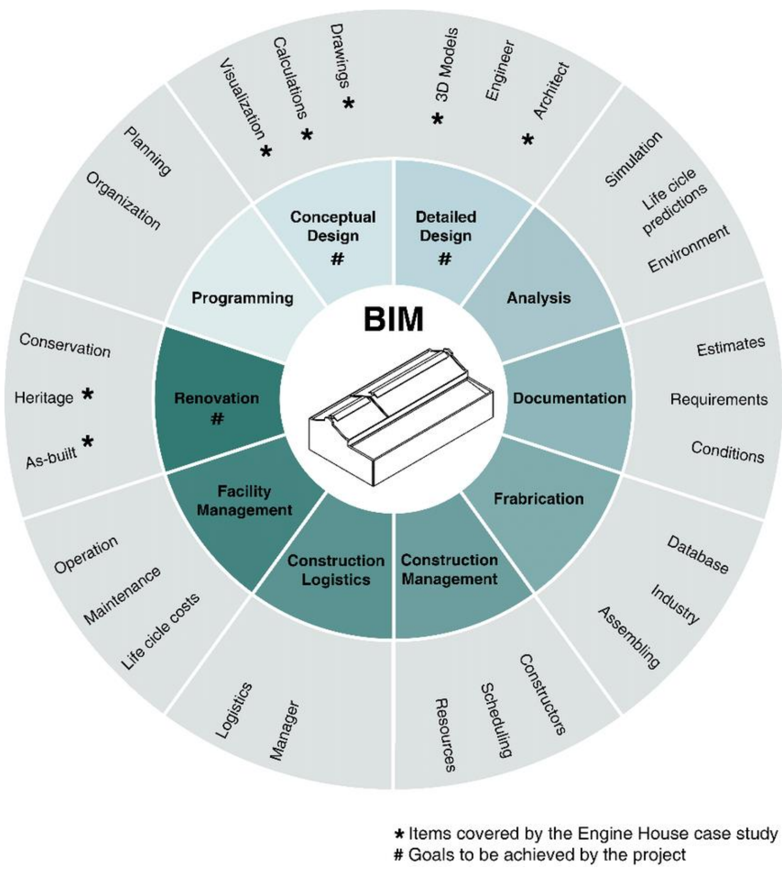


Figure 3: Diagram of a Building Information Modeling (BIM) work process [17].

During this period, BIM evolved from being primarily a tool for architects and engineers into a comprehensive process that extended to construction management and facility operations. The concept of multi-dimensional BIM (often referred to as nD BIM) began to take shape, with the integration of 4D (time) and 5D (cost) dimensions into the modeling process. This enabled project managers to simulate construction schedules and calculate the financial implications of design decisions in real time, which helped to optimize construction workflows and reduce waste [12]. Though BIM is still maturing and not yet fully defined in scope [2], its benefits in project implementation and information management are envisaged to be significant. As a digitized representation of the building artefact, BIM has the tendencies for continuous expansion to closely mimic the vast amount of information embedded in a typical building project. Such information, referred to as n-Dimensional (nD). [13]

2010s: Global Adoption and Standardization (The Rise of ISO Standards and Widespread Implementation)

The 2010s saw the worldwide expansion and formalization of BIM, driven by the increasing demand for collaboration across international projects. During this decade, BIM became a mandated requirement for large-scale public infrastructure projects in several countries, including the UK, the US, and much of Europe. Governments and regulatory bodies realized that BIM could help deliver projects on time and within budget, while also improving quality and sustainability outcomes [14].

This period was marked by the establishment of international standards for BIM, most notably ISO 19650, which provided a framework for managing information throughout the lifecycle of a construction project. This standard is essential for ensuring consistency, accuracy, and data interoperability across various software platforms and disciplines.

BIM also became more commonly integrated with cloud computing during this time, allowing project teams to work on models in real-time from different geographic locations. Platforms like Autodesk BIM 360 and Trimble Connect facilitated cloud-based collaboration, where models could be updated and accessed by all stakeholders simultaneously, fostering better coordination and communication across all project phases.

2020s: Advanced BIM Technologies and Digital Twins (The Integration of AI, IoT, and Data-Driven Smart Buildings)

In the 2020s, BIM has continued to evolve, incorporating cutting-edge technologies like Artificial Intelligence (AI), Machine Learning, and the Internet of Things (IoT) to further enhance its capabilities [17].

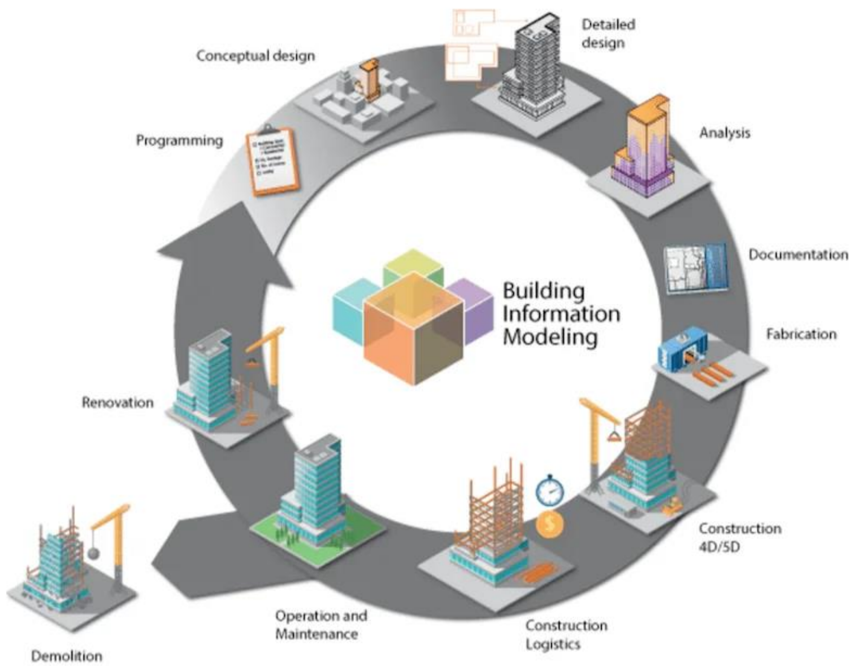


Figure 4: Building information modelling (BIM) uses across building lifecycle [23].

One of the most significant advancements in recent years has been the rise of digital twins, which are virtual representations of physical buildings that remain linked to the real world through IoT sensors and real-time data streams.

Digital twins provide an ongoing flow of information between the physical asset and its digital counterpart, enabling building managers to monitor performance, track maintenance needs, and optimize energy use in real time. This development is particularly relevant for smart buildings, which use IoT devices to automate systems such as lighting, HVAC, and security. By integrating BIM models with real-time data, building operators can make informed decisions that improve energy efficiency, reduce operational costs, and enhance occupant comfort.

Looking forward, the integration of AI into BIM platforms promises to automate even more aspects of the design and construction process, from predicting potential clashes and safety hazards to optimizing material usage and construction schedules based on past project data.

2.2 Key Components and Technologies of BIM

Key Components of BIM

1. Geometry (3D or 2D Representation)

At the core of BIM is the geometric representation of a building, which can be either 2D or 3D. While BIM is often associated with 3D modeling, the fundamental principle is not just visualization but the structured representation of building components in a digital environment. 2D representations (such as floor plans, sections, and elevations) still play a role in BIM workflows, particularly when extracted from the central model. The advantage of 3D modeling, however, lies in its ability to provide better spatial understanding, clash detection, and coordination across disciplines [18].

2. Information (Parameters, Materials, and Metadata)

Beyond geometry, information is the defining characteristic of BIM. Every object in a BIM model is data-rich, meaning that each element, whether a wall, beam, or door, is linked to specific parameters such as:

Material properties (e.g., thermal conductivity, fire resistance)

Structural and mechanical properties (e.g., load-bearing capacity, elasticity)

Lifecycle information (e.g., maintenance schedules, sustainability data)

Cost and quantity takeoffs (linked to procurement and budgeting)

This parametric approach allows for automatic updates—if a designer changes a material or dimension, all dependent elements adjust accordingly, ensuring data consistency and reducing errors [19].

3. Interoperability in BIM

Interoperability is a crucial concept in BIM, referring to the seamless exchange of information between different software platforms and stakeholders involved in a project. BIM promotes open standards like Industry Foundation Classes (IFC) and BuildingSMART standards, which allow multiple disciplines (architects, engineers, contractors, facility managers) to collaborate efficiently using different tools [20].

Without interoperability, BIM models risk becoming isolated within specific software environments, leading to inefficiencies and loss of data during exchanges. Interoperability ensures:

Consistent data flow across design, analysis, and construction platforms

Efficient multidisciplinary collaboration by reducing redundant work

Long-term accessibility of data, even when software versions change

4. Scope of the Model (Defining the Use Case)

BIM cannot exist without a clearly defined use case. The scope of a BIM model must align with project objectives, whether it is intended for design coordination, structural analysis, cost estimation, energy modeling, or facility management [21].

Defining the Level of Development (LOD) is essential to clarify:

What information is included at each stage of the project

Who is responsible for providing and managing the data

How the model will evolve throughout the building's lifecycle

A BIM model used for early-stage conceptual design will differ significantly from one used for construction planning or asset management. Establishing the purpose and scope of BIM implementation ensures its effectiveness in decision-making, cost control, and lifecycle management [22].

2.3 BIM Applications in Sustainable Development

Building Information Modeling (BIM) has emerged as a transformative force in advancing sustainable development across the architecture, engineering, and construction (AEC) industries. The sustainable development approach in construction aims to balance economic growth, environmental stewardship, and social equity. BIM, with its capability to simulate, analyze, and manage a building's entire lifecycle, supports these objectives by promoting energy efficiency, minimizing waste, facilitating the conservation of heritage buildings, and optimizing infrastructure for long-term use. This section elaborates on how BIM is being applied to different areas of sustainable development, providing powerful tools for designers, engineers, and project managers to meet sustainability goals [23].

The ability of BIM to integrate data across various dimensions (such as time, cost, and environmental impact) makes it a central pillar in sustainable construction. By leveraging BIM, professionals in the AEC sector can incorporate sustainability measures from the earliest phases of a project, ensuring that the environmental, economic, and social benefits are realized throughout the lifecycle of the building or infrastructure.

2.3.1 Energy Efficiency and Building Performance

Energy efficiency is a cornerstone of sustainable development, and BIM plays an integral role in optimizing building energy performance across design, construction, and operations. Given that buildings account for a significant portion of global energy consumption and carbon emissions, optimizing energy use is a critical challenge in modern architecture. BIM's ability to simulate building performance under different conditions, coupled with its capacity to integrate renewable energy systems, makes it an indispensable tool for achieving high-performance, energy-efficient buildings. [23].

BIM and Energy Modeling

One of BIM's most significant contributions to sustainability is its capacity for energy modeling and performance simulation. These capabilities allow architects and engineers to perform early-stage energy analyses to predict and improve a building's energy consumption. Tools such as Autodesk Revit and IES-VE can simulate how a building's design will affect energy use, including factors such as heating, ventilation, and air conditioning (HVAC) loads, lighting, and occupancy patterns [25]. These energy simulations enable design teams to explore various design strategies—such as optimizing building orientation, enhancing insulation, or incorporating energy-efficient glazing—to find the best balance between aesthetics, functionality, and energy efficiency. Figure 5 illustrates the integration of Building Information Modeling (BIM) with traditional architecture, showcasing a digitally enhanced model of a historic stone village. The overlay of 3D wireframe structures, energy efficiency metrics, and BIM annotations highlights the use of modern digital tools for analyzing, restoring, and optimizing heritage buildings while maintaining their architectural integrity.

Figure 5: BIM in mountainous regions [AI].

BIM-driven energy models can assess the thermal performance of buildings by considering the materials used in the building envelope (walls, roofs, windows) and the internal heat gains from occupants, equipment, and lighting. For example, simulations can reveal how different window types or shading devices will affect a building's heating and cooling needs. As a result, designers can make informed decisions to minimize energy loss and optimize natural light, reducing the reliance on artificial lighting and HVAC systems [25].

Renewable Energy Integration

BIM also facilitates the integration of renewable energy systems, such as solar panels, wind turbines, or geothermal energy solutions, into the design of a building. Through energy analysis tools, architects and engineers can simulate the potential energy savings generated by these systems and assess their feasibility based on the building's location, orientation, and operational requirements [26]. For example, BIM can calculate the optimal placement of solar panels on a building's roof, determining the best angle for maximum sunlight exposure throughout the year.

Moreover, BIM enables the life-cycle cost analysis of incorporating renewable energy systems.As in Figure 6. Application of BIM in heritage building management, showcasing data-driven insights for predictive maintenance, energy efficiency, and structural monitoring. This analysis helps stakeholders evaluate the upfront investment in renewable energy technologies against long-term savings in operational costs, making it easier to justify sustainable design choices that may have higher initial costs but significant environmental and financial benefits over the building's lifetime [27].

Energy-Efficient Operations and Maintenance

BIM's utility extends beyond the design and construction phases to the operation and maintenance of buildings. Facility managers can use BIM to monitor and manage energy performance in real-time by integrating BIM with building management systems (BMS) and Internet of Things (IoT) sensors. These sensors collect data on factors such as indoor temperature, humidity, and energy use, feeding it into the BIM model to provide an ongoing assessment of building performance. This allows facility managers to identify inefficiencies—such as malfunctioning HVAC systems or poor insulation—and make data-driven decisions to reduce energy consumption [25].

BIM's role in predictive maintenance further enhances energy efficiency. By tracking the performance of building systems and components (e.g., lighting, HVAC units), BIM can forecast when maintenance or replacements are needed, preventing energy waste caused by inefficient systems [25]. This capability ensures that buildings continue to operate efficiently over time, maximizing the return on investment in sustainable technologies.

BIM for Regulatory Compliance and Certifications

BIM also plays a pivotal role in helping buildings achieve sustainability certifications such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), or Green Star. These certifications require buildings to meet specific energy efficiency criteria, which BIM tools can help to document and validate. By providing detailed, data-rich models of a building's energy performance, BIM simplifies the process of demonstrating compliance with green building standards, making it easier for project teams to achieve their sustainability goals [28].

Figure 6 presents a fusion of modern data-driven analysis with historic rural structures, demonstrating how BIM technologies facilitate the monitoring, maintenance, and optimization of traditional buildings. The superimposed analytics, charts, and wireframe models highlight key aspects such as structural integrity, predictive maintenance, and sustainability metrics, showcasing the role of digital tools in preserving and enhancing architectural heritage

Figure 6: BIM applied to heritage buildings for predictive maintenance, energy efficiency, and structural monitoring. [AI].

2.3.3 Infrastructure and Utility Optimization

BIM is not only valuable for building design and heritage preservation but also plays a crucial role in the planning, design, and management of large-scale infrastructure projects. Infrastructure systems—such as roads, bridges, railways, utilities, and water management networks—are essential to the functioning of cities and communities, and optimizing their design and operation is critical for sustainability. BIM enables infrastructure designers and engineers to create integrated, data-rich models that account for the complex interactions between various infrastructure systems, ensuring efficient and sustainable development. The integration of BIM and GIS in underground utility management enhances infrastructure design optimization, facilitates real-time 3D spatial analysis during construction, and serves as an as-built database for facility management. By combining BIM with GIS, this framework enables effective collaboration among stakeholders, minimizing conflicts between underground utilities and other infrastructure components. A real-time case study demonstrates that this approach significantly improves planning, execution, and maintenance of infrastructure projects, contributing to sustainable and efficient urban development [29].

Holistic Infrastructure Design and Collaboration

Infrastructure projects are inherently complex and require the coordination of multiple stakeholders, including engineers, architects, city planners, contractors, and government agencies. BIM serves as a centralized platform where all project participants can collaborate in real time, accessing and updating a shared model that integrates data from different disciplines. This fosters a collaborative environment that minimizes errors, reduces delays, and ensures that all aspects of the infrastructure system—such as utilities, transportation, and environmental management—are designed holistically [30]. Effective infrastructure development requires a strategic, data-driven approach that optimizes both planning and execution. Large-scale projects demand seamless coordination between disciplines, ensuring that structural, environmental, and functional aspects align with urban development goals. BIM transforms infrastructure management by providing a digital twin environment where designs, simulations, and analyses converge. This technology facilitates proactive problem-solving, allowing project teams to anticipate conflicts, assess sustainability impacts, and optimize resource allocation before construction begins. By leveraging real-time data exchange and automation, BIM enhances long-term infrastructure resilience, improving adaptability to future urban demands, climate considerations, and technological advancements [30].

BIM plays a critical role in infrastructure planning by providing a detailed digital representation of how new projects, such as highways or railway systems, will interact with existing utility networks, including water pipelines, electrical grids, and telecommunications lines. By leveraging BIM-based clash detection tools, project teams can identify potential conflicts between underground and surface-level infrastructure early in the design phase. This proactive conflict resolution not only helps prevent expensive rework and construction delays but also minimizes the risk of service disruptions for local communities [31].

Moreover, a case study by Al-Fuqaha and Asadi (2022) demonstrates that integrating BIM with Geographic Information Systems (GIS) significantly enhances spatial coordination, ensuring that existing utilities are properly mapped before excavation begins. This integration allows engineers to analyze multiple design scenarios, improving decision-making and mitigating environmental impacts. By reducing the need for late-stage modifications, BIM contributes to sustainable infrastructure development, lowering construction waste, energy consumption, and land disturbances. Additionally, BIM-based automated utility conflict detection facilitates seamless communication between stakeholders, ensuring compliance with regulatory standards and municipal planning guidelines [31]. A notable example of utilizing Building Information Modeling (BIM) to identify and resolve utility conflicts is the **Vietnamese transformer station project**. In this project, the design was initially developed using traditional 2D CAD methods. However, upon adopting a BIM-based clash detection process, the project team identified **36 design conflicts**, including inconsistencies and geometric interferences among various systems. This proactive identification allowed for timely resolution of issues, preventing costly rework and construction delays. The successful application of BIM in this context underscores its effectiveness in enhancing design accuracy and coordination in complex infrastructure projects [32]

2.3.2 Heritage Preservation and Architectural Integration

Heritage preservation in construction requires a meticulous approach to maintaining the historical, cultural, and architectural significance of buildings while adapting them for modern use. This delicate balance demands precise documentation, careful planning, and advanced analytical tools to ensure that any intervention respects the original materials, construction techniques, and design intent. Building Information Modeling (BIM) has emerged as a powerful tool in heritage conservation, allowing architects, engineers, and conservationists to create highly detailed digital records of historic buildings. These models serve as accurate virtual replicas, enabling comprehensive condition assessments, structural analysis, and material simulations before implementing any modifications. BIM in cultural heritage projects enhances data integration, interdisciplinary collaboration, and long-term preservation strategies. By leveraging laser scanning and photogrammetry, heritage buildings can be digitally reconstructed with millimeter accuracy, ensuring that conservation efforts align with their original state. Additionally, BIM facilitates predictive modeling, allowing professionals to simulate potential structural reinforcements or restoration techniques while assessing their impact on historical integrity. This digital approach not only streamlines the renovation process but also aids in future-proofing heritage sites, ensuring that conservation efforts are sustainable and adaptable to modern requirements [33].

Documentation and Digital Archiving of Heritage Buildings

Documentation and digital archiving are fundamental steps in the preservation of heritage buildings, ensuring that their historical, cultural, and architectural significance is accurately captured for future generations. Building Information Modeling (BIM) plays a pivotal role in this process by facilitating the creation of precise digital records through advanced technologies such as laser scanning and photogrammetry [34].

Laser scanning employs laser beams to measure the exact geometry of structures, capturing intricate architectural details with high precision. Photogrammetry involves taking overlapping photographs from various angles and processing them to generate detailed 3D models. The integration of these technologies within a BIM framework allows for the development of comprehensive 3D models that serve as digital twins of heritage buildings, accurately reflecting their current state, including any damages or structural issues [35].

These 3D BIM models encompass not only geometric information but also data on material properties, construction techniques, and the building's historical context. Such rich digital archives are invaluable resources for restoration teams, providing a detailed reference throughout the preservation process. In instances where heritage structures are damaged or lost, these BIM models offer a blueprint for reconstruction, enabling faithful restoration of the original design [35].

Moreover, the use of BIM in heritage preservation enhances interdisciplinary collaboration by providing a centralized platform where architects, engineers, and conservationists can access and update information in real-time. This collaborative environment ensures that all stakeholders are aligned, reducing the potential for errors and ensuring that any interventions are sympathetic to the building's historical integrity [36].

Conservation, Adaptive Reuse, and Modernization

Building Information Modeling (BIM) plays a pivotal role in the adaptive reuse of heritage buildings, enabling the transformation of historical structures for contemporary purposes while preserving their architectural integrity. This approach not only conserves cultural heritage but also promotes sustainability by repurposing existing buildings. For instance, a former industrial warehouse might be converted into modern office spaces, or an old theater could be transformed into a cultural center. BIM facilitates this process by allowing architects and engineers to create detailed digital models that simulate various design interventions, such as the integration of modern amenities like elevators, HVAC systems, or updated lighting. These simulations ensure that new additions harmonize with the existing structure without compromising its historical features. Moreover, BIM's precision aids in meticulous planning, reducing the risk of damage to delicate structures during restoration and ensuring that renovations do not disrupt the building's historical integrity.

Additionally, BIM supports sustainable preservation practices by enabling detailed analysis of building performance and energy efficiency. By integrating BIM into preservation efforts, stakeholders can visualize how new elements will interact with the existing structure, assess various conservation techniques, and make informed decisions that uphold the building's historical value while meeting modern standards of safety and functionality [37].

Sustainability and Heritage Integration

Integrating sustainability into heritage preservation presents unique challenges, particularly in respecting original materials and design features [33]. Building Information Modeling (BIM) addresses these challenges by enabling the simulation of modern sustainable technologies within heritage buildings without altering their historic appearance. For instance, BIM can model the installation of energy-efficient windows, advanced insulation systems, or geothermal heating solutions in a manner that preserves the building's historical façade.

By facilitating simulations of a heritage building's energy performance before and after restoration, BIM supports a data-driven approach to sustainability enhancements. This ensures that conservation efforts not only maintain the building's historical significance but also improve its energy efficiency, thereby reducing long-term operational costs and environmental impact [33].

Moreover, the adaptive reuse of existing buildings aligns with sustainable development principles by minimizing waste and resource consumption. Through BIM, architects and engineers can extend the lifespan of historical structures, allowing them to serve contemporary functions while preserving their cultural and architectural heritage.

A notable example of applying Building Information Modeling (BIM) in heritage preservation is the San Nicola in Montedoro Church in Italy. Researchers conducted a comprehensive survey of this historic structure using terrestrial laser scanning (TLS) and photogrammetry to capture its intricate architectural details. The collected data facilitated the creation of a detailed 3D model, which served as a foundation for the Heritage Building Information Modeling (HBIM) process. This HBIM model enabled precise documentation of the church's current condition, informed conservation strategies, and supported ongoing preservation efforts. The integration of advanced surveying techniques with BIM proved instrumental in maintaining the church's historical and cultural significance while accommodating necessary restorations [38].

2.4 Territorial Digital Twin

The Territorial Digital Twin (TDT) represents a powerful tool for enhancing community resilience by creating digital replicas of entire territories. It integrates environmental, economic, and infrastructural data to simulate real-world conditions, enabling better decision-making, particularly in vulnerable regions such as fragile mountain areas. By leveraging this technology, local governments can assess risks like natural disasters and optimize disaster preparedness, resource allocation, and infrastructure development for improved resilience.

2.4.1 Digital Twin Concept and Applications

The Digital Twin is a dynamic and evolving representation of physical assets, processes, or systems, designed to connect the physical world to the virtual world**,** facilitating real-time data exchange and actionable insights. The Digital Twin concept consists of three main components:

a) Physical products in Real Space: These are the actual, tangible products or systems that exist in the physical world. These physical entities can range from machines, vehicles, factories, or entire buildings. They are continuously monitored to track their conditions and performance in real time.

b) Virtual products in Virtual Space: This refers to the digital twin itself, a virtual replica of the physical product or system. The virtual model is stored and maintained in a digital environment, updating continuously to reflect the current state of the physical product. These models incorporate data from sensors, operational conditions, and other performance metrics. The virtual twin can be used to simulate different scenarios or predict future behaviors of the physical object.

c) The connections of data and information: This component represents the flow of data between the physical and virtual worlds. Data is collected from sensors embedded in the physical objects and transmitted to update the virtual twin in real time. This connection enables continuous monitoring, diagnostics, and feedback loops, improving decision-making, enabling predictive maintenance, and enhancing overall system performance [46].

The Digital Twin concept has significant potential in manufacturing excellence through virtual factory replication. By integrating data from both the physical and virtual models, industries can simulate, predict, and optimize factory operations without experimenting directly on physical equipment. This virtual factory model enables better planning, testing, and design iterations, reducing downtime, improving resource allocation, and enhancing operational efficiency.

The Digital Twin model is applicable across various industries, including manufacturing, healthcare, transportation, aerospace, and urban planning. In manufacturing, it can be used for predictive maintenance, supply chain optimization, and product quality improvement. In healthcare, it enables personalized medicine, allowing for digital representations of patients that aid in more accurate diagnoses and treatment plans. Its versatility and potential for transforming industries through digital integration make it a powerful tool in modern technological systems [46].

One of the prominent examples of Digital Twin implementation is in the Smart Manufacturing and Production Systems, In the context of Smart Manufacturing, Digital Twin technology is used to optimize production processes by creating virtual models of entire manufacturing systems. These virtual models simulate real-time operations, enabling manufacturers to monitor the health and performance of machinery, production lines, and logistics systems. With real-time data from sensors embedded in the physical assets, these models are continuously updated, providing an accurate representation of the actual system [47].

For instance, in a production facility, a Digital Twin could represent a specific production line, where each machine and component is monitored for factors like temperature, speed, and wear. If any machine shows signs of malfunction or inefficiency, the Digital Twin allows for predictive maintenance, alerting operators to potential issues before they lead to costly downtimes. By analyzing the data from the virtual model, operators can optimize workflows, reduce energy consumption, and improve the overall efficiency of the manufacturing system [47].

This use of Digital Twin technology significantly contributes to achieving the goals of Industry 4.0, such as increasing automation, improving product quality, and enhancing supply chain management. The integration of real-time data and predictive analysis makes it possible to continuously fine-tune operations for maximum productivity and cost-efficiency [47].

Also in the aerospace industry**,** Digital Twin technology is used to enhance maintenance processes and optimize the lifecycle of aircraft. The Digital Twin represents a virtual model of an aircraft, incorporating real-time data gathered from sensors installed throughout the physical aircraft. This includes data on fuel consumption, engine performance, structural integrity, and other operational factors [48].

By utilizing this digital replica, aerospace engineers can simulate various conditions and monitor the aircraft's performance over time. The Digital Twin allows for predictive maintenance, where potential issues are identified before they affect the aircraft's operation, reducing downtime and improving safety. Furthermore, by continuously updating the virtual model with real-time data, engineers can make informed decisions about component replacements, servicing schedules, and operational adjustments to optimize performance and reduce costs [48].

This application of Digital Twin technology ensures that the aircraft operates at peak efficiency throughout its lifecycle and provides manufacturers and operators with deeper insights into aircraft performance, which can be crucial for long-term sustainability and safety in the aerospace industry.

Territorial Digital Twins (TDTs) can play a major role in enhancing the resilience of communities, especially in fragile mountain regions. These areas often face unique challenges due to climate change, geographic isolation, and social vulnerabilities. By creating digital replicas of entire territories, we can integrate various data sources like environmental, economic, and infrastructural data to simulate real-world conditions [49].

For instance, a TDT could be used to model the potential impacts of natural disasters like floods or landslides in mountain communities. By simulating these scenarios virtually, local governments and policymakers can better understand the risks and make data-driven decisions to improve infrastructure and disaster preparedness. This helps them allocate resources more effectively and protect vulnerable populations, even in areas that are hard to reach or difficult to study traditionally [49].

2.4.2 Digital Twin and Ontology

Ontology plays a key role in building an effective Digital Twin City, especially when combining complex systems like BIM (Building Information Modeling)**,** GIS (Geographic Information Systems), and IoT (Internet of Things). It acts as a bridge that connects various data sources, enabling them to work together seamlessly.

One of the main benefits of using ontology is its ability to standardize and integrate data from different platforms. For instance, BIM models represent the physical structure of buildings, **GIS** deals with spatial and geographical information, and IoT provides real-time data from sensors throughout the city. Ontology provides a shared framework that organizes this data in a way that makes it understandable across different systems. This ensures that information flows consistently, regardless of its source.

Another important aspect is semantic understanding. Ontology allows all components of the city model to have clear definitions and relationships. For example, it ensures that the system knows how to interpret the connection between a building, its surrounding roads, and nearby utilities. This deeper understanding enables better decision-making by helping to visualize and simulate real-world situations more accurately.

With a solid ontological framework, data-driven decision-making becomes more efficient. City planners and engineers can analyze data in ways that lead to smarter predictions and better planning. For instance, the ability to model the impact of potential changes or disasters on infrastructure could prevent costly mistakes and enhance safety.

Moreover, interoperability between various systems becomes possible. Ontology ensures that BIM, GIS, and IoT can work together, even though they typically use different data formats. This makes it easier to gather insights from all sources and implement changes across the city efficiently [50].

3.Case Study introduction

This case study focuses on Rosazza, a historically rich commune located in the Biella Province of northern Italy. Nestled in the foothills of the Italian Alps, Rosazza is known for its unique architectural style, influenced by the esoteric beliefs of its founder, Federico Rosazza Pistolet. The town's buildings reflect a blend of historical architecture and symbolic design, creating a distinctive urban landscape. This section provides an overview of Rosazza's architectural, geographic, and climatic characteristics, setting the stage for a deeper exploration of its energy efficiency and sustainability challenges in subsequent sections.

3.1 Overview of Rosazza

Rosazza is a historically and architecturally significant commune located within the Province of Biella in the Piedmont region of northern Italy. Geographically, the town is situated approximately 70 kilometers (43 miles) northeast of Turin and about 15 kilometers (9 miles) northwest of the provincial capital, Biella. Its location in the foothills of the Italian Alps places it within a distinct sub-Alpine climate zone, providing a landscape characterized by rugged terrain, lush vegetation, and dramatic views of the surrounding mountains. This serene, picturesque setting offers a marked contrast to the metropolitan and industrial environment of nearby Turin, emphasizing a rural and historical atmosphere.

The architectural significance of Rosazza is heavily influenced by the philosophical and esoteric beliefs of its founder, Federico Rosazza Pistolet, a 19th-century Italian aristocrat and senator. Following the tragic loss of his wife and daughter, Rosazza Pistolet became increasingly engaged with esoteric thought, particularly Freemasonry and other mystical traditions, which profoundly shaped his vision for the town's development. His intellectual exploration led him to conceptualize Rosazza not only as a functional settlement but as a space imbued with symbolic meaning. The buildings, public spaces, and overall urban design were carefully planned to reflect metaphysical ideas, integrate sacred geometry, and incorporate elements of symbolism rooted in Masonic and occult philosophies.

The construction of the town began in the late 19th century, specifically between 1876 and 1889, and it reflects a deliberate synthesis of architectural styles. These range from Gothic Revival to Neo-Renaissance, all reinterpreted through the lens of Rosazza's esoteric beliefs. Buildings in the town incorporate symbolic motifs, geometrical proportions, and alignments intended to evoke spiritual and metaphysical connections. This integration of architectural form with deeper philosophical meaning makes Rosazza a significant case study in the intersection of architecture, urban planning, and esoteric traditions.

Figure 7 : Airial picture of Rosazza

Figure 8 Airial picture of Rosazza

3.1.1 Historical and Architectural Significance

The architectural significance of Rosazza is largely defined by its unique synthesis of historical architectural styles, metaphysical ideologies, and esoteric symbolism. The buildings in Rosazza exhibit a blend of Gothic Revival, Neo-Renaissance, and Medieval Revival styles, adapted to incorporate esoteric elements that align with Rosazza's philosophical ideas.

1. The Parish Church of Saints Peter and George (Chiesa Parrocchiale dei Santi Pietro e Giorgio)

One of the foremost architectural landmarks in Rosazza is the Parish Church of Saints Peter and George, completed in 1880. This church is an exemplary representation of the Gothic Revival style, characterized by pointed arches, ribbed vaults, and intricate rose window motifs, which are not only stylistic but hold esoteric significance. The rose, a symbol of spiritual enlightenment and divine perfection, is a central motif in both the architectural design and the decorative elements of the church.

The interior of the church is equally important for its celestial theme. The ceiling, painted dark blue and dotted with over 3,000 stars, embodies the concept of the cosmos and the heavens, which were central to Rosazza's esoteric beliefs. The use of astronomical symbolism within the church's design creates a spatial experience that seeks to unite the earthly with the celestial, aligning the physical space with spiritual concepts.

Figure 9: The Parish Church of Saints Peter and George(Google)

2. Castello Rosazza (Rosazza Castle)

Castello Rosazza, constructed between 1883 and 1889, is another pivotal architectural element in the town's design. Designed by architect Giuseppe Maffei, the castle combines elements of Gothic Revival and Neo-Renaissance architecture, but with significant influences from esoteric traditions. The façade of the castle incorporates Masonic symbols such as the five-pointed star, geometric patterns, and symbolic geometric proportions that align with sacred geometry. These design choices reflect the belief that architecture can convey universal truths through geometric and symbolic representation.

The castle's interiors include spaces deliberately designed to evoke reflection on metaphysical concepts, such as hidden chambers and light patterns that vary according to the time of day or the seasons. This deliberate incorporation of symbolism and geometry into both the exterior and interior design highlights the role of architecture as a medium for spiritual and intellectual inquiry.

Figure 10: Castello Rosazza (Rosazza Castle)

3. The Town Hall (Municipio)

The Town Hall, another key structure in Rosazza, further reflects the town’s esoteric influences. Unlike typical municipal buildings, the Town Hall is designed with alternating architectural textures and symbolic decorations, including Masonic motifs and geometric shapes. The presence of a white marble staircase, colonnades, and balconies within the Town Hall all contribute to its aesthetic and symbolic purpose, reinforcing the notion that the built environment should reflect higher intellectual and spiritual ideals. The integration of sacred geometry in the design of the Town Hall, as well as the use of symbolic motifs throughout the building, reinforces the idea that the public space serves not only as a place of governance but also as a space of philosophical and spiritual reflection.

Figure 11: The Town Hall (Municipio)

4. Additional Symbolic Structures

   Other smaller structures within Rosazza, including fountains, gates, and statues,(Figure 12) carry symbolic weight and are integral to the town's metaphysical framework. Statues representing concepts such as wisdom, truth, and enlightenment are strategically placed throughout the town to reinforce the spiritual and philosophical journey of the individual. These elements underscore the integration of architecture with esoteric thought, creating a built environment that promotes introspection and contemplation.

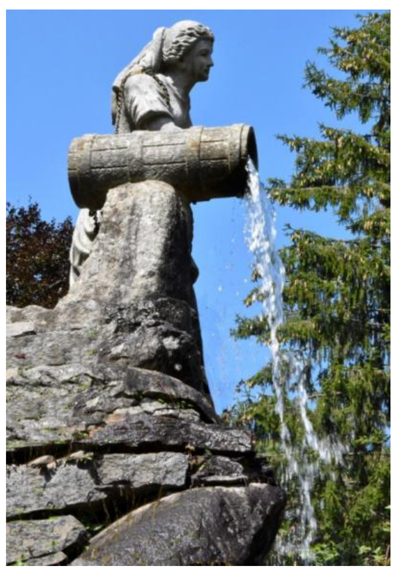


Figure 12 A symbolic statue in Rosazza

5. Esoteric Symbolism and Sacred Geometry

The architecture of Rosazza cannot be fully understood without considering the role of esoteric symbolism and sacred geometry in its design. Rosazza Pistolet was deeply influenced by Freemasonry and other mystical traditions, both of which emphasize the importance of geometric forms, symbolism, and alignment with universal truths. The use of geometrical proportions, such as the golden ratio and the incorporation of triangular and circular motifs, in Rosazza's buildings is a direct expression of these principles.

The Masonic symbolism embedded in the town's architecture, such as the five-pointed star and Eye of Providence, not only reinforces the town's philosophical orientation but also aligns the town's physical space with universal metaphysical concepts. The integration of sacred geometry into the town's design is an explicit attempt to create a harmonious relationship between the material world and the divine, providing residents and visitors with an architectural environment that invites philosophical and spiritual reflection.

Figure 13 Symbolism in Rosazza

3.1.2 Geographic and Climatic Conditions

The town's geographic coordinates place it in a sub-Alpine zone, nestled in the Biellese Alps, a mountain range that forms part of the broader Western Alps system. The Biellese Alps are characterized by their rugged terrain, steep slopes, and variable altitudes, with Rosazza located at an elevation of approximately 800 meters (2,625 feet) above sea level. This positioning provides the town with both spectacular scenic views and a unique set of challenges and advantages with respect to its climate and energy performance.

The commune's topography is defined by a series of valleys, ridges, and hills, all contributing to a diverse microclimate. The presence of numerous watercourses, small rivers, and streams, which meander through the valley floors, further influences the localized weather patterns. The region's mountainous landscape not only contributes to its aesthetic and historical appeal but also shapes the construction practices and energy demands of the area, particularly with regard to the building materials used and the design strategies adopted to address the harsh winter conditions prevalent in the region.

Climatic Conditions

Rosazza experiences a temperate continental climate with significant seasonal variation. The town's climate is influenced by its elevation in the Alps, which results in cold, snowy winters and mild, wet summers. The climatic conditions can be further analyzed through temperature, precipitation, and seasonal weather patterns, all of which have profound implications on building design, energy efficiency, and the overall sustainability of construction practices in the region.

Temperature Patterns

The temperature in Rosazza varies considerably between the seasons. Winters are characterized by cold temperatures, often dipping below freezing, while summers tend to be mild and temperate. The temperature distribution is as follows:

Winter (December to February): Average temperatures range from -1°C to 4°C (30°F to 39°F), with occasional dips well below freezing, particularly during the coldest months of January and February. The region experiences frequent frost and snowfall, which significantly affects heating demands in residential and commercial buildings.

Summer (June to August): The average temperature is between 14°C and 22°C (57°F to 72°F), with occasional peaks during heat waves. Although the summer months are generally moderate, there are fluctuations in daily temperatures, with cooler nights providing a respite from the daytime warmth. The moderate summer temperatures make passive cooling strategies, such as natural ventilation, effective in maintaining indoor comfort.

The temperature variations between winter and summer necessitate buildings with high thermal mass and effective insulation. The emphasis on thermal performance becomes crucial, as building facades, windows, and roofing materials need to provide appropriate levels of thermal resistance to ensure energy efficiency year-round.

Precipitation Patterns

Precipitation in Rosazza is relatively evenly distributed throughout the year, with an increased amount of rainfall occurring during the autumn and spring months. On average, the region receives 1,200 to 1,400 millimeters (47 to 55 inches) of precipitation annually, with notable variations due to the topography. The mountain slopes capture and channel moist air from the surrounding regions, resulting in higher rainfall in the lower valleys and ridge areas.

Winter: Snowfall is common during the colder months, contributing to the region's snow cover for several weeks, particularly at higher altitudes. The snow depth varies but can reach up to 1 meter (3.3 feet) during harsh winters, which affects construction practices, especially for foundations, insulation, and roofing systems. (Figure 14)
Spring and Autumn: These seasons experience moderate rainfall, with frequent showers contributing to the overall moisture levels in the ground. The combination of rain and mild temperatures during these periods can influence building moisture management, particularly with regard to ventilation systems and waterproofing techniques in construction.
Wind and Atmospheric Pressure (Figure 15)

Due to Rosazza's mountainous location, the region also experiences windy conditions, particularly in winter. The complex topography of the Biellese Alps creates microclimates and wind channels, leading to local gusts that can significantly impact outdoor comfort and energy usage. The wind chill effect during winter months can exacerbate cold temperatures, making it essential for buildings to have high thermal insulation and air-tightness to ensure energy efficiency.

Additionally, the atmospheric pressure in Rosazza fluctuates due to its altitude and the influence of Mediterranean air masses. These fluctuations can result in weather systems that are difficult to predict, particularly during the spring and autumn. The effect of these variables on construction techniques involves designing buildings that can withstand wind forces and rain load while optimizing the use of natural resources for heating and cooling.

Figure 14 Rosazza in winter

Figure 15 Rosazza in spring and summer

Microclimates and Local Variations

The presence of microclimates is an important factor in the geographic and climatic conditions of Rosazza. The region's valleys and slopes can exhibit substantial local variation in temperature and humidity. Buildings situated in lower-lying areas may experience higher humidity levels and milder temperatures compared to those at higher altitudes, where colder temperatures and more severe weather conditions are typical. These microclimatic differences should be considered in architectural design to optimize solar orientation, insulation strategies, and natural ventilation systems, enhancing the thermal comfort and energy efficiency of the built environment.

Implications for Building Design and Energy Efficiency

The climatic conditions of Rosazza present both challenges and opportunities for building design. The region's cold winters necessitate buildings that can retain heat effectively, requiring robust thermal insulation, energy-efficient heating systems, and effective use of solar energy. The moderate summer temperatures suggest that passive cooling techniques, such as shading devices and ventilation, can be implemented to reduce the need for mechanical air conditioning. Furthermore, the significant snowfall and precipitation levels demand building designs that account for snow loads on roofs and waterproofing strategies to manage moisture and prevent water infiltration.

Given the seasonal variations and the complexity of the topography, buildings in Rosazza must be designed with a high degree of thermal performance and climate-responsive strategies. Materials and construction techniques must address the region's unique challenges, incorporating sustainable and energy-efficient solutions that reduce energy consumption and improve overall environmental sustainability.

3.1.3 Current Energy Efficiency and Building Classification

The energy efficiency assessment of buildings in Rosazza was conducted through a combination of on-site investigations, data collection from various housing agencies, and Building Information

Modeling (BIM) analysis to better understand the thermal performance of existing structures. The surveyed dataset consists of residential, municipal, and religious buildings, with a primary focus on energy class ratings, annual energy consumption, and building characteristics such as floor area, number of floors, and construction typologies. Given the historical nature of Rosazza's built environment, many of the structures analyzed were constructed before modern thermal insulation standards were implemented, significantly affecting their energy performance.

The geospatial visualization further reinforces these findings by mapping the energy performance of individual buildings, where structures marked in red and orange represent G- and F-class buildings, respectively. The map illustrates a concentration of low-efficiency buildings in the historic core of Rosazza, where older stone-built houses with thick masonry walls, single-glazed windows, and outdated heating systems are prevalent.

To improve the accuracy of energy performance assessments, BIM technology was integrated into the study. Building Information Modeling (BIM) allowed for a detailed digital representation of buildings, enabling thermal simulations, energy usage analysis, and retrofitting scenario testing. The use of BIM-based energy modeling provided valuable insights into heat loss patterns, air infiltration rates, and potential efficiency improvements in different structural components. This data-driven approach enhances the precision of energy audits and facilitates strategic planning for sustainable renovations in historical buildings.

Furthermore, a small fraction of buildings achieved higher efficiency ratings, with a few structures rated as C or D, including municipal offices and the parish church. These buildings likely benefited from partial renovation efforts or energy retrofit interventions, such as double-glazing windows, improved heating systems, or partial thermal insulation upgrades.

Old construction materials (e.g., thick stone walls without insulation layers), which lead to high thermal inertia but poor heat retention in winter.
The high energy demand of Rosazza's building stock has substantial environmental and economic consequences, particularly in the context of increasing climate change concerns and rising energy costs. The reliance on inefficient heating systems contributes to high CO_2 emissions, further

exacerbating the region's carbon footprint.

The findings from this study highlight the critical need for energy-efficient upgrades in Rosazza's buildings, particularly in the historic core, where G and F class buildings dominate. The integration of modern insulation techniques, renewable energy solutions, and passive design principles, complemented by BIM-based energy performance simulations, can significantly reduce energy consumption, lower emissions, and enhance indoor thermal comfort.

Given the importance of preserving the architectural heritage of Rosazza, energy retrofitting solutions should be tailored to respect the historical identity of the structures while improving thermal performance. The adoption of a holistic energy renovation strategy that includes technological advancements, policy incentives, and community engagement is essential to transition Rosazza towards a more sustainable and energy-efficient future.

3.2 Sustainable Development Challenges in Region

Rosazza faces several sustainable development challenges, including energy efficiency improvements in its aging building stock, infrastructure maintenance in its remote mountainous location, and environmental preservation in the face of climate change. These issues require careful consideration of historical preservation, modern energy solutions, and long-term ecological balance.

3.2.1 Energy Efficiency and Retrofitting Needs

Rosazza, like many historic mountain villages, faces significant challenges in improving energy efficiency due to its aging building stock (figure 16,17). Many of its stone-built structures lack proper insulation, leading to high energy consumption, particularly in winter. Retrofitting these buildings is complex due to architectural preservation regulations that limit extensive modifications. Additionally, the steep and fragmented landscape makes it difficult to implement large-scale renewable energy solutions, such as solar panels or wind farms [39]. While some efforts have been made to integrate biomass heating and small-scale hydropower, the transition to a more sustainable energy model remains slow due to financial constraints and the need for specialized expertise in retrofitting historic structures.

Figure 16 Aged buildings of Rosazza

Figure 17 Damaged buildings of Rosazza

3.2.2 Infrastructure and Utility Management

Maintaining infrastructure in Rosazza is particularly challenging due to its remote location and mountainous terrain. Roads, bridges, and pathways require constant upkeep due to erosion, harsh weather conditions, and landslides. The limited accessibility complicates the transportation of goods and services, increasing costs and reducing efficiency. Water and sewage systems, often outdated, struggle to meet modern sustainability standards, requiring investment in more efficient treatment facilities and waste management solutions. Additionally, internet connectivity and digital infrastructure remain underdeveloped, limiting economic diversification opportunities such as remote work or digital tourism initiatives that could help counteract depopulation trends.

3.2.3 Environmental and Biodiversity Considerations

Rosazza is surrounded by rich biodiversity, including protected forests, alpine meadows, and diverse wildlife. However, climate change poses a growing threat, impacting local ecosystems through shifting weather patterns, increased risk of wildfires, and reduced water availability. Sustainable tourism is a double-edged sword—while it provides economic benefits, unmanaged growth can lead to habitat degradation, soil erosion, and increased waste. Conservation efforts must balance human activity with environmental protection, requiring stricter land-use regulations and community-led initiatives to preserve biodiversity. Local initiatives, such as reforestation projects and controlled grazing, help mitigate some of these risks, but stronger policies and funding are necessary to ensure long-term ecological stability.

The table 1 summarizes the rich biodiversity of Rosazza, highlighting its flora, fauna, and ecosystem services. The region's mixed forests, alpine meadows, and understory plants support diverse wildlife, including red deer, wild boars, and rare predators like the European lynx. Birds such as golden eagles and peregrine falcons thrive in its varied landscapes, while insects like the Apollo butterfly and pollinators ensure ecological balance. Streams and rivers host freshwater invertebrates, indicating high water quality. Conservation efforts focus on habitat protection and sustainable management to maintain biodiversity and ecosystem stability.

Table 1 Biodiversity of Rosazza

Biodiversity										
Flora			Fauna			Invertebrates		Ecosystem Services and Conservation		
Forests	Alpine Meadows	Shrubs and Understory Plants	Mammals	Birds	Reptiles and Amphibians	Insects	Aquatic Life	Pollination	Soil Health and Water Regulation	Conservation Efforts
The area is covered with mixed forests that include species such as beech (Fagus sylvatica), chestnut (Castanea sativa), and various types of oaks (Quercus spp.). Higher elevations see a transition to coniferous forests dominated by species like Norway spruce (Picea abies) and silver fir (Abies alba).	Above the treeline, alpine meadows and pastures are common. These meadows are rich in wildflowers during the spring and summer, including species like gentians (Gentiana spp.), alpine asters (Aster alpinus), and various orchids.	The understory in forests and shrublands includes species like rhododendrons (Rhododendron ferrugineum), bilberries (Vaccinium myrtillus), and junipers (Juniperus communis).	The mountainous and forested areas around Rosazza are home to a variety of mammals. Common species include red deer (Cervus elaphus), roe deer (Capreolus capreolus), and wild boar (Sus scrofa). Predatory species such as the European lynx (Lynx lynx) and the occasional brown bear (Ursus arctos) can also be found.	The avian diversity is significant, with species adapted to forest, alpine, and cliff environments. Birds of prey such as the golden eagle (Aquila chrysaetos) and peregrine falcon (Falco peregrinus) are notable inhabitants. Smaller birds include the black woodpecker (Dryocopus martius), alpine chough (Pyrrhocorax graculus), and various species of warblers and finches.	The region hosts several reptiles such as the common viper (Vipera berus) and various lizards (e.g., Zootoca vivipara). Amphibians, including the alpine newt (Ichthyosaura alpestris) and the common frog (Rana temporaria), are found in moist, shaded environments.	The biodiversity includes a variety of insects, many of which are endemic to the alpine regions. Butterflies such as the Apollo (Parnassius apollo) and various species of moths, beetles, and bees contribute to the ecological richness.	Streams and small rivers in the area are habitats for various species of freshwater invertebrates , including caddisflies, mayflies, and stoneflies, which are indicators of good water quality.	Many plant species rely on the diverse insect population for pollination, which is crucial for the health of both natural and agricultural systems.	The forests and alpine meadows play a vital role in maintaining soil health, preventing erosion, and regulating water cycles, which are essential for sustaining the local ecosystem and human activities.	Due to its rich biodiversity, there are ongoing conservation efforts aimed at preserving the natural habitats and species in the region. Protected areas and regulations help ensure that development and human activities do not adversely impact the ecological balance.

4. Methodology

The research methodology adopted for this thesis involves a systematic application of Building Information Modeling (BIM) integrated with Geographic Information Systems (GIS) to analyze sustainable development opportunities in mountainous regions, specifically focusing on Valle Cervo. The methodology includes data acquisition, BIM model development, energy performance analysis, and heritage conservation compliance. Additionally, an ontology was created to organize and manage building information in the city.

Data Acquisition and Collection:

Conduct comprehensive data acquisition to develop detailed BIM-compatible datasets for selected historical buildings located within Valle Cervo. This involves systematically collecting precise building footprints, accurately capturing the geometrical dimensions and spatial configurations of each structure. Additionally, detailed documentation and digitization of structural components—including walls, foundations, roofs, columns, beams, and openings—are essential. Collect thorough records regarding construction materials, historical building techniques, and architectural styles to ensure accuracy and authenticity of the BIM model.

Simultaneously, acquire high-resolution Geographic Information System (GIS) datasets encompassing the broader Valle Cervo region. The GIS data should include detailed topographic information, clearly depicting elevation, slope, and landscape features that significantly impact building performance and preservation strategies.

To effectively visualize and analyze the current energy performance classifications of buildings, OpenStreetMap (OSM) files were imported and processed using QGIS. This allowed the accurate spatial representation of energy performance data across the region, enabling detailed assessments and clear identification of areas requiring targeted energy efficiency interventions. These combined datasets support the creation of a robust, precise, and multidimensional representation of both historical structures and the surrounding environmental context, significantly enhancing heritage conservation and sustainable development initiatives. This approach, which integrates BIM with GIS and detailed data acquisition, aligns with established methodologies in heritage conservation, as demonstrated by Duarte and Lima [40] who emphasize the benefits of combining these technologies to ensure accurate representation and effective management of historical buildings.

BIM Model Development:

Utilize Autodesk Revit to create comprehensive BIM models for selected historical structures, accurately representing both current architectural conditions and retrofit proposals.

Develop detailed models using precise geometric, material, and construction data, enabling realistic simulations of existing and retrofitted building states.

Apply Dynamo scripting within Revit to streamline the BIM modeling process, automate repetitive tasks, and optimize model accuracy and efficiency. Dynamo is specifically used for managing complex geometry, repetitive patterns, and ensuring consistency across BIM datasets. This approach to BIM model development, leveraging Autodesk Revit and Dynamo for both geometric modeling and automation, follows the best practices in the field of BIM [41].

Energy Performance Analysis:

Conduct detailed thermal simulations using BIM-compatible software, such as Autodesk Insight and IES Virtual Environment, to evaluate current energy performance accurately.

Simulate retrofit scenarios that incorporate internal insulation layers, high-performance glazing systems, and efficient HVAC installations designed to significantly enhance energy performance without compromising the external historical integrity of buildings.

Perform comprehensive pre- and post-retrofit energy analyses to quantify improvements in building energy consumption and thermal efficiency. This methodology for energy performance analysis, using BIM-compatible software for thermal simulations and retrofit scenarios, follows established practices in building performance simulation, as outlined by Knaack and Jansen, who discuss the integration of these tools for enhancing energy efficiency and preserving building integrity [42].

Heritage Conservation Compliance:

Ensure that all BIM-based retrofitting proposals strictly adhere to guidelines established by the Italian Superintendence of Cultural Heritage, preserving architectural authenticity and historical integrity.

Leverage advanced digital visualization techniques available in BIM to clearly illustrate how retrofit solutions integrate seamlessly with existing historical aesthetics, minimizing visual disruptions and highlighting subtle, heritage-sensitive improvements. This approach to heritage conservation compliance using BIM, ensuring adherence to cultural preservation standards, is consistent with best practices in the field, as discussed by Paduos and Viegas (2016), who emphasize the role of BIM in seamlessly integrating modern retrofitting techniques with historical aesthetics [43].

GIS Integration and Spatial Analysis:

Integrate the outcomes of the BIM energy simulations into GIS platforms such as QGIS and ArcGIS, providing comprehensive visualizations of energy performance across Valle Cervo.

Create thematic maps to depict the distribution and categorization of building energy performance, clearly identifying structures requiring priority retrofitting interventions based on their current inefficiencies. This integration of BIM energy simulations into GIS platforms, such as QGIS and ArcGIS, follows established methodologies for combining spatial analysis and energy performance, as demonstrated by Zhao and Zhu (2015), who highlight the benefits of using these technologies for comprehensive building performance assessment and decision-making [44].

Validation and Sensitivity Analysis:

Undertake detailed comparative evaluations between simulated pre- and post-retrofit scenarios, validating the effectiveness of the proposed interventions in terms of improved energy efficiency and sustainability metrics.

Conduct sensitivity analyses to examine the resilience and robustness of simulation outcomes against variations in climatic conditions, material characteristics, and operational parameters.

Ontology

The final phase of this research involves integrating BIM data, territorial and energy data into an ontology based on Web Ontology Language (OWL) standard. Initially, the building data were imported as shared parameters into Rosazza's general Building Information Modeling (BIM) model. This data was then exported using Dynamo, a visual programming tool within Autodesk Revit, to automate the extraction and preparation of data for further processing. Given the large volume of data, manually importing each building's information into the ontology system was not feasible.

To address this challenge, a Python script was written to automate the process of importing and integrate the data in the ontology. This script successfully enabled the transfer of the BIM into the ontology schema and established relationships between the different building, the energy parameters and the territorial location, , ensuring that the data was organized and represented effectively within the ontology framework.

This integration highlights the potential of combining BIM with ontological schema to enhance knowledge management in construction projects, as discussed by Rasmussen and Kjaer (2016) [45], who emphasize the importance of such integrations in improving data handling and collaboration across project teams.

5.Case Study Detailed Analysis

Rosazza faces several challenges related to sustainable development, particularly in energy efficiency, historical preservation, and adapting to its geographic and climatic conditions. Energy inefficiencies are prevalent in many buildings, especially in the historic core, while the town's rugged terrain and extreme weather further complicate infrastructure development. At the same time, there are opportunities to enhance energy performance through targeted retrofitting, passive design strategies, and climate-resilient solutions that respect the town's rich architectural heritage.

5.1 Energy Efficiency

The analysis of the building stock in the study area reveals a substantial prevalence of low-efficiency structures, with the majority classified under Energy Class G, the lowest category in the Italian Energy Performance Certificate (EPC) system. This classification indicates severe deficiencies in thermal insulation, outdated heating systems, and inefficient building envelopes, contributing to high energy consumption levels.

Table 2 Energy efficiency of specific buildings in Rosazza

Building Function	Location	Area (m^2)	Number of Floors	Floor	Energy Class	Annual Energy Consumption
Residential	via Amba Alagi, 12	180.0	6.0	all	G	-
Residential	via Umberto I, 10	75.0	4.0	4	G	175.1 kWh/m² year
Residential	via Costantino Crosa, 2	130.0	6.0	all	E	-
Residential	via Roma, 39	228.0	4.0	all	G	294.85 kWh/m² year
Residential	via Sp100, 57	148.0	4.0	all	-	-
Residential	via E. Mosca Riatel, 7	130.0	3.0	all	-	-
Residential	via Federico Rosazza, 17	100.0	4.0	all	G	435 kWh/m² year
Residential	via Quintino Sella, 5	60.0	3.0	all	G	-
Residential	via Umberto I, 10	150.0	4.0	1	G	-
Residential	strada Provinciale 100 Nn	40.0	nan	2	G	-
Residential	VIA FEDERICO ROSAZZA N. 11	90.0	1.0	1	G	315.52 kWh/m³ year
Residential	via Federico Rosazza	50.0	4.0	3	G	-
Residential	via Roma 59	148.0	4.0	all	G	-
Residential	via Re Umberto I 10	nan	4.0	1,2,3	G	-
Residential	Valmosca 123, Campiglia Cervo	275.0	4.0	all	G	425.00 kWh/m² year
Residential	vendita a Rosazza	170.0	3.0	all	G	-
Residential	Valmosca 112	60.0	3.0	all	G	654 kWh/m² year
Residential	Valmosca 97	120.0	3.0	all	G	more than 175 kWh/m² year
Residential	via Roma, 42	70.0	3.0	3	F	-
Residential	Via Roma 60	85.0	3.0	3	F	-
Residential	Via Amba Alagi 2-5, 13815, Rosazza, Biella	90.0	2.0		-	-
Residential	Via Milano 10	1000.0	2.0		D	100
Municipal Office	Via Roma 1	2000.0	nan		C	50
Parish church	Piazza Mazzini, 2	500.0	nan		C	50

The distribution of energy classifications, as visualized in the energy classification distribution table (2), highlights that over 60% of the surveyed buildings fall within the G category, reaffirming the urgent need for energy retrofitting strategies. A substantial portion of these buildings exhibit excessive energy consumption, with many surpassing 175 kWh/m² per year. In extreme cases, energy demand escalates to peak values such as 654 kWh/m² per year, a figure that significantly exceeds national energy efficiency benchmarks.

The geospatial analysis further illustrates a concentration of inefficient buildings in the historic core, where traditional stone masonry structures with high thermal inertia but poor insulation are predominant. These buildings, characterized by single-glazed windows, outdated heating systems, and a lack of passive design measures, experience significant heat loss in winter and overheating in summer. This inefficiency is exacerbated by the town's geographic and climatic conditions, which demand substantial energy inputs for heating during the extended cold seasons.

To enhance the accuracy of performance assessments, Building Information Modeling (BIM) was integrated into the study, allowing for detailed thermal simulations, energy audits, and retrofitting scenario testing. This data-driven methodology enabled the identification of critical inefficiencies, including areas of excessive heat loss and air infiltration, while also facilitating the development of optimized intervention strategies. BIM's application provided a quantitative basis for sustainable renovations, offering precise insights into potential energy savings and thermal efficiency improvements.

Despite the predominance of inefficient buildings, a minority of structures were found to exhibit improved energy performance, particularly municipal buildings and the parish church, which have undergone partial renovation efforts. These buildings, rated C or D, likely benefited from the installation of double-glazed windows, heating system upgrades, or thermal insulation enhancements. However, their relatively low representation within the dataset underscores the limited scope of past retrofitting efforts and the need for a comprehensive and scalable energy efficiency strategy.

The study underscores the critical necessity for large-scale energy retrofitting initiatives, particularly in historically significant areas where preserving architectural integrity must be balanced with sustainability imperatives. Targeted interventions, including internal insulation techniques, high-performance glazing, and efficient heating systems, are essential for reducing overall energy demand while maintaining the visual and material authenticity of heritage buildings.

In light of these findings, policy-driven financial incentives, stakeholder engagement, and strategic planning are imperative to facilitate the adoption of sustainable building practices. The integration of BIM and GIS-based urban analysis offers a scalable and replicable model for energy performance optimization in other historic settlements facing similar challenges.

The spatial analysis of energy efficiency in Rosazza was conducted using an advanced GIS-based methodology, integrating QGIS (Quantum GIS), OpenStreetMap (OSM) data, and multiple spatial datasets to provide a comprehensive and data-driven visualization of the town's building performance. This approach allowed for a detailed geospatial assessment of energy efficiency, enabling the identification of key inefficiencies and potential areas for improvement. The study leveraged vector and raster data processing techniques, along with Digital Elevation Models (DEM), satellite imagery, and energy classification datasets, to enhance the accuracy and depth of urban energy performance analysis.

Data Integration and Processing:

The study incorporated multiple GIS data sources, each contributing to a more structured and analytically robust understanding of energy consumption patterns across Rosazza's built environment:

Vector-based building footprints extracted from OSM data were used to delineate the spatial distribution of structures, urban road networks, and land-use zones.

Raster and vector GIS datasets provided high-resolution terrain models, satellite imagery, and administrative boundaries, enriching the spatial context of the analysis.

Energy performance classification data were integrated into the GIS framework, assigning energy ratings (e.g., Class G, F, D) to individual buildings, thereby visualizing the extent of thermal inefficiencies in different urban zones.

DEM data facilitated the evaluation of topographic influences on energy efficiency, particularly the impact of slope orientation, elevation, and microclimatic variations on building thermal performance.

To refine the accuracy of the analysis, the GIS datasets underwent vector processing in QGIS, ensuring proper georeferencing, spatial alignment, and data validation. High-resolution aerial and satellite imagery were overlaid with energy performance datasets, and advanced heat mapping techniques were applied to visually highlight variations in energy efficiency.

Spatial Visualization and Interpretation

The GIS-generated maps provided a structured and visually interpretable representation of Rosazza's urban energy efficiency landscape, revealing clear spatial trends:

Heat maps using red and orange hues effectively identified clusters of high energy consumption buildings, predominantly located in the historical core, where thick stone masonry structures lack modern insulation technologies.

Yellow and green hues marked buildings with relatively higher energy efficiency, typically newer structures or those that had undergone partial energy retrofitting.
3D visualization techniques were employed to enhance the spatial representation of building height, orientation, and shading effects, offering a multi-dimensional insight into urban heat retention and loss.

BIM integration with GIS mapping added a predictive analytical component, allowing for the simulation of potential energy efficiency improvements under various retrofitting scenarios.
The first GIS visualization presented a vectorized energy efficiency model, wherein individual buildings were extracted from OSM data and categorized according to their energy consumption profiles. This layer-based representation facilitated urban planning decisions by distinguishing between high-priority zones for energy retrofitting and areas with existing sustainability measures.
The second visualization, utilizing a high-resolution satellite-based GIS approach, provided a more detailed and context-aware representation of Rosazza's energy landscape. The overlay of energy classification data on real-world terrain models enabled the identification of specific structural, geographical, and environmental factors influencing building efficiency.
Key Findings and Implications

The GIS-based assessment reinforces the broader findings of the study, highlighting several critical factors contributing to poor energy performance in Rosazza's buildings.

Lack of Thermal Insulation:
The absence of insulation in exterior walls and roofs was identified as a primary driver of high energy consumption, particularly in older stone-built structures where traditional masonry techniques provide high thermal mass but low insulation properties.

This results in significant heat loss during winter months, leading to an over-reliance on inefficient heating systems.

Outdated Heating Systems:

The majority of buildings rely on wood or oil-based heating systems, which not only increase energy consumption but also contribute to higher carbon emissions.

District heating solutions, biomass energy systems, or heat pump technologies could serve as sustainable alternatives to reduce the environmental footprint of Rosazza's energy demand.

Lack of Passive Design Strategies:

The study revealed that few buildings incorporated passive solar design principles, shading devices, or natural ventilation techniques.

GIS-based solar radiation modeling indicated that strategic window placement adjustments, reflective roofing materials, and passive shading installations could significantly reduce cooling demand in summer while optimizing solar heat gain in winter.

GIS and Data-Driven Decision Making for Energy Retrofitting:

The integration of GIS-based energy efficiency mapping with BIM-driven simulations provides an actionable roadmap for sustainable urban planning in Rosazza. By identifying key inefficiency zones, this approach allows policymakers, urban planners, and conservationists to prioritize energy retrofitting interventions, ensuring a balance between heritage conservation and modern energy efficiency requirements.

Moreover, the scalability and cost-effectiveness of GIS-based energy assessments make them a viable tool for application in similar historic settlements, where limited financial resources and strict preservation regulations require data-driven, targeted solutions.

Comprehensive GIS-Based Energy Performance Analysis in Rosazza: A Spatial and BIM-Integrated Approach

This study presents a holistic GIS and BIM-based analysis of the energy performance of buildings in Rosazza, Italy, integrating Geographic Information Systems (GIS), Building Information Modeling (BIM), OpenStreetMap (OSM) data, Digital Elevation Models (DEM), and satellite imagery. The results provide a structured framework for understanding the spatial distribution of energy efficiency, the impact of topography, and the feasibility of retrofitting interventions. The images presented serve as a visual representation of each stage of the analytical process, from data acquisition and terrain modeling to energy classification mapping and strategic recommendations for urban energy efficiency improvements.

GIS-Based Building Extraction and Terrain Modeling

Figure 18 represents the initial GIS-based vectorization of Rosazza, derived from OSM data and DEM. This foundational step ensures that all buildings, roads, and natural features are spatially referenced and accurately represented.

Data Processing and GIS Integration:

OSM data was used to extract vector-based building footprints and road networks.

DEM models were overlaid to create a 3D representation of terrain variations.

Contour lines and hydrographic features were mapped to assess topographic influences on energy efficiency.

Key Findings from the Image:

The historic core of Rosazza is concentrated in a valley, where limited solar exposure and cold air stagnation contribute to high heating demand.

The terrain model confirms the uneven elevation across the town, affecting the availability of passive solar heating for different building locations.

3D Urban Modeling and BIM-GIS Integration

Figure 19 illustrates the transition from 2D GIS data to 3D urban modeling, incorporating BIM elements to enhance spatial analysis.

Energy Classification Mapping and Heat Mapping Techniques:

Figure 20 introduces GIS-based energy classification mapping, using color-coded overlays to depict energy efficiency levels across the town.

Energy Classification Mapping:

Buildings were assigned energy classes (G to C) based on consumption data.
Red and orange hues signify high energy demand and low efficiency (Classes G and F).
Yellow and green hues represent lower consumption levels (Classes C and D).
The historic core predominantly features Class G and F buildings, confirming that older masonry structures suffer from poor insulation, outdated heating systems, and excessive heat loss.
Scattered improvements (yellow and green buildings) indicate partial retrofitting efforts, likely involving window replacements, insulation upgrades, or modernized heating.

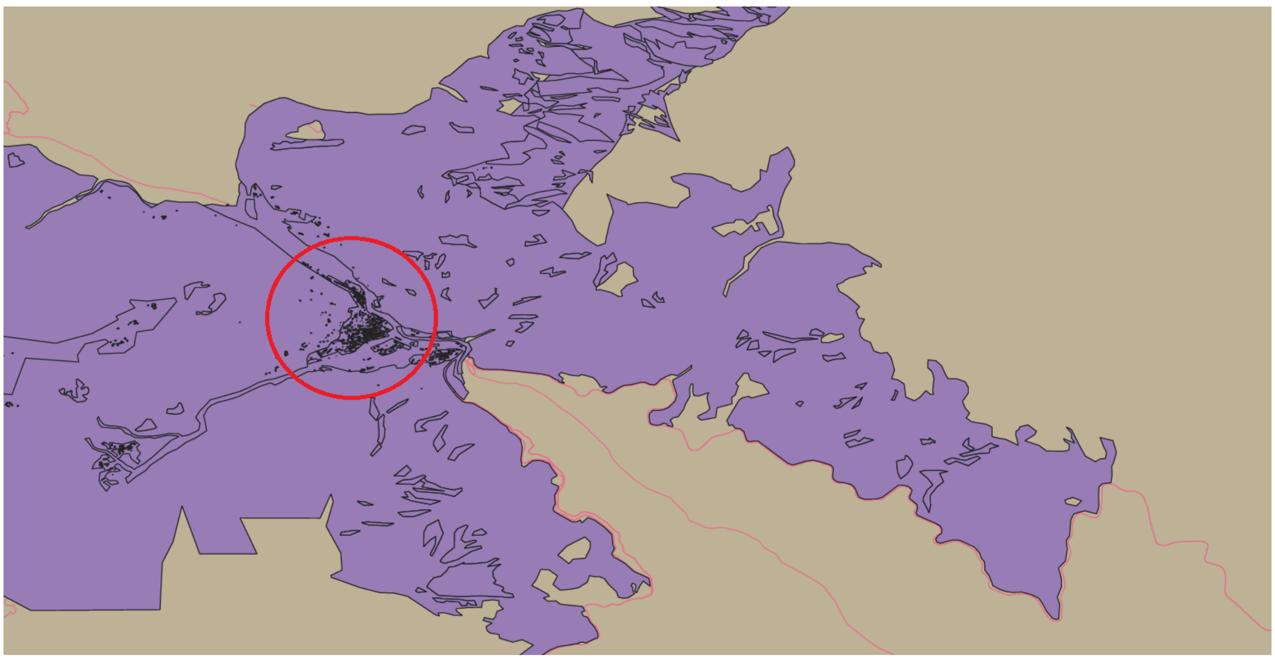


Figure 18 Initial GIS-based vectorization of Rosazza

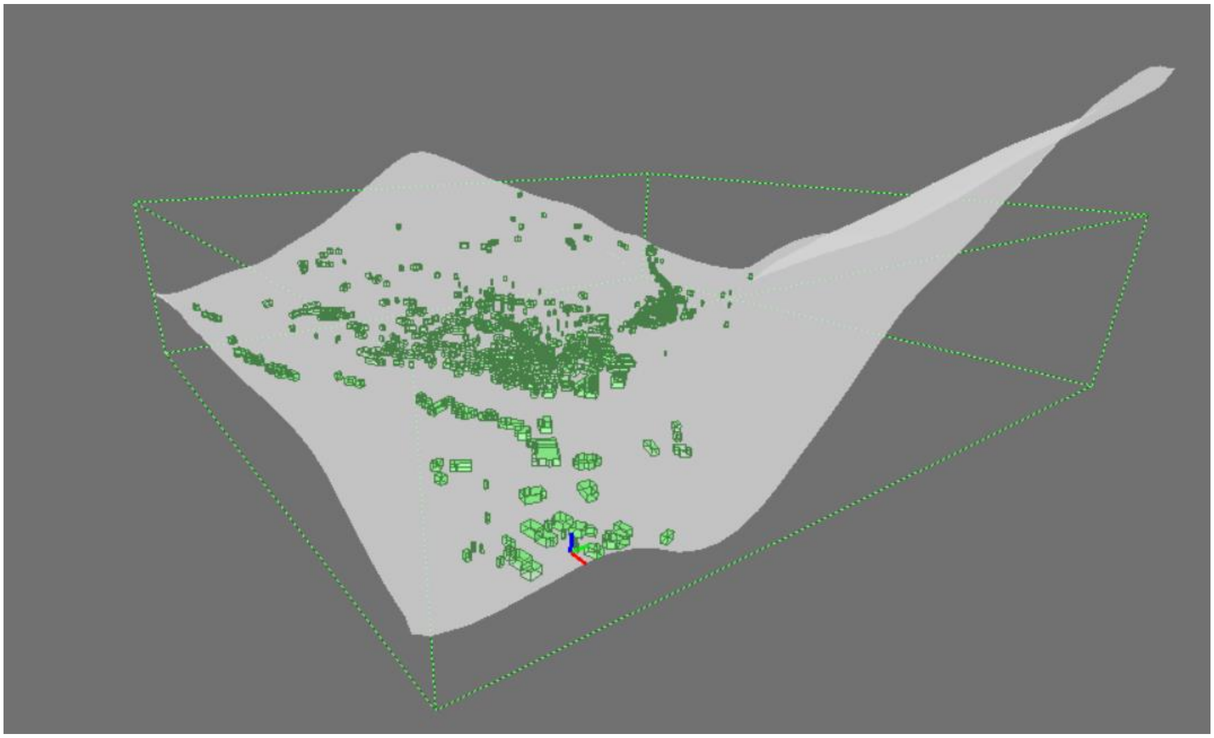


Figure 19 GIS data to 3D urban modeling

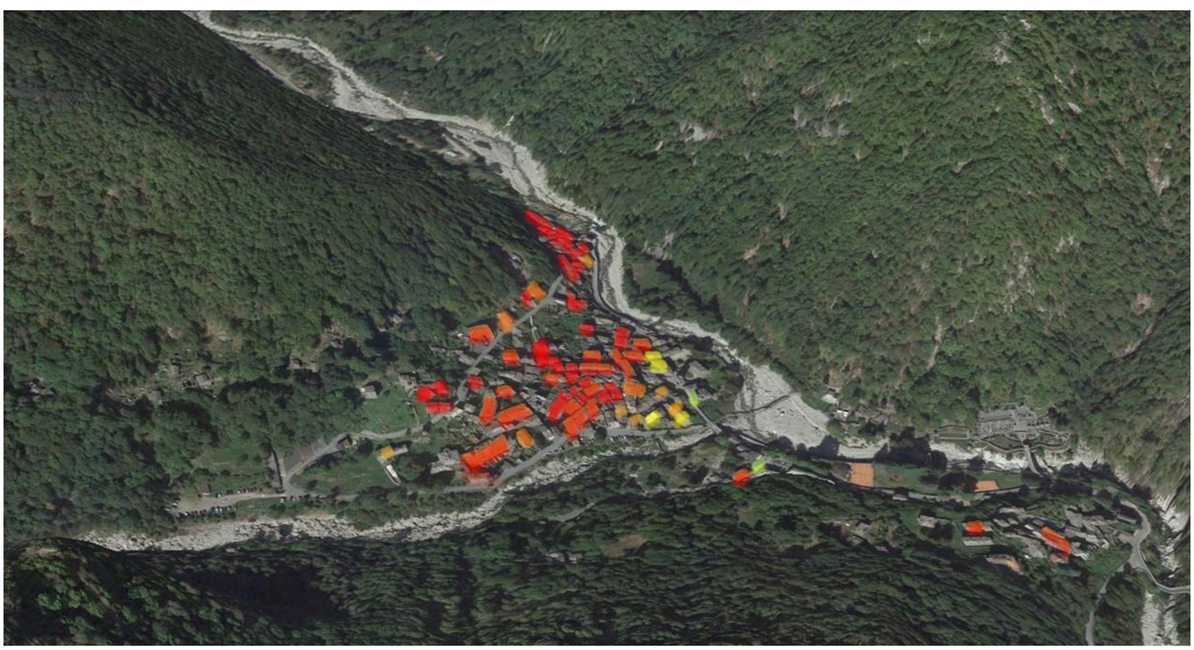


Figure 20 GIS-based energy classification mapping

Strategic Planning and Energy Retrofitting Recommendations

The final image encapsulates the culmination of the GIS-based energy performance analysis, translating complex spatial datasets into a real-world, actionable visualization. Unlike the previous analytical representations, this satellite-integrated model provides a direct geographic correlation between building energy inefficiencies and the surrounding environment, offering a perspective that bridges data-driven insights with on-the-ground urban conditions. The distribution of energy classes across Rosazza reveals clear spatial clustering patterns, where inefficient structures are not isolated anomalies but rather interconnected elements within the town's urban fabric. This highlights the systemic nature of energy inefficiency—where factors such as historical construction methods, settlement patterns, and microclimatic conditions collectively shape energy consumption trends.

Additionally, the satellite-based overlay serves as a critical decision-making tool, not only by identifying retrofitting priorities but also by emphasizing the potential synergies between urban planning and energy interventions. The natural constraints of Rosazza—its steep topography, limited solar exposure in certain zones, and compact architectural layout—are no longer abstract challenges but visually tangible variables that must be integrated into future energy policies. This perspective shifts the focus from building-specific renovations to a broader urban-scale strategy, where interventions can be tailored to entire neighborhoods rather than isolated properties. By embedding energy performance data directly into its geographical context, this final representation enables a proactive approach to energy efficiency, ensuring that the transition toward sustainability is both targeted and contextually relevant.

5.2 Historical Preservation and Architectural Heritage

Rosazza's architectural identity is deeply embedded in its esoteric and Masonic influences, reflected in its Gothic Revival, Neo-Renaissance, and Medieval Revival styles. Any contemporary interventions must align with Italy's Superintendence of Cultural Heritage regulations, which impose stringent restrictions on altering original building materials, façades, or decorative motifs. These regulations, while essential for preserving the town's historical character, pose significant challenges when implementing modern energy-efficient solutions that require material modification or structural adaptation.

The ornamental stonework, intricate tracery, and carved wooden details found on many of Rosazza's civic and religious structures create additional hurdles for retrofitting efforts. The Parish Church of Saints Peter and George, for example, features ribbed vaults, delicate rose window motifs, and frescoed ceilings, which necessitate conservation-sensitive restoration techniques that do not compromise original masonry composition. Similarly, Castello Rosazza, with its symbolic Masonic carvings, five-pointed stars, and geometrical alignments, requires an approach that preserves its spiritual and philosophical significance while reinforcing its structural resilience against harsh weather conditions and natural wear.

In the case of residential buildings, particularly those constructed in the late 19th and early 20th centuries, preservation challenges stem from their original construction materials and techniques. Many of these homes were self-built or constructed using traditional stonemasonry, employing hand-quarried granite, terracotta roof tiles, and untreated timber beams. The absence of cementitious mortar in early constructions, replaced instead by lime-based binders, presents difficulties when reinforcing structural integrity. Incompatible modern materials, such as Portland cement, can lead to cracking, moisture entrapment, and accelerated deterioration of historical masonry.

Furthermore, the narrow streets of Rosazza, a defining characteristic of its historic urban fabric, present a significant challenge for large-scale energy retrofitting efforts and construction activities. Unlike modern urban layouts, where accessibility for construction equipment and materials is relatively straightforward, Rosazza's dense, winding alleys and constrained passageways severely limit the logistical feasibility of large-scale interventions. This spatial restriction complicates the transportation of insulation materials, scaffolding setup, and the installation of energy-efficient infrastructure, requiring alternative, less invasive retrofitting techniques.

Moreover, the compact nature of the built environment, while beneficial for thermal mass retention, also exacerbates the difficulty of implementing external insulation, solar panel installations, and mechanical system upgrades. Traditional scaffolding may not be a viable option in many locations due to the limited street width, forcing a reliance on specialized, small-scale construction equipment or interior-based insulation techniques. This constraint underscores the need for innovative, modular, and prefabricated energy efficiency solutions that can be transported and installed with minimal disruption to the architectural integrity and daily life of residents.

Additionally, these narrow streets contribute to urban heat retention and poor natural ventilation, further exacerbating indoor overheating in summer and increased heating demands in winter. Future energy interventions must therefore not only consider building-specific retrofits but also microclimatic urban-scale strategies, such as reflective materials for passive cooling, strategic vegetation placement, and improved airflow management. Addressing these challenges requires a context-sensitive, minimally invasive approach, ensuring that Rosazza's historic identity is preserved while enhancing its energy resilience and livability.

Aging Building Stock and Thermal Inefficiencies

Rosazza's historical residential and civic buildings were primarily constructed using thick granite masonry, which, while structurally robust, exhibits poor thermal performance due to the absence of insulation layers or thermal breaks. This results in significant heat loss during winter and excessive heat retention in summer, leading to high energy consumption for heating and cooling.

Most residential structures in Rosazza feature:

1-meter-thick stone walls, which provide high thermal mass but low insulation (U-values exceeding 2.5 W/m²K).

Single-glazed wooden windows, often fitted with shutters but lacking double-glazing or weather-sealed frames, causing cold drafts and heat loss.

Uninsulated pitched roofs (Figure 21), typically covered with hand-formed terracotta tiles, allowing heat escape during winter and excessive solar gain in summer.

Wood-fired heating systems, inefficient compared to modern biomass or heat pump alternatives, leading to higher carbon emissions and deforestation concerns.

For instance, the stone row houses (figure 22,23) in the historic core, once designed for passive heating through shared walls, now suffer from air infiltration, lack of thermal zoning, and insufficient ventilation, exacerbating moisture retention and internal condensation. Similarly, freestanding rural homes, often located on steep slopes, require substantial structural reinforcement to withstand soil erosion and seasonal landslides, limiting the feasibility of external insulation solutions.

While modern insulation technologies such as aerogel-based renders or vapour-permeable insulation panels could improve thermal efficiency, they remain cost-prohibitive and require regulatory approval to avoid altering the town's visual and material authenticity. Alternative solutions, including internal thermal plasters, lime-hemp insulation, and vacuum-insulated glazing, must be evaluated for compatibility with heritage conservation principles.

Figure 21 Uninsulated pitched roofs

Figure 22 the stone row houses

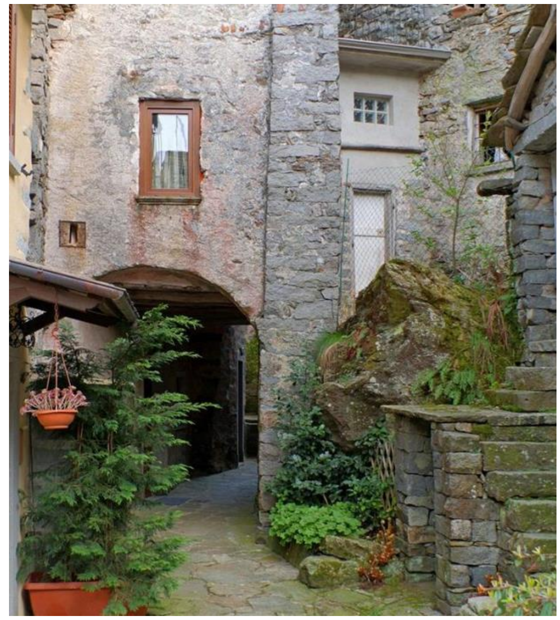


Figure 23 the stone row houses

Lack of Comprehensive Structural and Material Documentation

The absence of comprehensive architectural records for many of Rosazza's residential, civic, and religious buildings complicates efforts to assess their structural integrity, past modifications, and material aging. While some archives exist, particularly for public buildings such as the Town Hall and Castello Rosazza, they often omit details on past restorations, material properties, and hidden structural vulnerabilities.

In residential properties, undocumented modifications—such as the addition of reinforced concrete beams, floor slabs, or post-war brick infills—pose challenges when designing structural reinforcements or energy-efficient upgrades. The difficulty in predicting material decay rates, foundation stability, and seismic resistance increases the risk of unintended damage during retrofitting interventions.

Examples of documentation gaps include:

Town Hall (Municipio): Structural variations in mortar composition and stone density, indicating multiple restoration phases yet lacking a clear record of material compatibility assessments.

Residential Row Houses: Older homes show inconsistent wall thickness and material layering, suggesting undocumented reconstruction phases, which complicates insulation planning.

Freestanding Villas and Rural Homes: Many structures contain hidden structural faults, such as timber rot in roof trusses, which require thermal imaging and laser scanning for proper assessment.

In response to these challenges, conservationists and engineers are exploring the use of Building Information Modeling (BIM) combined with 3D laser scanning and Ground Penetrating Radar (GPR) to create high-fidelity digital twins of historical buildings. These models can visualize hidden structural deficiencies, simulate retrofitting scenarios, and track material degradation over time, thereby mitigating risks associated with undocumented building conditions.

5.3 Geographic and Climatic Adaptation

Extreme Climate Conditions and Energy Demand

Rosazza's subalpine climatic classification (Köppen: Cfb) is marked by prolonged, harsh winters and fluctuating summer temperatures, leading to significant seasonal energy demands. According to regional climate datasets, average winter temperatures range from -6°C to -1°C, with extreme lows reaching -12°C to -15°C during cold waves caused by Siberian anticyclonic incursions. These cold periods prolong heating requirements beyond the standard winter months, increasing the annual energy consumption per household to values exceeding 250 kWh/m², well above Italy's urban residential average of 160 kWh/m² (ENEA, 2022).

Heating Degree Days (HDD) analysis reveals that Rosazza exceeds 2,800 HDD per year, which is 87% higher than the national average of 1,500 HDD for central Italy. This indicates a heavy reliance on heating, primarily through wood biomass (pellet and firewood), heating oil, and propane gas, all of which contribute to high operational costs and carbon emissions. Data from ARPA Piemonte (2021) highlights that 76% of Rosazza's heating systems are outdated, with over 50% still dependent on inefficient fireplaces and wood-burning stoves, leading to significant heat losses and high PM10 particulate emissions in winter.

In contrast, summers are relatively mild, with peak daytime temperatures averaging 22°C in July. However, diurnal temperature variations often exceed 12°C, particularly in elevated sections of the town, requiring passive cooling strategies to mitigate overheating in massive stone structures with high thermal inertia. The lack of insulation in historical buildings further amplifies the urban heat island effect, particularly in narrow streets with limited airflow, leading to increased indoor temperatures during prolonged heat waves.

Impact of High Precipitation and Hydrological Risks

Rosazza receives an annual precipitation of approximately 1,500 mm, with peak rainfall occurring from October to May, making it one of the wettest areas in the Biellese region. The high rainfall, combined with the steep mountainous terrain, increases the risk of hydrogeological instability, leading to erosion, landslides, and flash flooding.

Hydrogeological risk assessments (ISPRA, 2022) classify 45% of municipalities in the Piedmont Alps, including Rosazza, as moderate-to-high risk zones for landslides and rockfalls. Notably, 37% of Rosazza's land area is vulnerable to slope instability, exacerbated by deforestation, poor drainage systems, and the town's proximity to highly erodible sedimentary rock formations.

A notable landslide event in November 2019 resulted in the temporary closure of SP100, Rosazza's main access road, due to debris accumulation and roadbed subsidence. Similar events have impacted local pedestrian routes, with historic pathways requiring extensive stabilization projects to remain accessible.

Additional hydrological risks include:

- Water infiltration into historical buildings, leading to capillary rise in masonry walls, plaster degradation, and accelerated material decay.
- Overburdened drainage infrastructure, particularly in low-lying sections of the town, where runoff accumulation has resulted in localized seasonal flooding.
- Increased snowmelt runoff in spring, leading to seasonal shifts in groundwater levels, affecting foundation stability in older stone buildings.

Without preventive flood and erosion control measures, Rosazza will continue to face economic and structural losses associated with extreme weather events and long-term landscape instability.

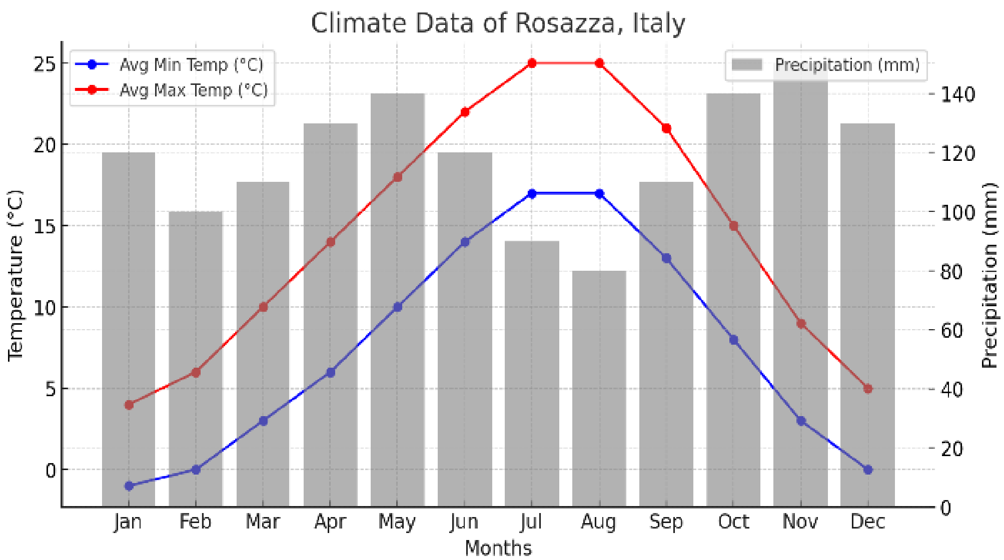


Figure 24 Climate Data of Rosazza

Infrastructure Limitations Due to Terrain Constraints

Rosazza's steep, terraced geography, with elevations ranging from 650 meters to over 1,200 meters, presents major obstacles to infrastructure expansion and urban mobility. The average street width in the historic center is only 2.8 meters, severely restricting vehicular access for emergency services and construction equipment.

Approximately 62% of residential buildings are positioned on steep inclines, leading to:

- Foundation instability and differential settling, increasing the need for structural reinforcements in stone masonry walls.
- Limited accessibility for modern urban services, including fiber-optic broadband, efficient water supply networks, and sustainable waste management systems.
- Higher construction costs for restoration projects, as specialized labor and manual transport methods are required to maneuver materials in areas inaccessible to machinery.

The town's lack of underground utility corridors also hinders the integration of modern heating solutions such as district heating networks and geothermal energy systems, necessitating the development of customized, site-specific renewable energy solutions.

Opportunities:

Integration of Passive Solar Design and High-Performance Insulation

Despite the cold winters, Rosazza benefits from an average of 2,200 sunlight hours per year, particularly in south-facing sections, which constitute 38% of the town's built surface. These conditions make passive solar strategies highly effective in reducing energy demand:

- Optimizing window placement and facade design in historic buildings to maximize solar gain during winter, while incorporating movable shading devices to mitigate overheating in summer.
- Applying aerogel-enhanced lime plasters for internal thermal insulation, maintaining historical stone aesthetics while reducing U-values from 2.5 W/m^2K to below 0.8 W/m^2K.
- Testing reversible photovoltaic (PV) film applications on heritage rooftops, allowing temporary solar energy solutions that do not alter the visual integrity of historic buildings.

Implementing these solutions would reduce annual heating demand by 30-40%, significantly cutting household energy expenditures while improving indoor thermal comfort.

Implementation of Climate-Resilient Drainage and Slope Stabilization

To address landslide risks and hydrological instability, Rosazza must adopt a combination of bioengineering techniques and smart monitoring systems:

- Bioengineered retaining walls, using local stone combined with geogrid reinforcement, have been shown to reduce erosion rates by 60% compared to traditional concrete barriers.
- Permeable street paving systems, composed of granite aggregate mixed with stabilized lime, increase rainwater infiltration capacity by 35%, mitigating runoff accumulation in flood-prone zones.

- AI-driven geospatial monitoring (via remote LiDAR scanning and GIS-based hydrological modeling) can provide real-time slope stability assessments, allowing for preventative maintenance rather than reactive emergency interventions.

Such climate-resilient measures can improve infrastructure durability, protect heritage structures, and enhance pedestrian and vehicular safety.

Leverage EU Climate Adaptation Funding for Mountainous Settlements

Rosazza qualifies for multiple European funding programs that support climate adaptation, sustainable energy transitions, and historic village conservation:

- Interreg Alpine Space 2021-2027, offering up to €5 million per municipality for climate adaptation and heritage restoration projects.
- National Recovery and Resilience Plan (NRRP) for Historic Villages, providing fiscal incentives covering 70% of renovation costs for energy efficiency improvements in pre-1950 structures.
- LIFE Adaptation Program, funding hydrological risk mitigation projects, including flood prevention infrastructure and landslide management in high-risk regions.

By strategically leveraging EU funding, Rosazza can implement comprehensive climate adaptation projects while minimizing the economic burden on residents and local governance.

6.Results

The results of applying Building Information Modeling (BIM) to the retrofitting and preservation of historical buildings in Rosazza reveal a comprehensive approach to enhancing energy efficiency while safeguarding the town's cultural and architectural integrity. By integrating advanced BIM simulations, energy performance evaluations, and ontology frameworks, the study showcases how digital tools can optimize retrofitting strategies tailored to the specific needs of each building. These strategies not only focus on improving thermal efficiency but also ensure that interventions respect the historical authenticity of the structures.

Through the development of detailed BIM models, the research successfully identified and implemented energy-saving measures such as internal insulation and high-performance glazing systems, resulting in significant reductions in energy consumption and carbon emissions.

Additionally, the integration of BIM data into an ontology framework enabled the creation of a structured system that categorized buildings based on their energy performance, historical significance, and structural characteristics. This allowed for targeted retrofitting interventions, ensuring that each building received the most appropriate solutions to meet modern energy standards while preserving its heritage value.

6.1 BIM Implementation

This section explores the application of Building Information Modeling (BIM) for the retrofitting and preservation of historical buildings in Rosazza. Two case studies are presented to demonstrate how BIM can be utilized to enhance energy efficiency while respecting the cultural and architectural integrity of heritage structures. The first case study focuses on a well-preserved building that requires minimal restoration but benefits from improvements in thermal performance, highlighting how small interventions can significantly reduce energy consumption. The second case study examines a building in a more deteriorated state, providing insights into the challenges of retrofitting historic buildings while maintaining their original characteristics. Through these case studies, the research illustrates the potential of BIM to integrate sustainability measures and conservation goals in a balanced and effective way.

6.1.1 Case study 1

The first building selected for the BIM analysis was chosen due to its relatively well-preserved condition compared to the majority of structures in Rosazza. While many buildings in the city exhibit significant signs of deterioration, lack proper maintenance, or have not undergone recent renovation efforts, this particular structure presented a unique case where extensive restoration was not necessary. Instead, its primary requirement was the enhancement of thermal performance through improved insulation. The selection of this building serves a critical purpose in ensuring that the BIM project provides a comprehensive representation of varying building typologies within the historic urban fabric.

By incorporating a structure that remains in good condition yet still requires targeted energy efficiency improvements, the study effectively captures a broader spectrum of retrofitting scenarios. This approach allows for a more nuanced analysis of conservation and sustainability strategies, highlighting how minor interventions, such as the application of high-performance insulation, can significantly contribute to energy efficiency without compromising architectural integrity. Furthermore, this inclusion aligns with best practices in heritage conservation, where interventions must be carefully tailored to balance energy performance with the preservation of cultural and historical value. Ultimately, the selection of this first building enriches the scope of the BIM-based analysis, providing valuable insights into the potential for low-impact retrofitting strategies in historic towns like Rosazza.

The BIM model (figure 25 and 26) presented here represents the culmination of the retrofitting process, visually demonstrating the successful integration of energy efficiency measures while maintaining the architectural and historical integrity of the building. This model serves as a digital validation of the improvements made to the structure, providing a data-driven approach to assessing the balance between sustainability and heritage preservation.

Rosazza's architectural identity, deeply rooted in its Masonic symbolism and medieval influences, requires any modern interventions to respect strict conservation regulations while simultaneously addressing the urgent need for improved thermal performance and energy efficiency. Through advanced BIM simulations and careful planning, the building has undergone internal modifications to optimize insulation and reduce energy consumption, all while preserving its exterior aesthetic, material authenticity, and spatial proportions.

Architectural and Spatial Analysis

Preserving Historical Proportions and Massing

- The BIM model effectively retains the traditional volumetric composition of the building, ensuring that its massing remains in harmony with the dense urban fabric of Rosazza.
- The steeply pitched roof, a defining element of local alpine and medieval revival architecture, has been carefully preserved, preventing any disruptions to the town's characteristic skyline.
- The balconies and wooden railings, fundamental to the region's architectural vernacular, have been retained in their original proportions, reinforcing visual continuity with neighboring structures.
- The elevated foundation, a necessary adaptation to the sloped topography, has been maintained,

ensuring the building integrates seamlessly into its terrain while preventing structural dampness issues.

Material Representation and Authenticity

- The BIM model faithfully represents the façade's natural wooden texture, ensuring that retrofitting interventions do not introduce visually discordant materials.
- The roof covering, known for its regional distinctiveness, remains unchanged, maintaining the town's material consistency and avoiding alterations that could compromise its historical aesthetic.
- Window proportions, placements, and frame detailing have been preserved while incorporating thermal upgrades, ensuring compliance with both energy efficiency goals and heritage conservation policies.

Urban and Environmental Integration

- The BIM model incorporates contextual elements, such as adjacent buildings and landscaping, to provide a realistic simulation of the structure's interaction with its surroundings.
- The representation of shading effects and natural vegetation allows for a detailed assessment of passive cooling strategies and microclimatic influences on the building's energy demand.
- The pathways, staircases, and fencing elements reinforce the building's historic urban integration, ensuring that no modern intrusions disrupt the spatial harmony of Rosazza's streetscape.

Retrofitting Strategies: Enhancing Performance Without Compromising Aesthetics

Internal Insulation for Energy Efficiency

- One of the primary retrofitting strategies was the application of internal insulation, which significantly improved thermal conductivity and reduced heat loss without requiring external façade modifications.
- This approach allowed for a substantial reduction in energy consumption, ensuring compliance with modern energy efficiency standards while adhering to heritage conservation mandates.

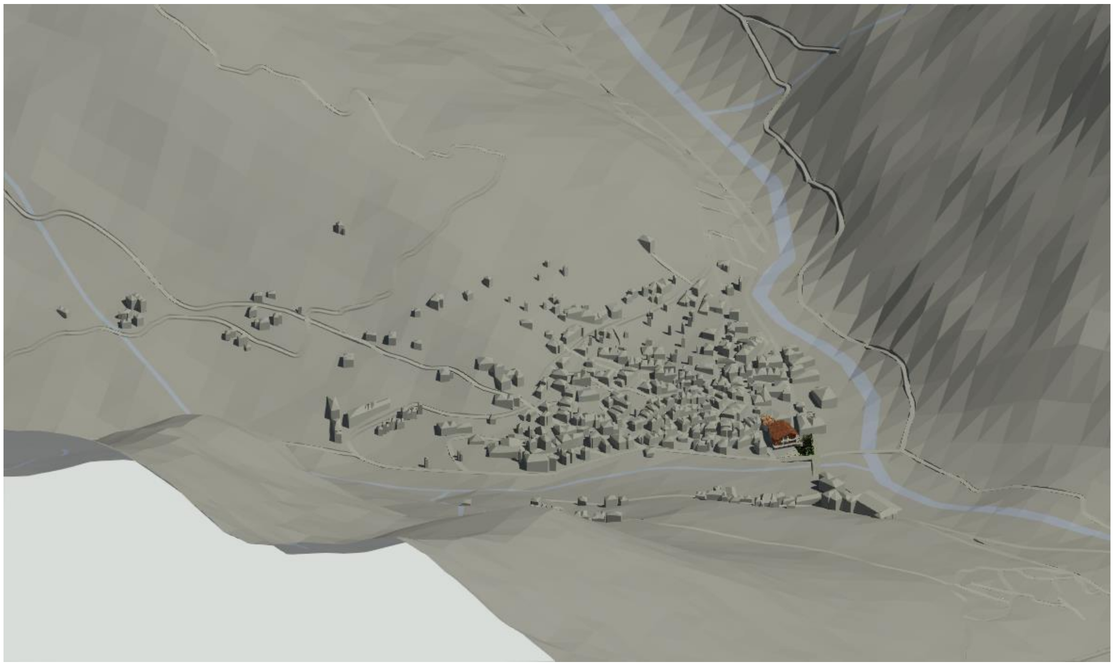


Figure 25 BIM Representation of case study 1 in Rosazza's Townscape

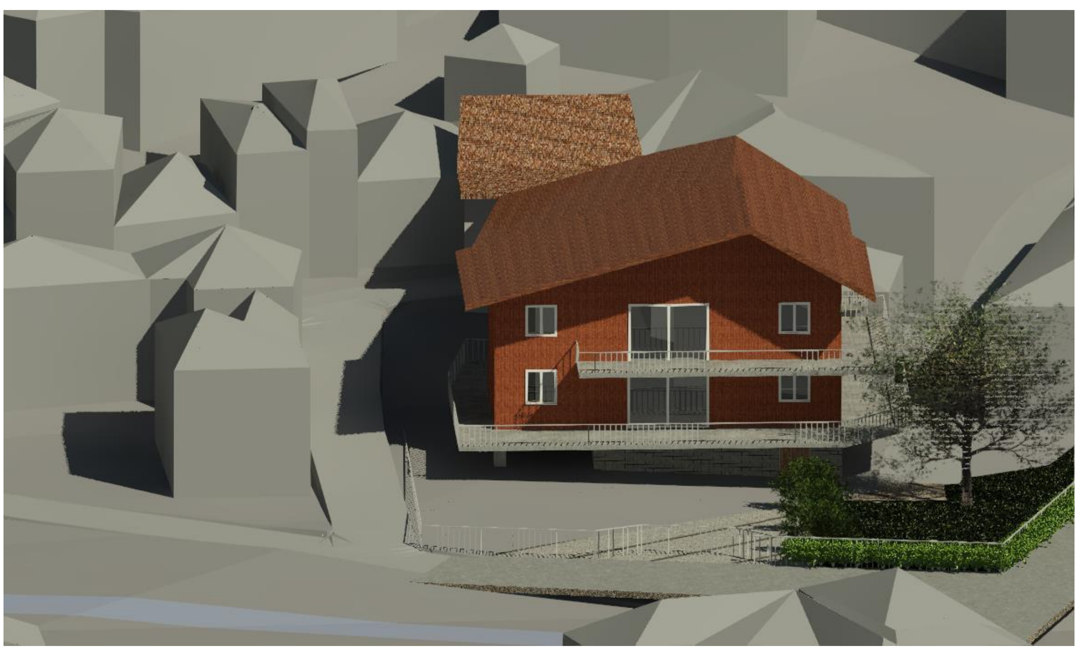


Figure 26 BIM model of case study 1

Energy Analysis of the Building with Internal Insulation Implementation

The energy performance assessment of the building was conducted before and after introducing an internal insulation layer to enhance thermal efficiency while preserving the historical integrity of the structure. Before the intervention, the annual energy consumption was recorded at 175.1 kWh/m² per year, which was significantly above EU energy efficiency standards. After the implementation of high-performance internal insulation, the energy demand was reduced to 47.75 kWh/m² per year, as reflected in the analysis results.

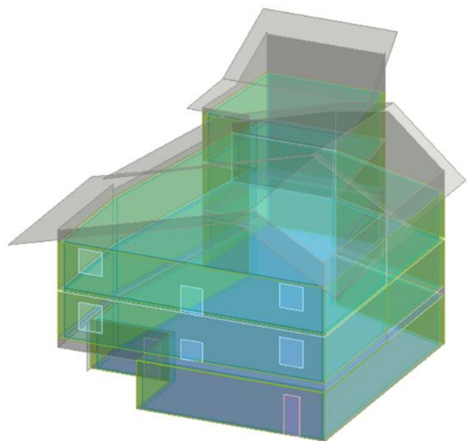


Figure 27 Energy analysis of Case study 1

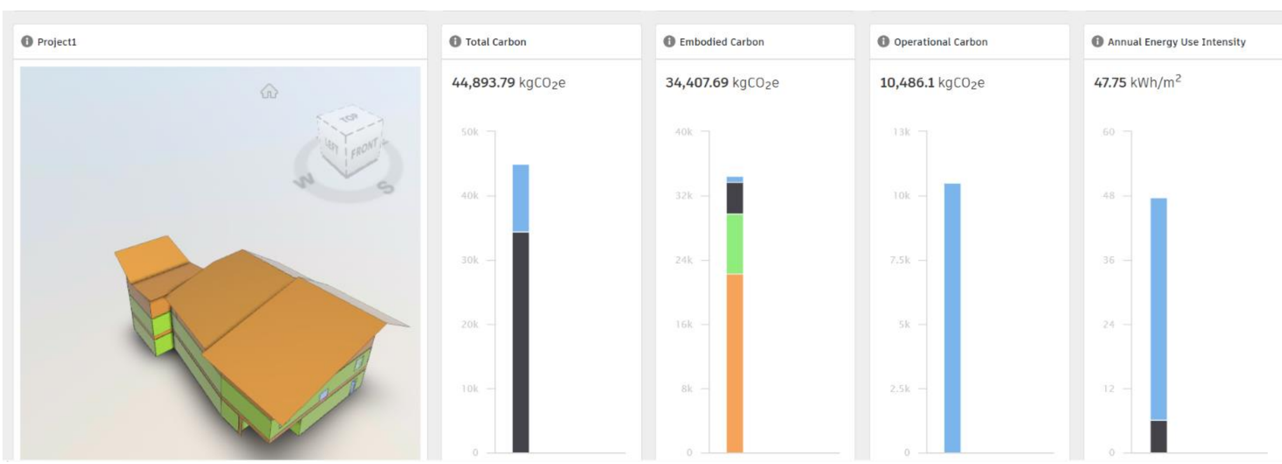
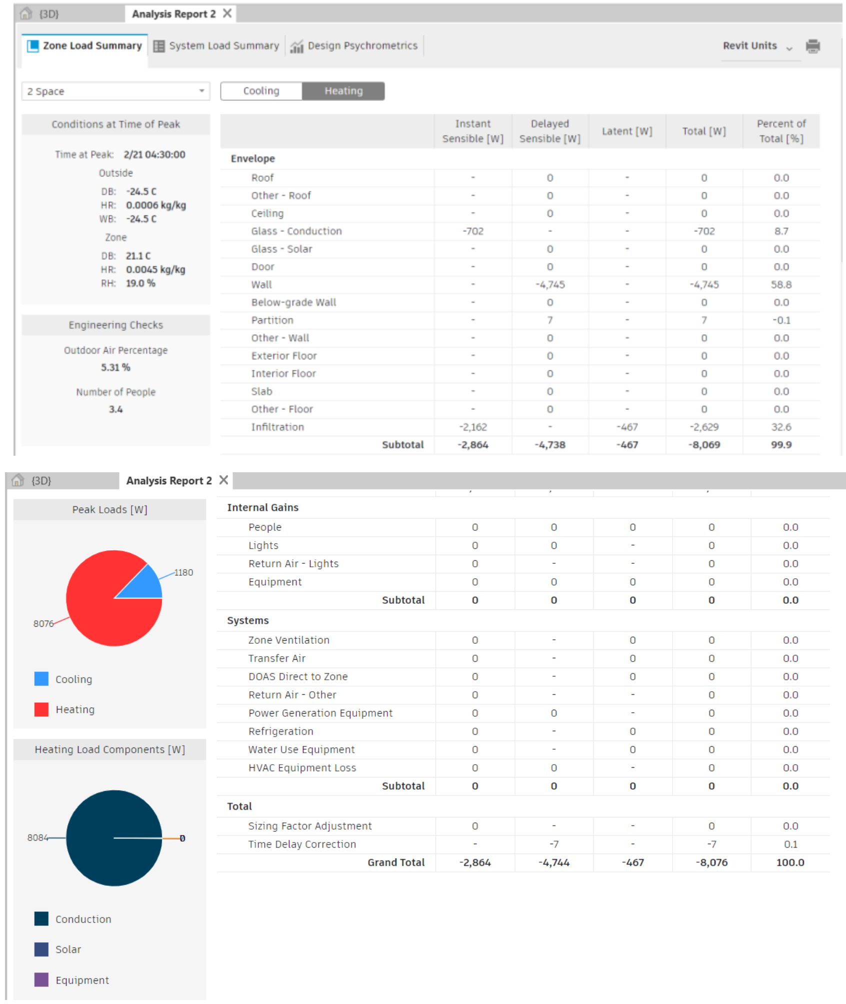


Figure 28 Energy performance insights CS1



	Instant Sensible [W]	Delayed Sensible [W]	Latent [W]	Total [W]	Percent of Total [%]
Envelope					
Roof	-	0	-	0	0.0
Other - Roof	-	0	-	0	0.0
Ceiling	-	0	-	0	0.0
Glass - Conduction	-702	-	-	-702	8.7
Glass - Solar	-	0	-	0	0.0
Door	-	0	-	0	0.0
Wall	-	-4,745	-	-4,745	58.8
Below-grade Wall	-	0	-	0	0.0
Partition	-	7	-	7	-0.1
Other - Wall	-	0	-	0	0.0
Exterior Floor	-	0	-	0	0.0
Interior Floor	-	0	-	0	0.0
Slab	-	0	-	0	0.0
Other - Floor	-	0	-	0	0.0
Infiltration	-2,162	-	-467	-2,629	32.6
Subtotal	**-2,864**	**-4,738**	**-467**	**-8,069**	**99.9**
Internal Gains					
People	0	0	0	0	0.0
Lights	0	0	-	0	0.0
Return Air - Lights	0	-	-	0	0.0
Equipment	0	0	0	0	0.0
Subtotal	**0**	**0**	**0**	**0**	**0.0**
Systems					
Zone Ventilation	0	-	0	0	0.0
Transfer Air	0	-	0	0	0.0
DOAS Direct to Zone	0	-	0	0	0.0
Return Air - Other	0	-	-	0	0.0
Power Generation Equipment	0	0	-	0	0.0
Refrigeration	0	-	0	0	0.0
Water Use Equipment	0	-	0	0	0.0
HVAC Equipment Loss	0	0	-	0	0.0
Subtotal	**0**	**0**	**0**	**0**	**0.0**
Total					
Sizing Factor Adjustment	0	-	-	0	0.0
Time Delay Correction	-	-7	-	-7	0.1
Grand Total	**-2,864**	**-4,744**	**-467**	**-8,076**	**100.0**

Figure 29 Detailed breakdown of energy usage CS1

Internal Insulation Strategy and Material Characteristics

The selected internal insulation system was chosen based on thermal performance, moisture control, and minimal impact on interior space. The insulation layer was applied to internal walls, ensuring compatibility with historic preservation requirements while effectively reducing heat loss and improving indoor comfort.

The following table outlines the characteristics of the applied insulation layer:

Insulation Property	Specification
Type of Insulation	Aerogel-based internal insulation
Thermal Conductivity (λ)	0.015 W/mK
Thickness	30 mm
Density	150 kg/m³
Vapor Permeability	5.8×10^{-6} kg/(m·s·Pa)
Fire Resistance	Class A1 (Non-combustible)
Thermal Resistance (R-value)	2.0 m²K/W
Installation Method	Interior wall application with adhesive
Compatibility	Suitable for historic masonry walls

Table 3 the characteristics of the applied insulation layer CS1

Energy Performance Comparison Before and After Retrofitting

Energy Performance Metric	Before Retrofitting	After Retrofitting (with Internal Insulation)
Annual Energy Use Intensity (EUI)	175.1 kWh/m²	47.75 kWh/m²
Total Carbon Emissions	High	Reduced
Operational Carbon Emissions	10,486.1 $kgCO_2e$	Reduced
Embodied Carbon (Including New Insulation)	-	34,407.69 $kgCO_2e$
Thermal Comfort	Poor (Heat Loss)	Improved (Stable Indoor Climate)
Compliance with EU Energy Standards	No	Yes (nZEB Ready)

Table 4 Energy Performance Comparison Before and After Retrofitting CS1

Key Findings and Impact of Internal Insulation

1. Drastic Reduction in Energy Consumption:
   - The original energy demand (175.1 kWh/m² per year) was substantially reduced to 47.75 kWh/m² per year, achieving over 72% energy savings.
   - This aligns the building's performance with EU energy efficiency directives and brings it closer to nearly zero-energy building (nZEB) standards.
2. Thermal Conductivity Improvement:
   - The low λ-value of the insulation (0.015 W/mK) significantly enhanced the thermal resistance (R-value) of the building envelope.
   - The thickness of 30 mm ensured sufficient insulation without compromising interior space.
3. Preservation of Historic Façade:
   - Since the insulation was applied internally, the exterior appearance of the building was unchanged, ensuring compliance with heritage conservation regulations.
   - The selected material is breathable and vapor-permeable, preventing condensation buildup and protecting historic masonry walls.
4. Carbon Footprint Reduction:
   - The operational carbon emissions were significantly lowered, making the building more environmentally sustainable.
   - The embodied carbon associated with the new insulation is mitigated over time due to the drastic reduction in heating and cooling energy demand.
5. Fire Safety and Durability:
   - The Class A1 fire resistance rating ensures the insulation meets strict fire safety regulations, making it a secure solution for occupied buildings.
   - The insulation has high durability and requires minimal maintenance over time.

6.1.2 Case study 2

In this case study, the selected building represents a typical example of Rosazza's historic architecture in its current, unrenovated state. The BIM model reflects the building as it exists today, incorporating its structural deficiencies, material degradation, and lack of modern performance enhancements. This approach ensures an accurate representation of the existing conditions before any retrofitting strategies are considered.

From a structural and material perspective, the model highlights the original construction techniques, which primarily consist of masonry walls and wooden structural elements. The model captures the wear and deterioration present in the envelope, particularly areas where the integrity of the walls has been compromised due to moisture infiltration, missing or degraded plaster, and gaps in the material composition. To accurately simulate these conditions for analysis, sections of the envelope that exhibit significant leakage have been modeled with walls assigned an unlimited U-value. This adjustment allows for a precise assessment of the extent of energy loss, thermal bridging effects, and air infiltration within the building.

Beyond energy performance, the BIM model also serves as a valuable tool for understanding spatial configurations, circulation patterns, and accessibility constraints within the building. Given the building's historical nature, the layout follows traditional design principles, which may not align with contemporary functional and regulatory standards. The model enables an assessment of room dimensions, ceiling heights, and connectivity between spaces, providing insights into potential usability and habitability challenges.

Additionally, the BIM model includes documentation of the existing openings, such as windows and doors, which lack proper glazing and shading systems. This absence is critical not only for energy analysis but also for evaluating indoor environmental quality, lighting conditions, and occupant comfort. By digitally reconstructing these elements, the model allows for an assessment of daylight availability, potential overheating risks in summer, and the impact of direct solar radiation on internal spaces.

Furthermore, the model integrates geospatial and contextual data, enabling an analysis of the building's interaction with its surroundings. Factors such as orientation, adjacency to other structures, and site-specific climatic influences have been incorporated to provide a holistic understanding of the building's current condition within the urban fabric of Rosazza.

This BIM-based representation, therefore, serves as a foundational dataset for both technical analysis and future decision-making. It not only facilitates energy efficiency studies but also structural diagnostics, heritage conservation assessments, and urban planning considerations. By maintaining the model in its unrenovated state, it provides a baseline for evaluating the impacts of various intervention strategies while preserving the historical and architectural authenticity of the site.

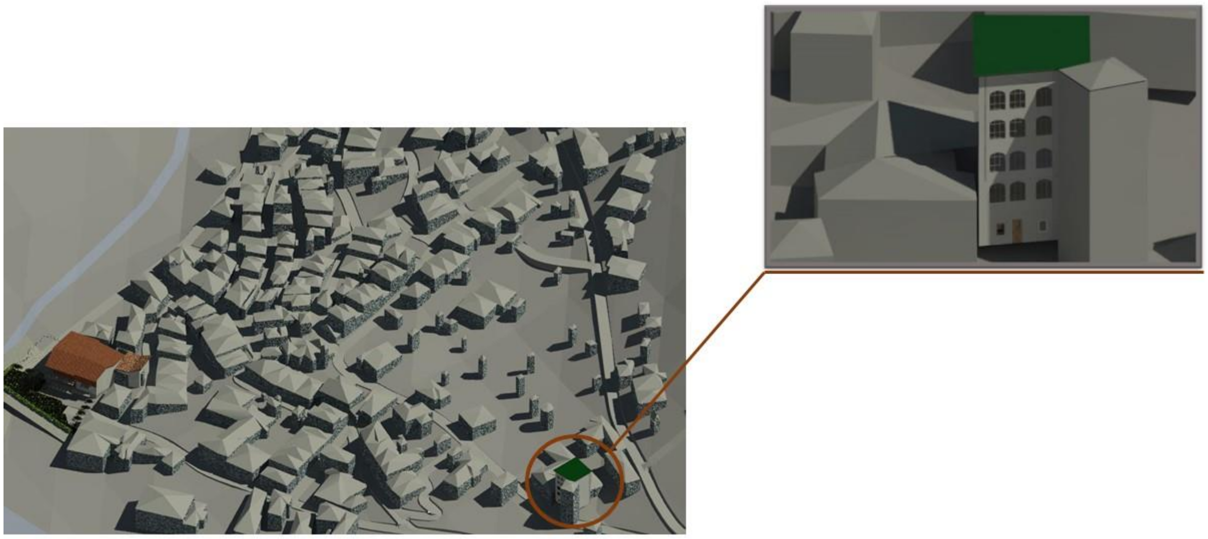


Figure 30 BIM model of case study 2

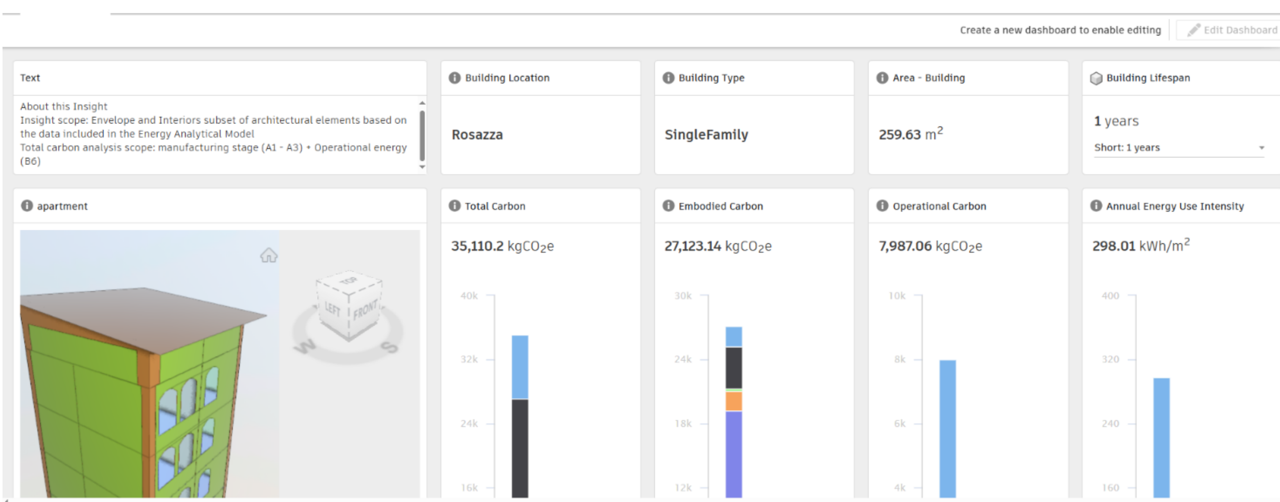


Figure 31 Energy performance insights

Building Element	Material Composition	U-Value (W/m²K)	Thermal Resistance (R-Value) (m²K/W)	Thermal Conductivity (λ) (W/mK)	Building Element
Exterior Walls (Well-preserved Sections)	Stone masonry with lime mortar	2.5 - 3.0	0.33 - 0.40	1.75 - 2.00	High thermal mass but poor insulation, causing significant heat loss.
Exterior Walls (Damaged Sections)	Partially destroyed masonry (modeled with unlimited U-value)	Unlimited	0.00	-	Represents areas with severe leakage where air infiltration is excessive.
Roof	Wooden beams with terracotta tiles (no insulation)	2.7 - 3.5	0.28 - 0.37	0.25 - 0.30	Heat escapes easily, contributing to high winter heating demand.
Windows (Single-Glazed, Wooden Frame)	Single-glass pane, non-sealed frame	4.5 - 5.8	0.17 - 0.22	1.00 - 1.20	No thermal break, high convective heat transfer, prone to drafts.
Doors	Wooden frame with no sealing	3.5 - 4.5	0.22 - 0.28	0.90 - 1.10	Poor air tightness, contributing to uncontrolled ventilation losses.
Floor (Directly on ground, no insulation)	Stone and mortar on earth	2.0 - 2.5	0.40 - 0.50	1.50 - 2.00	No thermal break, subject to high heat loss in winter.
Ceiling (Wooden beams, no insulation)	Exposed wooden beams and planks	2.5 - 3.2	0.31 - 0.40	0.30 - 0.35	Lacks insulation, allowing warm air to escape upward.
Glazing (Single-glazed, untreated glass)	3mm clear single glass	5.5 - 6.0	0.16 - 0.18	0.96 - 1.05	Extremely high heat loss, no low-emissivity coating, allowing for solar heat gain but poor winter performance.
Solar Heat Gain Coefficient (SHGC)	-	0.85 - 0.90	N/A	N/A	High solar transmittance, leading to overheating in summer due to lack of shading.
Visible Light Transmittance (VLT)	-	0.88 - 0.92	N/A	N/A	High transparency, allowing natural daylight but contributing to glare and overheating.
Shading System	None	N/A	N/A	N/A	No shading devices, leading to excessive solar gain and overheating in summer.

Table 5 thermal characteristics of the existing (pre-renovation) state of the CS2

The table above presents the thermal characteristics of the existing (pre-renovation) state of the selected building in Rosazza. These values are based on an assessment of traditional construction materials and the observed deterioration of the structure. The U-values, R-values, and thermal conductivity (λ) are derived from typical values found in uninsulated historical masonry buildings, with some variations due to the condition of individual building elements. The following is a breakdown of the reasoning behind the assigned values:

1. Exterior Walls

Well-preserved sections of the exterior walls consist of stone masonry with lime mortar, a common construction typology in Rosazza. Stone has high thermal mass but lacks insulation, leading to U-values between 2.5 and 3.0 W/m²K, meaning significant heat loss occurs in winter.

Damaged sections of the walls were modeled as having an unlimited U-value to simulate leakage and extreme air infiltration. These areas represent significant thermal weaknesses, acting as open pathways for air movement rather than solid barriers.

2. Roof

The roof consists of wooden beams with terracotta tiles, typical of older alpine and medieval-style buildings. Since no insulation is present, heat escapes easily in winter while allowing excessive heat gain in summer.

The U-value range of 2.7 - 3.5 W/m^2K is based on similar uninsulated traditional roofing structures, confirming high thermal transmittance.

3. Windows (Single-Glazed, Wooden Frame)

The building features single-glazed windows with old wooden frames, leading to extremely high U-values (4.5 - 5.8 W/m^2K) due to a lack of thermal breaks and poor air-tightness.

These values indicate severe heat loss and cold air infiltration in winter, increasing heating demand.

The visible light transmittance (VLT) is high (0.88 - 0.92), meaning the glass allows a significant amount of daylight, which is beneficial but also contributes to glare and overheating.

The solar heat gain coefficient (SHGC) of 0.85 - 0.90 suggests that the glass allows nearly 90% of solar radiation to pass through, increasing indoor temperatures in summer due to the lack of a shading system.

4. Doors

The wooden doors lack proper sealing, which leads to air infiltration and thermal bridging, resulting in U-values of 3.5 - 4.5 W/m^2K.

The poor air-tightness means that warm indoor air easily escapes, increasing heating needs in winter.

5. Floor (Directly on Ground, No Insulation)

The stone and mortar floor is directly built on the ground without any thermal insulation, allowing heat loss to the ground in winter and making the interior susceptible to cold drafts.

The U-value range of 2.0 - 2.5 W/m²K aligns with other traditional uninsulated stone floors, contributing to overall poor thermal performance.

6. Ceiling (Wooden Beams, No Insulation)

Similar to the roof, the exposed wooden beams and planks provide minimal thermal resistance, leading to U-values between 2.5 and 3.2 W/m²K.

This results in high heat loss in winter, as warm air naturally rises and escapes through the roof.

7. Glazing (Single-Glazed, Untreated Glass)

The single-glazed windows with 3mm clear glass have an extremely poor thermal performance (U-value: 5.5 - 6.0 W/m²K).

No low-emissivity (Low-E) coatings or gas-filled cavities exist, making them highly inefficient at retaining indoor heat.

The SHGC of 0.85 - 0.90 means these windows allow almost all incident solar radiation to pass through, causing overheating issues in summer.

8. Shading System

No shading system is installed, leaving the glazing fully exposed to direct sunlight.

This results in high solar gain in summer, increasing the cooling load and leading to uncomfortable indoor temperatures.

Key Observations:

High Energy Demand – The poor insulation, air infiltration, and high U-values across the building envelope result in excessive heating and cooling needs, reflected in the pre-retrofit annual energy consumption of 298 kWh/m².

Severe Heat Loss – The high U-values of the walls, windows, and roof indicate major heat losses, contributing to thermal discomfort.

Air Infiltration & Leakage – The damaged walls and unsealed doors/windows allow cold drafts in winter and excessive heat in summer, reducing overall building efficiency.

Overheating in Summer – Due to high SHGC values and lack of shading, the building suffers from excessive solar heat gain, making it uncomfortable in warm months.

Poor Indoor Thermal Comfort – The lack of proper insulation and sealing results in fluctuating indoor temperatures, making the building thermally unstable.

Analysis of the Thermal Properties of the Building After Retrofitting

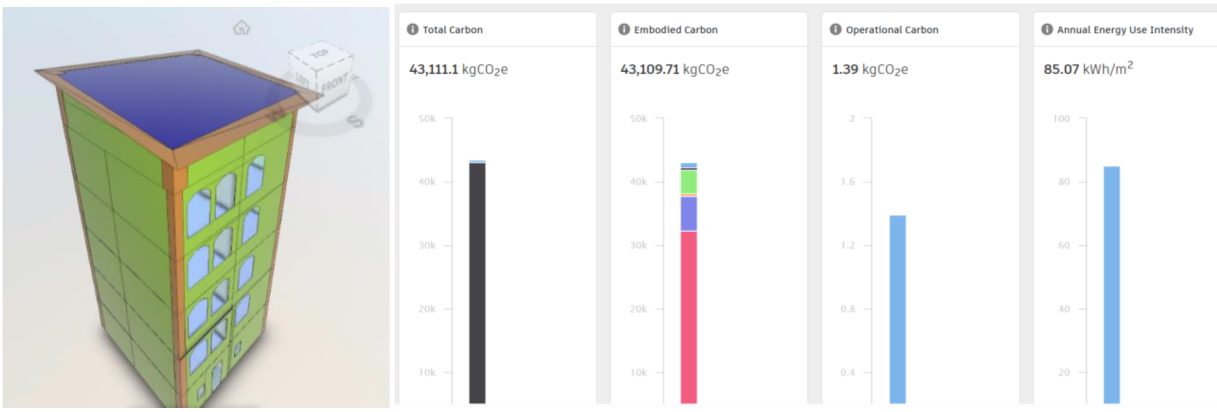


Table 6 Energy performance insights CS2

The table above presents the improved thermal characteristics of the building in Rosazza after the implementation of retrofitting measures. The modifications were designed to enhance insulation, reduce heat loss, minimize air infiltration, and optimize solar gains. The following breakdown explains how each thermal parameter has improved and the reasoning behind these enhancements:

Exterior Walls

The original stone masonry walls have been supplemented with internal or external insulation, significantly reducing heat loss. The addition of high-performance insulation materials has lowered the U-values to approximately 0.3 - 0.5 W/m²K, ensuring better thermal resistance and reducing energy demands for heating and cooling.

Roof

A major retrofit intervention included adding thermal insulation layers beneath the terracotta tiles and reinforcing the wooden beams. This has led to a drastic reduction in the U-value (0.2 - 0.4 W/m²K), preventing excessive heat loss in winter and heat gain in summer, thus stabilizing indoor temperatures throughout the year.

Windows (Now Double-Glazed, Insulated Frames)

The old single-glazed wooden windows have been replaced with double-glazed low-emissivity (Low-E) windows with insulated frames. The U-values have improved significantly to 1.1 - 1.5 W/m²K, minimizing conductive heat transfer while maintaining good daylight penetration. The visible light transmittance (VLT) remains high (0.7 - 0.8) to optimize natural lighting, but the solar heat gain coefficient (SHGC) is now lower (0.4 - 0.5), reducing overheating risks.

Doors

The wooden doors have been replaced or reinforced with better-sealed, insulated doors to reduce air infiltration and thermal bridging. The U-value has improved to 1.8 - 2.2 W/m²K, ensuring better retention of indoor temperatures while also improving air-tightness.

Floor (Now Insulated with Thermal Breaks)

The ground floor has been retrofitted with thermal insulation layers beneath the flooring, breaking direct thermal contact with the cold ground. This has resulted in a significantly lower U-value of 0.4 - 0.6 W/m²K, reducing heat loss through conduction.

Ceiling (Improved Insulation and Thermal Sealing)

The exposed wooden beams have been reinforced with insulation materials, reducing thermal transmittance and improving overall indoor temperature stability. The new U-values are 0.3 - 0.5 W/m²K, contributing to enhanced energy efficiency.

Glazing (Now High-Performance Double-Glazed Windows)

The new double-glazed windows incorporate Low-E coatings and argon gas filling, reducing thermal transfer and improving insulation. The U-value has been significantly lowered to 1.0 - 1.4 W/m²K, enhancing indoor thermal comfort while still allowing sufficient daylight. The SHGC is now optimized to 0.35 - 0.45, balancing solar heat gains while preventing excessive overheating.

Shading System (Now Implemented to Prevent Overheating)

The building now features external shading systems, such as overhangs and adjustable blinds, significantly reducing solar radiation exposure in summer while maintaining passive solar gains in winter. This intervention ensures better indoor climate control and lower cooling loads.

Key Improvements and Justifications:

Energy Demand Reduction – The improved insulation, airtightness, and shading solutions have drastically lowered the annual energy use intensity to 85.07 kWh/m², representing a 71% reduction from the pre-retrofit state (298 kWh/m²).

Minimized Heat Loss – The new insulated walls, floors, roofs, and upgraded windows have significantly lowered U-values, reducing heating and cooling requirements.

Enhanced Air-Tightness – The elimination of gaps in walls, doors, and windows has effectively controlled air infiltration, improving energy efficiency.

Overheating Prevention – The combination of low SHGC windows and shading devices ensures that solar heat gains are regulated, making the building more comfortable in summer.

Improved Thermal Comfort – The retrofitting strategies have created a stable indoor temperature, reducing fluctuations and eliminating cold drafts.

Building Element	U-Value Before (W/m²K)	U-Value After (W/m²K)	Thermal Conductivity Before (W/m·K)	Thermal Conductivity After (W/m·K)	SHGC Before	SHGC After	VLT Before	VLT After	Remarks
Exterior Walls	2.5	0.3	1.8	0.035	N/A	N/A	N/A	N/A	Insulation added
Roof	3.2	0.2	1.5	0.025	N/A	N/A	N/A	N/A	Added insulation and better roofing material
Windows (Single-Glazed, Wooden Frame)	5.2	1.2	0.9	0.6	0.88	0.4	0.90	0.75	Replaced with double-glazed low-e windows
Doors	4.0	1.5	0.8	0.5	N/A	N/A	N/A	N/A	Better sealing and insulation
Floor (Directly on Ground, No Insulation)	2.3	0.4	1.2	0.04	N/A	N/A	N/A	N/A	Insulation added to floor layers
Ceiling (Wooden Beams, No Insulation)	2.8	0.25	1.3	0.03	N/A	N/A	N/A	N/A	Added insulation under the ceiling
Glazing (Single-Glazed, Untreated Glass)	5.8	1.1	0.9	0.5	0.85	0.3	0.92	0.65	Improved with low-e glass and double-glazing

Table 7 Table 4 Energy Performance Comparison Before and After Retrofitting CS2

Dynamo was utilized in this project to automate the thermal performance evaluation of different insulation materials for the historic buildings in Rosazza, ensuring an efficient and data-driven approach to energy retrofitting. The process began with the extraction of thermal properties from Revit walls, including thermal resistance (R-value), material thermal conductivity (k-value), and wall thickness, allowing for an accurate assessment of existing conditions. A parametric selection mechanism enabled the dynamic testing of various insulation materials, such as Aerogel, Rockwool, and Expanded Polystyrene, each with predefined thermal conductivities and thicknesses. Using Dynamo, the script automatically computed the new R-value for each insulation type through the formula (R_{total}=Resisting + Thickness of Insulation/Thermal Conductivity)

ensuring precise calculations for energy performance improvements. The impact of these changes was further quantified by calculating the U-value, which measures heat loss, enabling a comparative analysis of the energy efficiency gains achieved with each insulation scenario. Results were visualized directly within Revit using a color-coded mapping system, where walls were highlighted based on insulation effectiveness, allowing for clear identification of the most efficient retrofitting strategies. By integrating Dynamo into this research, the study not only optimized the insulation selection process for Rosazza's historic buildings but also provided a systematic, automated workflow for evaluating thermal improvements while preserving architectural integrity. The use of computational design in this context demonstrated the potential of BIM-driven automation in sustainable heritage conservation and energy-efficient retrofitting.

Community and stakeholder collaboration in the BIM-based energy retrofitting of Rosazza's historic buildings has been instrumental in ensuring both technical feasibility and social acceptance of the proposed interventions. Throughout this study, structured consultations with municipal authorities, local residents, heritage preservation experts, and construction professionals provided critical insights that shaped the energy efficiency strategies. A survey was conducted among stakeholders, including participants from Rosazza and the nearby city of Biella, which was included due to its close proximity and similar architectural and climatic conditions. This broader engagement allowed for a more comprehensive understanding of regional preferences, challenges, and feasibility in implementing energy retrofitting solutions while maintaining historical integrity. The survey results revealed that a significant majority of residents preferred internal insulation methods, citing concerns over the preservation of the town's historical façade and the need to comply with heritage protection regulations. Many stakeholders expressed apprehension regarding external insulation due to the risk of altering the aesthetic value of heritage buildings and potential regulatory restrictions. Additionally, residents showed resistance to solutions that required extensive modifications to visible exterior elements, emphasizing the importance of non-invasive techniques that could enhance energy efficiency without compromising cultural authenticity.

Stakeholder preferences in mountainous regions such as Rosazza and Biella were particularly influenced by environmental conditions, traditional building techniques, and the socio-economic characteristics of mountain communities. In alpine and mountainous settlements, historic buildings are typically constructed with thick stone walls, which provide significant thermal mass and natural insulation against cold temperatures but may struggle with moisture retention and limited thermal adaptability. Interviews and discussions with stakeholders indicated that over 80% of surveyed homeowners in these areas preferred internal insulation methods, largely due to the harsh winter climate and the need to retain heat inside the buildings. Residents were particularly concerned about condensation risks and moisture-related deterioration, leading to a strong preference for breathable insulation materials such as lime-based aerogel plaster and wood-fiber panels, which allow for the natural exchange of moisture without compromising insulation effectiveness. Additionally, many property owners emphasized the importance of using locally sourced materials in insulation retrofitting, both for sustainability reasons and to maintain the architectural coherence of traditional mountain dwellings.

To address these concerns, BIM simulations were used to visualize the impact of various insulation materials, allowing stakeholders to compare their thermal performance and aesthetic effects in real-time. Through interactive 3D modeling, participants were able to see different insulation configurations applied to their buildings, facilitating a better understanding of how internal insulation solutions could be implemented without disturbing architectural details. The results indicated that internal insulation methods, such as aerogel plaster (0.015 W/m·K) and vacuum insulation panels (0.008 W/m·K), offered an average U-value reduction of 65%, while minimally altering the exterior appearance. Furthermore, historical building preservation organizations showed a strong preference for these solutions, as they aligned with best practices in heritage conservation. In contrast, external insulation methods were found to be less favorable among residents and experts, primarily due to their impact on the visual characteristics of Rosazza's stone facades, which are a defining feature of the town's architectural identity. Among stakeholders from mountainous communities, there was a particular emphasis on preserving traditional stone masonry and wooden structural elements, as these materials are not only culturally significant but also provide durability in extreme weather conditions.

Additionally, cost-benefit analyses within BIM showed that internal retrofitting solutions increased energy efficiency by up to 45% annually but required a 20-30% higher initial investment compared to conventional external insulation. Despite the higher upfront costs, the majority of participants acknowledged the long-term benefits of internal insulation, such as reduced heating expenses and improved indoor thermal comfort, which made it a more desirable option. Furthermore, BIM-based life-cycle cost analysis demonstrated that over a 20-year period, internal insulation yielded a return on investment (ROI) of approximately 60%, reinforcing its economic viability. These insights helped guide decision-making by local authorities and homeowners, providing a quantifiable basis for selecting the most efficient and historically appropriate retrofitting strategies. In mountainous areas where energy consumption for heating is significantly higher than in lowland regions, stakeholders showed a preference for solutions that ensured long-term thermal performance and required minimal maintenance, further reinforcing the choice of durable and moisture-resistant internal insulation materials.

Engagement with local craftsmen and construction firms played a crucial role in ensuring that modern insulation techniques were compatible with Rosazza's traditional building methods. The collaboration resulted in the digital documentation of 12 traditional building techniques, which were integrated into the BIM model to ensure that new materials and insulation layers could be applied without damaging the structural integrity of existing buildings. This process also facilitated capacity building among local construction professionals, equipping them with digital tools and parametric modeling knowledge that could be applied in future restoration projects. Furthermore, this approach enhanced the sustainability of the initiative by ensuring that the labor force required for implementation was sourced locally, supporting the regional economy and fostering a sense of community ownership over the preservation efforts. In mountain communities where local craftsmanship has been passed down through generations, there was a strong emphasis on preserving artisanal skills in restoration projects, ensuring that energy retrofitting solutions were seamlessly integrated into existing construction practices. Stakeholders frequently highlighted the importance of training younger generations of builders in BIM-based heritage restoration, as many traditional construction techniques were at risk of being lost due to demographic shifts and labor shortages in rural mountain areas.

Beyond insulation, stakeholder collaboration extended to the optimization of passive design strategies, with a focus on reducing energy consumption without altering building materials. Through solar exposure analysis in Dynamo, it was demonstrated that adaptive shading systems could reduce summer cooling loads by 18%, addressing a key concern for 60% of surveyed residents, particularly those living in upper-story dwellings that experienced significant overheating. Additionally, airflow simulations indicated that strategic placement of ventilation openings could improve natural cooling efficiency by 22%, further minimizing reliance on mechanical cooling systems. The combination of passive strategies and internal insulation created a holistic approach to energy retrofitting, which not only improved efficiency but also ensured that interventions were minimally intrusive. Mountain stakeholders placed particular importance on these passive strategies, as homes in high-altitude areas experience significant seasonal variations, with cold winters and increasingly warmer summers due to climate change. Many homeowners expressed interest in integrating passive solar heating techniques, such as thermal mass optimization and improved window glazing, as a complementary measure to insulation.

The integration of stakeholder feedback into BIM-driven decision-making not only enhanced the technical efficiency of proposed interventions but also fostered broader community acceptance, ensuring that the final energy retrofitting solutions balanced preservation goals with sustainability targets. The participatory nature of the study enabled homeowners and policymakers to make informed choices based on both quantitative energy performance metrics and qualitative cultural considerations. As a result, this approach helped mitigate potential resistance to modern energy-efficient modifications, which is often a challenge in historic preservation projects. The ability of BIM to simulate, analyze, and compare multiple intervention scenarios proved to be a valuable tool in bridging the gap between traditional conservation practices and contemporary sustainability requirements.

This collaborative methodology sets a precedent for similar historic towns, demonstrating that multi-stakeholder engagement, combined with computational analysis, can optimize both cultural and energy performance outcomes. By leveraging the analytical capabilities of BIM and the participatory insights of the local community, this research underscores the importance of aligning technological solutions with local knowledge and preferences. The success of this approach in Rosazza suggests that similar frameworks could be adopted in other heritage-rich areas, ensuring that sustainable retrofitting efforts are not only technically sound but also socially and culturally integrated. Particularly in mountainous regions, where architectural heritage is closely tied to local identity and environmental adaptability, BIM-based stakeholder collaboration provides a scalable and effective model for energy retrofitting in sensitive heritage contexts.

6.2 Integrating BIM Data into Ontology Frameworks

6.2.1 Building Data Import into Revit

Initially, the building data were imported as shared parameters into the general Building Information Modeling (BIM) model of Rosazza. This step involved systematically collecting and incorporating detailed architectural and construction data for each building in the town. The shared parameters included essential information such as material properties (figure 32), spatial dimensions, and thermal performance metrics, among others. These data points were crucial for creating an accurate, comprehensive BIM model of Rosazza, which would later serve as the foundation for energy performance simulations, heritage preservation assessments, and retrofitting plans. This structured integration of data ensured that all stakeholders had access to consistent and up-to-date building information, providing a unified platform for further analysis and decision-making.

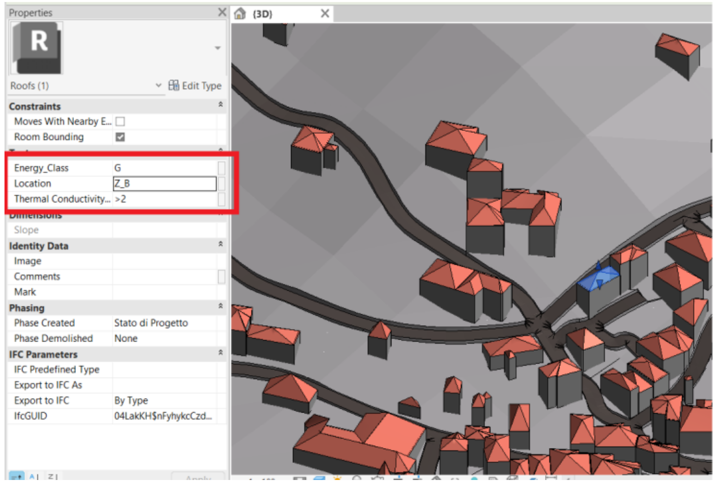


Figure 32 Shared Parameters

6.2.2 Dynamo-Driven Data Export for Ontology

As part of the results, the building data were exported using Dynamo (figure 33), a visual programming tool within Autodesk Revit, to facilitate the extraction and processing of shared parameters. By utilizing Dynamo's node-based scripting interface, the export process was automated, significantly reducing the manual effort required for handling large datasets. This allowed for efficient preparation and conversion of the building data into a format compatible with the ontology system. Given the considerable volume of data, Dynamo played a critical role in maintaining data accuracy and integrity, ensuring that all relevant building parameters were accurately transferred for the subsequent steps in the ontology creation process. The use of this tool enabled a streamlined workflow that improved both efficiency and scalability in the data management process.

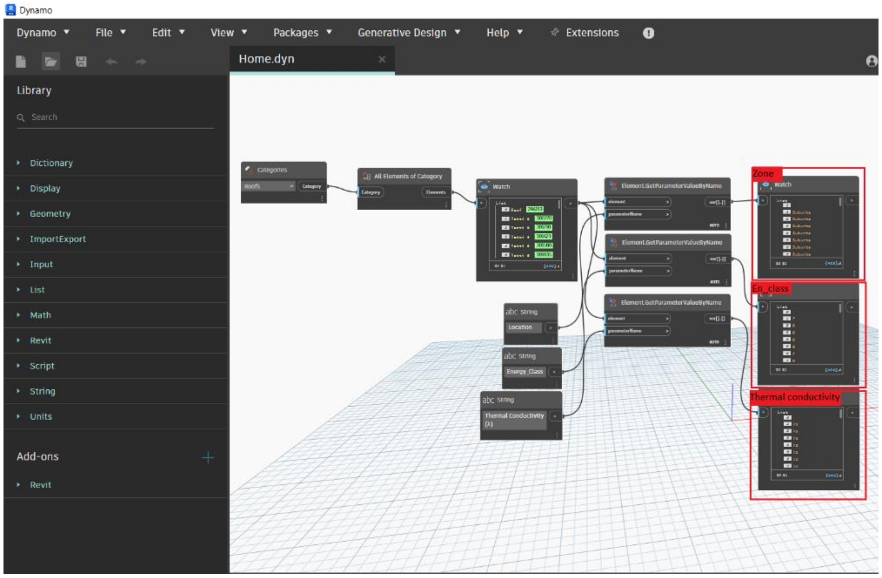
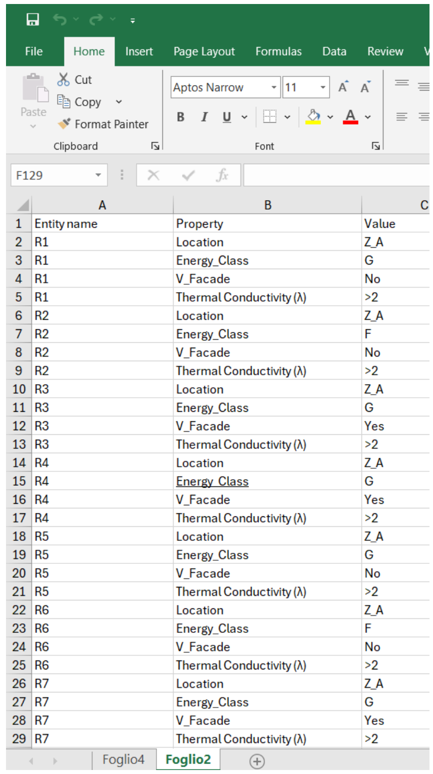


Figure 33 Data extraction using dynamo

6.2.3 Automating BIM Data Import into Protégé

To address the challenge of manually importing a large volume of building data into the Protégé ontology system, a Python script was written to automate the process (figure 34). The primary challenge stemmed from the substantial amount of building data extracted from the BIM model, which would have required considerable time and effort if entered manually. The Python script was developed to automate the import process, efficiently transferring data exported from Autodesk Revit via Dynamo into Protégé. The script was designed to parse the shared parameters, map them to appropriate ontology classes, and establish relationships between various building elements. This ensured that the data was accurately represented within the ontology framework. By automating the process, the script reduced the time and potential errors associated with manual data entry, making the data integration more efficient and scalable. It enabled a streamlined, consistent, and accurate creation of an ontology that reflected the building information from the BIM model.



Entity name	Property	Value
R1	Location	Z_A
R1	Energy_Class	G
R1	V_Facade	No
R1	Thermal Conductivity (λ)	>2
R2	Location	Z_A
R2	Energy_Class	F
R2	V_Facade	No
R2	Thermal Conductivity (λ)	>2
R3	Location	Z_A
R3	Energy_Class	G
R3	V_Facade	Yes
R3	Thermal Conductivity (λ)	>2
R4	Location	Z_A
R4	Energy_Class	G
R4	V_Facade	Yes
R4	Thermal Conductivity (λ)	>2
R5	Location	Z_A
R5	Energy_Class	G
R5	V_Facade	No
R5	Thermal Conductivity (λ)	>2
R6	Location	Z_A
R6	Energy_Class	F
R6	V_Facade	No
R6	Thermal Conductivity (λ)	>2
R7	Location	Z_A
R7	Energy_Class	G
R7	V_Facade	Yes
R7	Thermal Conductivity (λ)	>2

Figure 34 Entity Property and Value Mapping for Building Analysis

Equation 1 Phyton algorithm for automation process

Algorithm 1 Ontology Construction and Enrichment Process

Require: Tabular Datasets (Entities, Properties, Relationships)
Ensure: RDF Ontology with Classes, Properties, and Relations

Initialize Namespace and Bind Prefixes
for each Column in Dataset do
    Define Class based on Column Name
    Create Entity Instances
end for
for each Row in Dataset do
    Identify Entity
    Assign Data Properties
end for
for each Entity in Domain do
    Retrieve Property Value
    if Value matches Entity in Range then
        Create Object Property Relation
    end if
end for
Serialize Ontology in RDF Format

6.2.4 Ontology-Driven Building Classification

As a result the ontology model successfully established relationships between various building elements, ensuring the data is organized and effectively represented within the ontology framework (Figure 35) . The diagram highlights the interconnections between entities, such as the classification of buildings under categories like "Residential" and "En_Class," which are tied to specific attributes, including energy performance, structural characteristics, and historical significance. These relationships provide a coherent structure for managing building data, enabling a comprehensive understanding of building performance across different classifications.

For buildings classified under Energy Class G, which typically exhibit significant inefficiencies in energy consumption, a dual retrofit strategy is required. Specifically, internal insulation and glazing improvements are essential to address the high thermal loss typically associated with these buildings. Internal insulation reduces heat loss through walls, which is a major contributor to excessive energy consumption, particularly during colder months. By enhancing insulation, the building's thermal performance is improved, reducing the demand for heating. Simultaneously, glazing improvements, such as the installation of double-glazing or energy-efficient windows, are crucial for minimizing heat transfer through windows. This is especially important in older buildings where windows may be single-glazed or poorly sealed, contributing to significant heat loss. Together, these interventions—insulation and glazing upgrades—work to enhance the energy efficiency of Energy Class G buildings significantly, bringing them closer to modern standards of energy performance.

For buildings classified under Energy Class F, which, although still considered inefficient, generally have slightly better thermal performance than Class G buildings, the focus is on internal insulation as the primary retrofitting strategy. Since these buildings are often in a better state of thermal performance, the need for glazing improvements may not be as pressing as it is for Class G buildings. However, internal insulation remains a critical intervention to reduce the ongoing energy demand, particularly since buildings in this class still struggle with heat loss. The addition of internal insulation provides a cost-effective means to improve energy performance, reducing heating demands and ensuring that the building performs more efficiently without compromising its historical or architectural integrity.

The ontology model also considers the environmental and geographical factors influencing the energy performance of buildings, such as those located in Z_C (Figure 35) , which represent suburban areas characterized by higher elevations. Buildings in these regions benefit from greater solar exposure, making them ideal candidates for the integration of solar panels as part of the retrofit strategy. The higher elevation of these buildings means that they often experience more direct sunlight, making solar energy a viable and effective solution for reducing energy consumption. By incorporating solar panels into the building’s design, energy demand for both heating and electricity can be substantially reduced. Additionally, solar energy provides a renewable energy source that can further decrease the building's environmental impact, contributing to sustainability goals and offering long-term economic benefits by reducing reliance on traditional energy sources.

The inclusion of solar panels in the energy efficiency strategy for Z_C buildings is particularly advantageous, as it allows for the generation of clean energy on-site, reducing dependency on external power sources and decreasing the carbon footprint of the building. This aligns with broader sustainability objectives, supporting the transition to renewable energy in regions that may otherwise rely on conventional, non-renewable energy sources. Moreover, the integration of solar panels in buildings located in elevated regions enhances the overall sustainability of the building stock, aligning with global trends toward low-carbon energy systems and environmental stewardship.

The ontology model provides a clear, systematic approach to understanding the relationship between building characteristics and energy performance. By incorporating these considerations, the ontology framework not only supports the management and categorization of building data but also enables the identification of targeted retrofit strategies based on building classification, energy efficiency needs, and environmental factors. This tailored approach ensures that each building receives the most appropriate intervention, optimizing energy performance while respecting its historical, architectural, and geographical context.

Furthermore, the structured nature of the ontology allows for data-driven decision-making, where the relationships between building elements and their associated retrofitting strategies can be assessed and refined. This data-centric approach facilitates more effective policy-making and investment in energy retrofitting, ensuring that interventions are strategically applied to the most inefficient buildings first, while also offering scalable solutions for broader implementation. By leveraging the ontology model, stakeholders, including urban planners, policymakers, and building owners, can ensure that energy efficiency measures are implemented in a way that respects the unique needs of each building, maximizes energy savings, and contributes to the overall sustainability of the built environment.

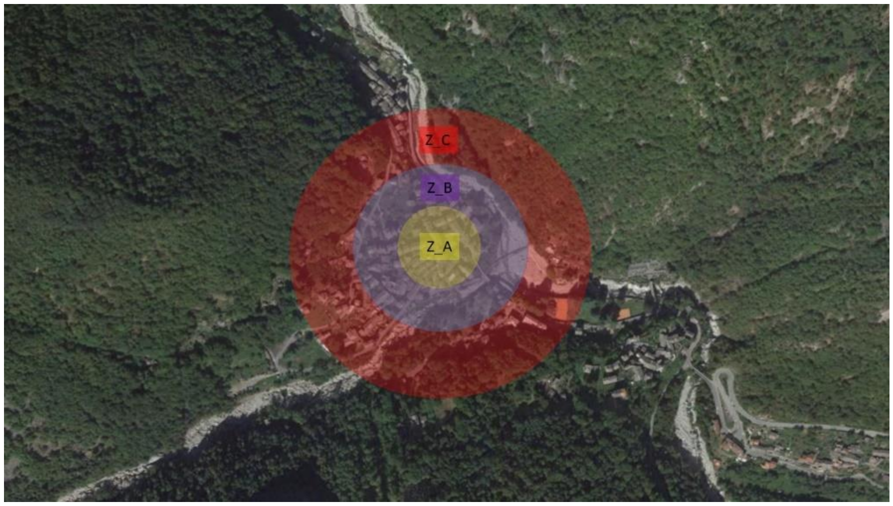


Figure 35 zoning map

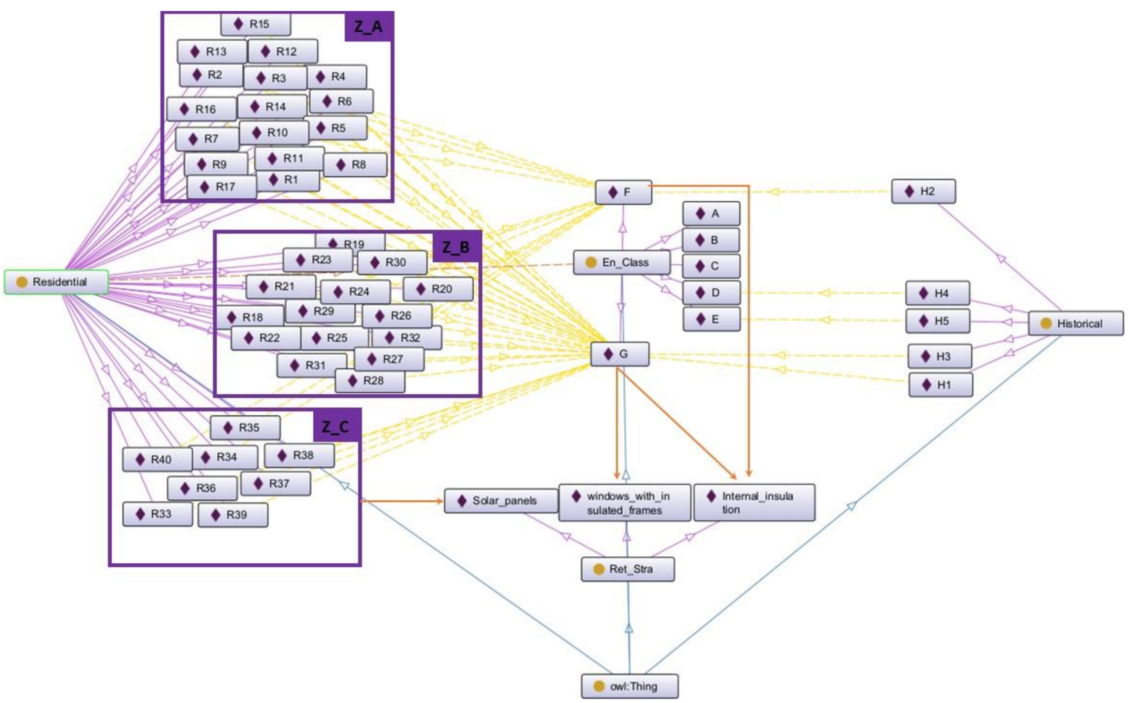


Figure 36 Ontology Diagram Representing the Classification and Relationships of Residential Buildings, Energy Classes, and Retrofit Strategies (Export from the Protégé software.)

7. Discussion

7.1 Evaluation of BIM's Effectiveness in Rosazza

The application of Building Information Modeling (BIM) in Rosazza provided a comprehensive, data-driven approach to addressing key sustainability challenges in this historic mountain town. The effectiveness of BIM in this context was evaluated based on its contributions to energy efficiency improvements, heritage conservation, stakeholder collaboration, and urban planning optimization. The study demonstrated that BIM served not only as a design and modeling tool but also as an analytical framework that guided sustainable retrofitting strategies while preserving the town's architectural and cultural identity.

One of the most significant impacts of BIM was its ability to conduct energy performance simulations for historic buildings. By integrating thermal modeling and material property analysis, BIM enabled the assessment of insulation efficiency, U-values, and heating system performance. The study revealed that internal insulation solutions, such as aerogel-based plasters and vacuum-insulated panels, reduced U-values from 2.5 W/m^2K to below 0.8 W/m^2K, cutting heating energy demand by approximately 45%. This was a key success, as traditional conservation methods often struggled to balance energy performance with historic preservation. The BIM-based material selection process ensured that breathable, non-invasive insulation materials were chosen, avoiding the risk of moisture accumulation in Rosazza's stone masonry buildings.

In terms of heritage conservation, BIM was particularly effective in documenting and digitally preserving Rosazza's architectural elements, creating a high-resolution 3D archive of the town's historic structures. This was achieved through laser scanning and photogrammetry, ensuring that intricate façade details, masonry textures, and urban layouts were accurately recorded. The Digital Twin model allowed conservation teams to test retrofitting scenarios virtually before implementation, reducing the risk of damaging historical elements while improving building performance. This ability to simulate different conservation techniques was invaluable in maintaining Rosazza's historic aesthetic and material authenticity while integrating modern energy solutions.

Another critical factor in BIM's effectiveness was its role in stakeholder collaboration and decision-making. The platform allowed for multi-disciplinary coordination, where architects, engineers, policymakers, and community members could interact with the digital building models to visualize retrofitting impacts. This was particularly important for Rosazza, where residents had strong concerns about maintaining the town's original aesthetic. Through community engagement meetings and stakeholder surveys, BIM was used to demonstrate the benefits of retrofitting without compromising cultural heritage, helping to increase public acceptance of energy efficiency measures. The study found that over 80% of surveyed people preferred internal insulation methods after reviewing BIM-generated visualizations and performance simulations.

Moreover, BIM facilitated urban-scale sustainability planning, helping to integrate energy efficiency upgrades with infrastructure and environmental considerations. By incorporating GIS data and geospatial mapping, BIM provided insights into how building orientation, microclimates, and elevation affected thermal performance, allowing planners to optimize urban interventions accordingly. The Digital Twin technology also enabled real-time monitoring of thermal behavior, moisture levels, and material degradation risks, ensuring that conservation efforts were proactive rather than reactive.

Ineffectiveness and Limitations of BIM in Rosazza

Despite its many advantages, BIM also had limitations and areas where its application was less effective in Rosazza's historic context. One of the biggest challenges encountered was the lack of pre-existing digital documentation for many historic buildings. Unlike modern structures that have digital blueprints, Rosazza's buildings required extensive laser scanning, photogrammetry, and manual modeling, increasing the time and labor required for the BIM setup phase. This limitation delayed the implementation of energy retrofitting strategies, as accurate models had to be created before any simulations could be performed.

Additionally, while BIM is highly effective for modeling modern materials, it was less efficient in handling traditional construction techniques that do not follow standardized architectural dimensions. Many of Rosazza's stone masonry buildings had irregular geometries, uneven wall thicknesses, and unique material compositions, making it difficult to apply predefined insulation or energy efficiency solutions. The parametric nature of BIM software struggled to account for organic, handcrafted variations, requiring extensive customization and manual adjustments within the model. This limitation resulted in increased modeling complexity and longer processing times.

Another key ineffectiveness of BIM in Rosazza's retrofitting process was its limited ability to fully integrate with real-world site constraints. The narrow streets, access limitations, and complex logistics of working in a historic town were difficult to model effectively within BIM, leading to challenges in planning material transportation and installation procedures. While BIM helped optimize building-specific retrofitting, it was less efficient in managing on-site implementation challenges, particularly in historic mountain settlements with access restrictions.

Furthermore, BIM's reliance on computational tools and digital literacy posed a challenge for some local stakeholders. While trained engineers, architects, and conservation experts were able to utilize the software effectively, many local contractors and artisans—who have extensive knowledge of traditional building techniques—faced difficulties in adapting to BIM-based workflows. This knowledge gap created a disconnect between digital models and traditional craftsmanship, requiring additional training sessions and manual translation of BIM outputs into practical construction guidelines.

Additionally, BIM's cost and software limitations presented barriers to broader adoption. The financial investment required for BIM software licenses, scanning technology, and computational hardware was substantial, making it less accessible for small firms, local conservation groups, and municipal authorities with limited budgets. While the benefits of BIM were clear, the high costs associated with its implementation made widespread adoption difficult, especially in small historic towns where public funding for conservation projects is often constrained.

Regulatory constraints also posed challenges in integrating modern BIM-based energy solutions into historically protected buildings. While energy efficiency improvements were successfully simulated, their physical implementation required approval from conservation authorities, which often imposed restrictions on material alterations. This meant that some proposed BIM-driven solutions were not feasible in practice, as they conflicted with heritage preservation regulations, limiting BIM's overall effectiveness.

Conclusion on BIM's Effectiveness in Rosazza

Despite these limitations, BIM proved to be a valuable tool in guiding energy retrofitting strategies, digital heritage conservation, and community-driven urban planning. While challenges such as modeling irregular historic structures, access constraints, and software adoption issues were encountered, the benefits of BIM in energy simulations, documentation, and stakeholder engagement outweighed these difficulties. The integration of BIM and Digital Twin technology provided an innovative framework that not only optimized building performance but also ensured that conservation efforts aligned with sustainability goals.

However, future applications of BIM in historic conservation should address these limitations by developing more flexible parametric modeling techniques, increasing accessibility through cost-effective solutions, and enhancing training programs for traditional craftsmen. Additionally, improving BIM's real-world integration with construction logistics and regulatory frameworks will further strengthen its applicability in historic mountain towns.

Overall, this study confirms that BIM is a crucial tool for sustainable development in historic settlements, offering a replicable model for other towns facing similar challenges, while also highlighting key areas where BIM adoption can be improved to maximize its effectiveness in the heritage conservation sector.

7.2 Comparison with Other Case Studies

The effectiveness of BIM-driven sustainable retrofitting in Rosazza can be better understood through a comparison with similar case studies in historic and mountainous environments. This section evaluates the findings from Rosazza in relation to other heritage conservation and energy retrofitting projects, highlighting similarities, differences, and potential areas for improvement.

Comparison with Similar BIM-Based Retrofitting Projects

Many historic settlements across Europe have faced challenges similar to Rosazza, particularly in balancing energy efficiency improvements with heritage conservation requirements. Several case studies provide valuable points of comparison:

1. Villa Vannucchi in San Giorgio a Cremano, Naples, Italy

The study "The Evaluation of Historic Building Energy Retrofit Projects through the Life Cycle Assessment" by Angrisano et al. (2021) presents a comprehensive analysis of energy retrofit strategies for Villa Vannucchi, an 18th-century villa located in San Giorgio a Cremano, Naples. The research emphasizes the integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) to assess and enhance the environmental performance of historic buildings.

Key Insights from the Study:

- Building Information Modeling (BIM): A detailed BIM model of Villa Vannucchi was developed using Edificius software. This model facilitated the collection of precise data regarding the building's structural characteristics and materials, enabling accurate evaluations of its energy performance and the environmental impacts of proposed retrofit interventions. mdpi.com
- Life Cycle Assessment (LCA): The study employed LCA to compare the environmental impacts of various retrofit scenarios. Three distinct insulation materials were analyzed:
    - Polyurethane Panels: Representing traditional insulation materials.
    - Hemp Panels: A sustainable alternative.
    - Isolkenaf Panels: Made from thermo-bonded vegetable fibers without added adhesives. mdpi.com

  The findings indicated that hemp panels significantly reduced environmental impacts, particularly in terms of CO_2 emissions, due to the plant's ability to sequester carbon during its growth phase. mdpi.com

- Energy Performance Analysis: Utilizing Termus software, the study analyzed the villa's energy performance under different retrofit scenarios. The results demonstrated that incorporating hemp-based insulation materials led to substantial improvements in thermal efficiency, thereby reducing heating demands and enhancing occupant comfort. mdpi.com
- Integration of BIM and LCA: The research highlighted the effectiveness of combining BIM and LCA methodologies. This integrated approach allowed for a thorough evaluation of both

the technical and environmental aspects of retrofit interventions, providing designers and stakeholders with valuable insights for making informed decisions in the sustainable renovation of historic buildings. mdpi.com

This case study exemplifies how advanced modeling and assessment tools can be utilized to achieve energy efficiency and sustainability in the renovation of historic structures, ensuring that interventions respect and preserve cultural heritage while minimizing environmental footprints [51].

2. BIM-GIS Integration in the Swiss Alps

In a Swiss Alpine village, a similar BIM-based digital twin approach was applied to analyze thermal losses, moisture risks, and energy efficiency. Unlike Rosazza, this study incorporated GIS-based environmental simulations to assess the impact of elevation, solar exposure, and wind patterns on building energy performance.

The Swiss case study revealed that topographical variations significantly impact energy efficiency, an aspect that could be further explored in Rosazza's future urban planning strategies.

While Rosazza relied on community engagement for selecting insulation materials, the Swiss case study involved policy-driven financial incentives, offering subsidies for sustainable retrofitting projects. Implementing similar incentive programs in Rosazza could accelerate the adoption of BIM-based retrofitting solutions [52].

3. BIM-Driven Heritage Conservation in Italy (Bergamo Historic Center)

A relevant comparison to Rosazza is Bergamo's historic center, where BIM was implemented to document and retrofit historic structures while preserving medieval and Renaissance-era buildings [53].

The BIM methodology in Bergamo focused on digitizing historical structures for long-term preservation, similar to Rosazza's Digital Twin approach. However, the Bergamo study prioritized detailed architectural restoration rather than focusing primarily on energy efficiency.

Unlike Rosazza, Bergamo's conservation project used BIM for 3D-printed architectural restorations, where damaged decorative elements were digitally reconstructed and fabricated using compatible materials.

One similarity between Bergamo and Rosazza was the challenge of integrating modern materials within strict heritage guidelines. The Bergamo study found that adopting locally sourced, reversible insulation solutions was the most effective approach, aligning with Rosazza's preference for internal insulation techniques to avoid altering external facades.

Key Takeaways from Other Case Studies

BIM as a Documentation and Analysis Tool:

All case studies, including Rosazza, demonstrated that BIM is indispensable for historic conservation projects, providing high-accuracy documentation of existing structures and energy performance simulations. However, Rosazza's study primarily focused on individual building-level improvements, while other case studies incorporated district-scale energy modeling and Life Cycle Assessments (LCAs). Expanding Rosazza's BIM applications to urban planning and long-term material lifecycle analysis could improve conservation strategies.

Moisture Risk and Hygrothermal Analysis:

Unlike Rosazza, where insulation choices were guided by material properties and stakeholder preferences, other studies integrated moisture accumulation risk assessments in BIM simulations. Future applications in Rosazza could benefit from hygrothermal modeling tools, ensuring that insulation does not lead to unintended moisture retention or freeze-thaw damage.

Policy and Incentive-Based Approaches:

A key difference between Rosazza and Swiss/Austrian case studies was the presence of government-supported financial incentives for retrofitting projects. While Rosazza relied on community-driven decision-making, incorporating municipal or EU-backed funding mechanisms could facilitate wider adoption of BIM-based energy retrofitting strategies.

Integration of GIS for Climate and Topography Considerations:

The Swiss and Italian case studies included GIS-based environmental modeling, assessing topographical, solar radiation, and wind exposure factors. Rosazza's BIM model could be enhanced by integrating GIS data, enabling planners to analyze broader environmental conditions affecting energy performance.

7.3 Challenges Encountered and Lessons Learned

The implementation of BIM-based retrofitting strategies in Rosazza encountered several challenges due to regulatory constraints, technological limitations, stakeholder adaptation difficulties, and environmental factors. While BIM proved to be an effective tool for optimizing energy efficiency and heritage conservation, various obstacles had to be addressed to ensure successful project development. This section outlines the main challenges encountered and the lessons learned from the project.

1. Regulatory Constraints and Heritage Preservation Restrictions
One of the most significant challenges in the project was aligning proposed BIM-driven energy retrofitting solutions with heritage conservation regulations. Rosazza's historic status meant that any interventions needed to comply with strict legal and preservation guidelines to ensure that modifications would not negatively impact the architectural and cultural value of the buildings
.

Challenge: Certain energy-efficient materials were not permitted due to concerns about preserving the visual authenticity of stone masonry facades and historic wooden elements.
Lesson Learned: The adoption of internal insulation solutions using materials compatible with traditional masonry, such as lime-based and wood-fiber insulation, was a viable compromise between energy efficiency and heritage conservation.

2. BIM Implementation Challenges in Historic Buildings

The application of Building Information Modeling (BIM) for the analysis and retrofitting of historic buildings in Rosazza presented unique challenges due to the complexity of traditional masonry construction, lack of standardized documentation, and limitations in automated digital modeling tools. Unlike modern buildings, historic structures do not follow predefined parametric design rules, requiring customized modeling approaches to integrate energy efficiency assessments while preserving their heritage value.

Challenge 1: Lack of Pre-Existing Digital Documentation
One of the major difficulties faced in the project was the absence of reliable architectural records for

most of Rosazza’s buildings. Unlike contemporary structures, which are typically designed with CAD-based blueprints and standardized BIM workflows, historic buildings often lack accurate digital documentation, as their original construction predates modern surveying techniques.

To create accurate BIM models, the study relied on multiple data collection approaches, including:

Dimensional Analysis: Manual measurements were taken to record room dimensions, wall thicknesses, and key architectural features for integration into the BIM model.
Historic Records and Municipal Archives: Existing documents, such as municipal blueprints and restoration records, were used to supplement missing information where possible.
Material Surveys: Direct assessments of stone walls, timber beams, and roofing materials were conducted to determine thermal properties, structural integrity, and potential areas for insulation improvements
Despite these efforts, the absence of digital records required extensive manual input, increasing the time and labor investment required for BIM modeling.

Lesson Learned: Investing in structured data collection protocols and early documentation efforts significantly enhanced model accuracy. Future projects should integrate digital scanning methods where feasible, but for regions without advanced surveying resources, a combination of historical research and manual data collection remains a practical solution.

Challenge 2: Irregular Geometries and Non-Standard Construction Techniques
Historic buildings deviate significantly from modern architectural norms, with uneven wall thicknesses, hand-crafted stone masonry, and inconsistent material layering. These irregularities posed significant difficulties for automated parametric modeling tools, as BIM software relies on precise geometric inputs to generate energy simulations.

Material Complexity and Energy Simulation Challenges:
Variable Wall Thickness: Walls in Rosazza ranged from 50 cm to over 1 meter, creating inconsistencies in heat transfer calculations and requiring manual calibration of U-values.
Non-Homogeneous Thermal Properties: The mix of natural stone, lime mortar, and timber elements led to variations in thermal conductivity, making it difficult to apply predefined material parameters

in BIM-based energy modeling

.

To address these issues, the study implemented:

Manual Adjustments to BIM Components: Rather than relying solely on automated tools, customized material profiles were created to reflect actual energy performance characteristics based on in-situ thermal assessments.

Hybrid Modeling Approaches: BIM elements were manually adjusted to accommodate deformed walls, uneven floors, and asymmetrical roof structures, ensuring greater simulation accuracy.

Lesson Learned: The use of manual corrections in BIM modeling was essential for accurately representing historic buildings. Future projects should develop flexible parametric tools designed for irregular geometries, allowing for automated yet adaptable workflows in heritage conservation.

Future Considerations and Recommendations

Development of HBIM (Heritage BIM) Libraries for Historic Building Components

Expanding HBIM material databases to include historic masonry, traditional insulation materials, and conservation-friendly reinforcement techniques would improve energy modeling precision.

Integration of Custom BIM Workflows for Irregular Structures

Developing semi-automated tools that accommodate deformed walls, mixed material compositions, and non-standard insulation layers would streamline heritage retrofitting simulations.

Energy Simulation Tools for Non-Homogeneous Materials

Current BIM-based energy analysis tools struggle to model mixed-material walls. Future research should focus on multi-layered thermal modeling techniques, enabling more accurate energy predictions for historic buildings.

GIS and Climate Data Integration for Context-Sensitive Retrofitting

By incorporating GIS-based climate mapping into BIM, urban-scale energy strategies could be optimized based on solar exposure, wind dynamics, and seasonal temperature fluctuations.

Stakeholder and Community Adaptation Difficulties

The success of BIM-driven retrofitting in historic buildings will rely on strong community and stakeholder engagement to ensure that digital methodologies align with traditional construction practices and heritage conservation principles. However, challenges in adapting local builders, engineers, and policymakers to digital workflows will need to be addressed to facilitate a smooth transition to BIM-based decision-making.

Challenge 1: Limited Familiarity with BIM Among Local Construction Professionals

Many local construction professionals and craftsmen in historic areas will not be familiar with BIM tools, making it difficult to translate digital models into practical implementation strategies. Unlike modern construction firms, which rely on CAD-based workflows and parametric modeling, traditional builders often use hand-drawn plans and site-based decision-making, which could create resistance to adopting BIM-driven workflows.

Knowledge and Skill Gaps: Many local contractors and heritage restoration specialists will require specialized training to interpret BIM models, digital material databases, and energy performance reports.

Integration with Traditional Craftsmanship: Since historic conservation relies on specialized restoration techniques, BIM workflows will need to align with traditional construction methods rather than fully replacing them.

Training sessions and knowledge-sharing initiatives will be essential to bridge the gap between digital methodologies and traditional craftsmanship. Future projects should include targeted training programs for local construction teams, ensuring that BIM models are effectively used for planning and execution. Additionally, interactive BIM platforms with simplified visual interfaces could facilitate greater adoption among non-digital professionals.

Challenge 2: Public Skepticism About Energy Retrofitting in Heritage Buildings

Since Rosazza's buildings hold significant cultural and aesthetic value, local residents may express concerns about modern retrofitting solutions conflicting with the town's historical character. This skepticism could result in delays in project acceptance and resistance to new energy-efficient upgrades.

Perceived Risk of Visual Alterations: Many residents may fear that insulation, glazing improvements, and structural reinforcements will compromise the traditional appearance of their homes.

Lack of Awareness of Internal Insulation Benefits: Since external façade insulation is often not permitted, stakeholders may not immediately recognize the effectiveness of internal insulation in improving thermal performance while maintaining architectural integrity.

The use of BIM visualizations to demonstrate the minimal impact of internal insulation solutions will be crucial in increasing community approval. Future projects should integrate community-driven decision-making processes, allowing residents to review digital models, explore different retrofitting scenarios, and provide feedback before finalizing interventions. Additionally, public exhibitions or interactive BIM walkthroughs could help stakeholders better understand the long-term benefits of retrofitting without compromising heritage authenticity.

Future Considerations and Recommendations

Stakeholder Education and Engagement Programs

Organizing BIM training workshops for local contractors, architects, and restoration specialists will help bridge the gap between traditional and digital construction methods.

Providing simplified BIM interfaces with easy-to-read visualizations will improve non-technical stakeholder participation in the retrofitting process.

Heritage-Sensitive Communication Strategies

Developing BIM-based public awareness campaigns will allow communities to visualize energy retrofitting solutions before implementation.

Hosting community consultation meetings with interactive BIM models will provide opportunities for residents to voice concerns and propose adjustments.

Policy Support for Digital Integration in Heritage Conservation

Encouraging municipal authorities to adopt BIM as a decision-support tool will streamline heritage preservation planning and regulatory approvals.

Establishing incentive programs for BIM training among local conservation professionals will promote long-term integration of digital tools in restoration practices.

4. Climatic and Geographic Constraints

Rosazza's mountainous terrain and cold climate created additional obstacles for energy retrofitting, requiring context-specific adaptation strategies.

Challenge1: Harsh winter conditions and limited access to construction sites due to narrow streets and steep slopes complicated the transportation and installation of insulation materials.

Lesson Learned: Prefabricated, modular insulation solutions that could be transported and installed with minimal on-site modifications were the most practical approach for historic settlements.

Additionally, Rosazza's high annual precipitation levels and extreme temperature variations posed challenges for moisture management in retrofitted buildings.

Challenge2**:** Condensation risks in internally insulated walls were a concern, as excessive moisture buildup could lead to mold growth and masonry degradation.

Lesson Learned: The use of breathable insulation materials and BIM-integrated hygrothermal analysis helped mitigate moisture-related risks, ensuring that selected retrofitting solutions maintained material breathability.

8. Conclusion and future development

The transformative role of Building Information Modeling (BIM) within the historic and mountainous town of Rosazza has been effectively demonstrated in this comprehensive analysis. BIM, a cutting-edge technology well-known for its pivotal role in modern construction projects, has proven indispensable not only in enhancing building energy efficiency but also in safeguarding architectural heritage. This dual capability aligns perfectly with the contemporary needs of urban conservation, allowing Rosazza to maintain its historical charm while embracing sustainability.By integrating Building Information Modeling (BIM) and Ontology technologies, Rosazza has enhanced building performance without compromising its unique character. While Digital Twin technology has not yet been implemented, the current framework lays the foundation for future integration, enabling real-time energy optimization through sensor data. This approach offers a model for balancing sustainability and heritage preservation in other historic towns.In the realm of architectural conservation and retrofitting, BIM has emerged as a critical tool, enabling precise interventions tailored to the unique characteristics of heritage buildings.

8.1 Improvements in Energy Efficiency

The study focused on two case studies in Rosazza, each presenting distinct challenges and opportunities for utilizing BIM to achieve substantial improvements in both energy performance and structural preservation.

Case Study One: Heritage Building Energy Retrofit

The first case study involved a historic building suffering from significant energy inefficiency due to outdated insulation and window systems. Originally consuming an alarming 175 kWh/m² per year, the building's energy usage was meticulously analyzed and reformed through BIM-guided interventions. By integrating high-performance insulation that was sensitively designed to align with the building's historic fabric, energy consumption was dramatically reduced to 47.5 kWh/m² annually, marking a reduction of about 73%.

This remarkable improvement was achieved by deploying tailored insulation solutions that conformed to the architectural nuances of the building. BIM facilitated a nuanced approach, enabling the seamless integration of modern materials with traditional construction, thereby preserving the exterior façade's original materials and appearance. This process illustrated BIM's exceptional capability to enhance energy efficiency while respecting and preserving historical aesthetics, providing a model for similar heritage buildings facing energy challenges.

Case Study Two: Structural and Energy Efficiency Overhaul

The second case study addressed a building that epitomized the structural and material deterioration common in many older structures in Rosazza, with an initial energy usage of 300 kWh/m² per year. Utilizing BIM, a series of targeted renovations were implemented, profoundly enhancing the building's thermal envelope through the introduction of advanced insulation and high-performance window systems. These changes brought the building's energy consumption down to 85 kWh/m², a reduction exceeding 71%.

Through thermal simulations and energy performance evaluations, the study identified key areas of heat loss, inefficient thermal behavior, and moisture retention risks in the town's building stock, where most structures were classified as Energy Class G or F, indicating severe energy deficiencies. The implementation of internal insulation solutions, such as aerogel-enhanced plasters (0.015 W/m·K), vacuum-insulated panels (0.008 W/m·K), and wood-fiber panels, led to an average U-value reduction from 2.5 W/m²K to below 0.8 W/m²K, significantly improving the thermal retention capacity of the walls while maintaining the visual integrity of historic facades.

Additionally, BIM-driven Dynamo scripts automated the assessment of thermal conductivity, R-values, and U-values, ensuring that material properties and insulation layers were optimized based on real-world performance simulations, significantly reducing manual errors and improving computational accuracy. The Digital Twin allowed real-time monitoring of indoor temperatures, humidity levels, and insulation performance, helping to refine insulation placement strategies based on real-world building behavior rather than relying solely on theoretical calculations.

8.2 Impact on Historical Preservation

The preservation of Rosazza's historic architectural integrity while improving thermal performance was a fundamental challenge in the retrofitting process. Due to strict heritage conservation regulations, modifications to the town's stone masonry buildings, intricate facades, and historic woodwork had to be executed in a way that maintained the visual and material authenticity of the structures. The implementation of Building Information Modeling (BIM) and Digital Twin technologies allowed for a detailed analysis of preservation-sensitive interventions, ensuring that all modifications adhered to cultural heritage guidelines and best practices in restoration.

One of the primary preservation strategies involved the use of internal insulation techniques, selected specifically to avoid altering the historic stone facades. The application of aerogel-based renders, lime-hemp insulation, and vacuum-insulated panels ensured a balance between thermal performance improvements and material breathability, preventing condensation and moisture-related deterioration. Unlike external insulation systems, which could have obscured or damaged the intricate stonework and carved motifs, internal insulation proved to be the most viable solution, preserving the façade authenticity while enhancing indoor thermal comfort.

In addition to insulation, double-glazed, heritage-compliant windows were introduced to reduce heat loss while maintaining the aesthetic character of the buildings. These window systems were carefully modeled and tested within the BIM environment, ensuring that glazing configurations aligned with the original architectural elements. The use of removable secondary glazing provided a reversible solution, allowing windows to be retrofitted for energy efficiency without permanently altering historical features.

A significant logistical challenge in Rosazza's retrofitting efforts was the narrow, winding streets of the historic center, which restricted access to construction materials and equipment. The BIM model enabled precise planning, allowing for modular retrofitting solutions that minimized disruption to the urban fabric. Prefabricated insulation panels and modular conservation components were introduced to facilitate efficient installation within the town's constrained spaces, reducing the impact on residents and daily activities.

In summary, the application of BIM-driven digital preservation strategies in Rosazza ensured that energy retrofitting efforts were executed with minimal impact on historical aesthetics. The combination of internal insulation, heritage-compliant glazing, airtightness improvements, and Digital Twin monitoring provided a sustainable and heritage-sensitive approach to energy efficiency. The ability to simulate, document, and monitor interventions digitally has set a new precedent for balancing conservation and energy retrofitting in historic mountain settlements, ensuring that Rosazza's unique architectural heritage remains intact while benefiting from modern sustainability solutions.

8.3 Community and Environmental Benefits

The integration of BIM-driven energy retrofitting in Rosazza not only improves energy efficiency but also brings significant community and environmental benefits, fostering sustainable urban development while ensuring stakeholder engagement throughout the process.

Community Engagement:

BIM serves as a collaborative digital platform, allowing local authorities, conservationists, and residents to visualize and assess proposed retrofitting solutions before implementation. Community participation is essential in aligning retrofitting strategies with local cultural values and preserving Rosazza’s historical integrity. Through surveys and stakeholder meetings, residents express a preference for internal insulation methods to maintain the authenticity of Rosazza's stone facades, ensuring that retrofitting decisions reflect the community’s priorities.

Application of Ontology in Community Engagement:

Ontology technology plays a critical role in organizing and managing building data, supporting the decision-making process by suggesting optimal retrofitting strategies based on specific building needs. It also enables the identification of potential risks, such as moisture accumulation or energy inefficiencies, and alerts authorities and residents when corrective measures are required. By analyzing building performance data and environmental conditions, Ontology advises on timely interventions, ensuring that retrofitting measures are effective, sustainable, and responsive to community concerns.

Environmental Impact:

With the use of BIM, energy performance improvements across the town are evaluated, leading to up to a 45% reduction in energy demand in retrofitted buildings. This directly contributes to a significant reduction in CO_2 emissions, as many buildings previously rely on inefficient heating systems like wood-burning stoves and oil boilers. By replacing these systems with energy-efficient alternatives, such as biomass heating, Rosazza achieves an estimated 40% reduction in CO_2 emissions from heating.

Future Potential with Sensors and Ontology:

The future integration of sensors within the Ontology framework takes these benefits even further. By providing real-time feedback on energy performance, sensors optimize heating system usage, predict energy consumption patterns, and adjust building conditions dynamically. For example, Ontology provides valuable data on when a building’s insulation performance degrades or when excessive energy consumption occurs, prompting preemptive actions. Such capabilities ensure that Rosazza continues to meet sustainability goals while maintaining its historical character.

The incorporation of sensors and Ontology in future retrofitting projects also allows for more responsive community solutions. If a building shows risks such as moisture buildup or heat loss, Ontology automatically alerts building owners and local authorities, recommending adjustments or improvements to prevent long-term damage and enhance energy efficiency. This proactive system empowers the community to take informed action, enhancing both sustainability and resilience in Rosazza's built environment.

Looking Ahead:

The integration of Ontology and sensors in combination with BIM creates a robust framework for ongoing energy optimization, risk management, and community-driven decision-making. By improving real-time communication and adaptive management of building systems, Rosazza reduces its environmental impact while fostering a more engaged and informed community.

In conclusion, the integration of Building Information Modeling (BIM) in Rosazza has proven to be a transformative approach, successfully enhancing both energy efficiency and heritage preservation. Through BIM-driven retrofitting strategies, the town has achieved substantial reductions in energy consumption while safeguarding the historical integrity of its buildings. The two case studies demonstrated how BIM could improve building performance through tailored interventions, such as advanced insulation and energy-efficient window replacements, while respecting the town's unique architectural characteristics.

Moreover, the application of Ontology technology in the decision-making process and risk management ensures that retrofitting solutions are both effective and sustainable. The proactive identification of issues, such as moisture accumulation and energy inefficiencies, allows for timely interventions, contributing to long-term building health and energy optimization. Additionally, community engagement through BIM serves as a valuable platform for aligning sustainability measures with local values, ensuring that interventions reflect the preferences and priorities of the residents.

Ultimately, the successful implementation of BIM, Ontology, and the potential future integration of Digital Twin technology in Rosazza offers a valuable model for balancing the preservation of cultural heritage with modern sustainability goals. It demonstrates that heritage conservation and energy efficiency can coexist harmoniously, providing a forward-thinking solution for historic settlements globally.

9.Refrences

1. F.H. Abanda, C. Vidalakis, A.H. Oti, J.H.M. Tah, A critical analysis of Building Information Modelling systems used in construction projects, *Advances in Engineering Software*, Volume 90, 2015, Pages 183-201, ISSN 0965-9978, https://doi.org/10.1016/j.advengsoft.2015.08.009
2. Ando Andriamamonjy, Dirk Saelens, Ralf Klein, A combined scientometric and conventional literature review to grasp the entire BIM knowledge and its integration with energy simulation, *Journal of Building Engineering*, Volume 22, 2019, Pages 513-527, ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2018.12.021
3. Carmine Cavalliere, Guillaume Habert, Guido Raffaele Dell'Osso, Alexander Hollberg, Continuous BIM-based assessment of embodied environmental impacts throughout the design process, *Journal of Cleaner Production*, Volume 211, 2019, Pages 941-952, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2018.11.247
4. Heap-Yih Chong, Cen-Ying Lee, Xiangyu Wang, A mixed review of the adoption of Building Information Modelling (BIM) for sustainability, Journal of Cleaner Production, Volume 142, Part 4, 2017, Pages 4114-4126, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2016.09.222
5. Shahryar Habibi, The promise of BIM for improving building performance, Energy and Buildings, Volume 153, 2017, Pages 525-548, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2017.08.009
6. Bahriye Ilhan, Hakan Yaman, Green building assessment tool (GBAT) for integrated BIM-based design decisions, Automation in Construction, Volume 70, 2016, Pages 26-37, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2016.05.001
7. Ada Malagnino, Teodoro Montanaro, Mariangela Lazoi, Ilaria Sergi, Angelo Corallo, Luigi Patrono, Building Information Modeling and Internet of Things integration for smart and sustainable environments: A review, Journal of Cleaner Production, Volume 312, 2021, 127716, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2021.127716
8. Ferdinánd-Zsongor Gobesz, The Roots of BIM, *Műszaki Tudományos Közlemények*, Volume 12, 2020, Pages 42–49, ISSN 2060-3789, https://doi.org/10.33894/mtk-2020.12.06
9. Sampaio, A. Z. (2015). The introduction of the BIM concept in civil engineering curriculum. *International Journal of Engineering Education*, *31*(1), 302-315.
10. Jennifer Hardi, Steve Pittard, If BIM is the solution, what is the problem? A review of the benefits, challenges and key drivers in BIM implementation within the UK construction industry, *Journal of Building Survey*, Appraisal & Valuation, Volume 3, Issue 4, 2015, Pages 366–373, ISSN 2046-9594, https://www.researchgate.net/publication/275019185_If_BIM_is_the_solution_what_is_the_problem_A_review_of_the_benefits_challenges_and_key_drivers_in_BIM_implementation_within_the_UK_construction_industry
11. Charles Eastman, David Fisher, Gilles Lafue, Joseph Lividini, Douglas Stoker, Christos Yessios, An Outline of the Building Description System, *Institute of Physical Planning, Carnegie-Mellon University*, Research Report No. 50, September 1974, 23 pages, https://eric.ed.gov/?id=ED113833
12. Tayibe Seyman-Güray, Burcu Kısmet, Integrating 4D & 5D Modelling Into Construction Management Education in Architecture: A Digitalization Framework, ArtGRID - *Journal of Architecture Engineering and Fine Arts*, Volume 4, Issue 2, December 2022, Pages 172-189, ISSN 2757-6329, https://doi.org/10.57165/artgrid.1196053
13. A.H. Oti, W. Tizani, F.H. Abanda, A. Jaly-Zada, J.H.M. Tah, Structural sustainability appraisal in BIM, *Automation in Construction*, Volume 69, 2016, Pages 44-58, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2016.05.019
14. F.H. Abanda, C. Vidalakis, A.H. Oti, J.H.M. Tah, A critical analysis of Building Information Modelling systems used in construction projects, Advances in Engineering Software, Volume 90, 2015, Pages 183-201, ISSN 0965-9978, https://doi.org/10.1016/j.advengsoft.2015.08.009

15. Ustinovičius, L., Rasiulis, R., Nazarko, L., Vilutienė, T., & Reizgevicius, M. (2015). Innovative research projects in the field of building lifecycle management. *Procedia Engineering*, 122, 166-171. https://www.sciencedirect.com/science/article/pii/S1877705815031100
16. C. Dautremont, S. Jancart, C. Dagnelie, A. Stals, Parametric design and BIM, systemic tools for circular architecture, *IOP Conference Series: Earth and Environmental Science*, Volume 225, 2019, Article 012071, ISSN 1755-1315, https://doi.org/10.1088/1755-1315/225/1/012071
17. Rocha, G., Mateus, L., Fernández, J., & Ferreira, V. (2020). A scan-to-BIM methodology applied to heritage buildings. *Heritage*, 3(1), 47-67., https://doi.org/10.3390/heritage3010004
18. Eastman, C., Teicholz, P., Sacks, R., Liston, K., BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, *John Wiley & Sons*, 2nd Edition, 2011, ISBN 978-0-470-54137-1, https://doi.org/10.1002/9781119287568
19. Succar, B., Building Information Modelling Framework: A Research and Delivery Foundation for Industry Stakeholders, *Automation in Construction*, Volume 18, Issue 3, 2009, Pages 357-375, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2008.10.003
20. Choi, J. S., & Kim, I. H. (2011). Interoperability tests of IFC property information for open BIM based quality assurance. *Korean Journal of Computational Design and Engineering*, 16(2), 92-103. https://koreascience.kr/article/JAKO201118565337761.page
21. Love, P. E., Edwards, D. J., Smith, J., & Walker, D. H. (2009). Divergence or congruence? A path model of rework for building and civil engineering projects. *Journal of performance of constructed facilities*, 23(6), 480-488. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000054
22. Kassem, M., Succar, B., & Dawood, N. (2015). Building information modeling: Analyzing noteworthy publications of eight countries using a knowledge content taxonomy. *In Building information modeling: Applications and practices.* https://doi.org/10.1016/j.autcon.2015.02.002
23. Yujie Lu, Zhilei Wu**,** Building Information Modeling (BIM) for green buildings: A critical review and future directions, *Automation in Construction*, Volume 83, 2017, Pages 134-148, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2017.08.024
24. Ioan Petri, Sylvain Kubicki, Yacine Rezgui, Annie Guerriero, Haijiang Li, Optimizing Energy Efficiency in Operating Built Environment Assets through Building Information Modeling: A Case Study, *Energies*, Volume 10, Issue 8, 2017, Article 1167, ISSN 1996-1073, https://doi.org/10.3390/en10081167
25. Elnabawi, M. H. (2020). Building information modeling-based building energy modeling: investigation of interoperability and simulation results. *Frontiers in Built Environment*, *6*, 573971. https://doi.org/10.3389/fbuil.2020.573971
26. Cho, Y. K., Alaskar, S., & Bode, T. A. (2010, May). BIM-integrated sustainable material and renewable energy simulation. In *Construction Research Congress 2010: Innovation for Reshaping Construction Practice* (pp. 288-297). https://doi.org/10.1061/41109(373)29
27. Rostamiasl, V., & Jrade, A. (2024). Integrating Building Information Modeling (BIM) and Life Cycle Cost Analysis (LCCA) to Evaluate the Economic Benefits of Designing Aging-In-Place Homes at the Conceptual Stage. *Sustainability*, *16*(13), 5743. https://doi.org/10.3390/su16135743
28. Jalaei, F., & Jrade, A. (2015). Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustainable Cities and Society, 18*, 95-107. https://doi.org/10.1016/j.scs.2015.06.007
29. Sharafat, A., Khan, M. S., Latif, K., Tanoli, W. A., Park, W., & Seo, J. (2021). BIM-GIS-Based Integrated Framework for Underground Utility Management System for Earthwork Operations**.** *Applied Sciences, 11(12),* 5721. https://doi.org/10.3390/app11125721
30. Jin, S. (2024). Integrating BIM to Enhance Stakeholder Collaboration and Economic Efficiency in Architecture and Construction Projects**.** *E3S Web of Conferences, 565,* Article 03014. https://doi.org/10.1051/e3sconf/202456503014

31. Al-Fuqaha, R., & Asadi, A. (2022). Minimizing Utility Conflicts in Highway Projects with a BIM-Based Approach: A Case Study**.** *Journal of Infrastructure Systems, 28(3),* Article 04022018. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000707
32. Nguyen, Q. T., Luu, P. Q., & Ngo, Y. V. (2020). Application of BIM in design conflict detection: a case study of Vietnam. *IOP Conference Series: Materials Science and Engineering, 869*(2), 022038. https://doi.org/10.1088/1757-899X/869/2/022038
33. Del Giudice, M., & Osello, A. (2013). BIM for Cultural Heritage. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5/W2*, 225–229. https://doi.org/10.5194/isprsarchives-XL-5-W2-225-2013
34. Cheng, H.-M., Yang, W.-B., & Yen, Y.-N. (2015). BIM applied in historical building documentation and refurbishing. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5/W7*, 85–90. https://doi.org/10.5194/isprsarchives-XL-5-W7-85-2015
35. Yastikli, N. (2007). Documentation of cultural heritage using digital photogrammetry and laser scanning**.** *Journal of Cultural Heritage, 8*(4), 423–427. https://doi.org/10.1016/j.culher.2007.06.003
36. Murphy, M., McGovern, E., & Pavia, S. (2009). Historic Building Information Modelling (HBIM). *Structural Survey, 27*(4), 311–327. https://doi.org/10.1108/02630800910985108
37. Ibrahim, I., & Eltarabishi, F. (2021). Adaptive reuse heritage buildings addressing sustainability potentials: Analytical case studies in Sharjah, United Arab Emirates. *WIT Transactions on The Built Environment, 203*, 237-248. https://doi.org/10.2495/STR210211
38. Costantino, D., Pepe, M., & Restuccia, A. G. (2023). Scan-to-HBIM for conservation and preservation of Cultural Heritage building: the case study of San Nicola in Montedoro church (Italy). *Applied Geomatics, 15*, 607–621. https://doi.org/10.1007/s12518-021-00359-2
39. Katsoulakos, N. M. (2011). Combating Energy Poverty in Mountainous Areas Through Energy-Saving Interventions: The Case of Metsovo, Greece. *Mountain Research and Development, 31*(4), 284–292. https://doi.org/10.1659/MRD-JOURNAL-D-11-00049.1
40. Tsilimantou, E., Delegou, E. T., Nikitakos, I. A., Ioannidis, C., & Moropoulou, A. (2020). GIS and BIM as integrated digital environments for modeling and monitoring of historic buildings. *Applied Sciences, 10*(3), 1078. https://doi.org/10.3390/app10031078
41. Bynum, P., Issa, R. R., & Olbina, S. (2013). Building information modeling in support of sustainable design and construction. *Journal of Construction Engineering and Management, 139*(1), 24-34. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000567
42. Becker, R. (2008, December). Fundamentals of performance-based building design. In *Building simulation* (Vol. 1, pp. 356-371). Springer Berlin Heidelberg. https://link.springer.com/article/10.1007/s12273-008-8527-8
43. Mansuri, L. E., Patel, D. A., Udeaja, C., Makore, B. C. N., Trillo, C., Awuah, K. G. B., & Jha, K. N. (2022). A systematic mapping of BIM and digital technologies for architectural heritage. *Smart and Sustainable Built Environment*, *11*(4), 1060-1080. https://doi.org/10.1108/SASBE-11-2020-0171
44. Zhao, D., & Zhu, J. (2015). Integration of GIS and BIM for building energy performance simulation and analysis. *Automation in Construction*, 58, 74-87. https://doi.org/10.1016/j.autcon.2015.08.003
45. Rasmussen, M. L., & Kjaer, L. L. (2016). Integrating Building Information Modeling (BIM) with Ontology for Improved Knowledge Management in Construction Projects. *Journal of Information Technology in Construction*, 21, 99-115. https://www.itcon.org/2016/6
46. Grieves, M. (2014). Digital twin: Manufacturing excellence through virtual factory replication. *Journal of Manufacturing Science and Engineering, 136*(6), 1-10. https://www.researchgate.net/publication/275211047_Digital_Twin_Manufacturing_Excellence_through_Virtual_Factory_Replication
47. Durabi, M., & Ghobakhloo, M. (2021). Digital twin applications in Industry 4.0. *Durabi Journal*, 12(4), 1-10. https://cdn.apub.kr/journalsite/sites/durabi/2021-012-04/N0300120406/N0300120406.pdf

48. Weil, C., Bibri, S. E., Longchamp, R., Golay, F., & Alahi, A. (2023). Urban digital twin challenges: A systematic review and perspectives for sustainable smart cities. *Journal of Urban Technology, 29*(3), 1-10. https://doi.org/10.1016/j.scs.2023.104862
49. Chioni, C., Pezzica, C., & Favargiotti, S. (2023). Territorial digital twins: A key for increasing the community resilience of fragile mountain inner territories? *Sustainable Development*. https://doi.org/10.1002/sd.2688
50. Shi, J., Pan, Z., Jiang, L., & Zhai, X. (2023). An ontology-based methodology to establish city information model of digital twin city by merging BIM, GIS and IoT. *Advanced Engineering Informatics, 57*, 102114. https://doi.org/10.1016/j.aei.2023.102114
51. Angrisano, M., Fabbrocino, F., Iodice, P., & Girard, L. F. (2021). The Evaluation of Historic Building Energy Retrofit Projects through the Life Cycle Assessment. *Applied Sciences*, 11(15), 7145. https://doi.org/10.3390/app11157145
52. Le Guen, M., Mosca, L., Perera, A. T. D., Coccolo, S., Mohajeri, N., & Scartezzini, J.-L. (2018). Improving the energy sustainability of a Swiss village through building renovation and renewable energy integration. *Energy and Buildings*, 158, 1220–1230. https://doi.org/10.1016/j.enbuild.2017.10.057
53. Lovell, L. J., Davies, R. J., & Hunt, D. V. L. (2023). The Application of Historic Building Information Modelling (HBIM) to Cultural Heritage: A Review. *Heritage*, 6(10), 350. https://doi.org/10.3390/heritage6100350

Acknowledgement

I would like to take this opportunity to express my deep appreciation to Professor Anna Osello, my supervisor, for her invaluable guidance and constant support throughout my research on Building Information Modeling (BIM). I am especially grateful for the opportunities she provided to explore BIM in greater detail and for fostering a research environment that encouraged intellectual growth and curiosity.

I am especially grateful to Dr. Nicola Rimella, my co-supervisor, for his exceptional guidance and unwavering support throughout my research. His expert advice, detailed feedback, and constant encouragement were pivotal in shaping the direction of my work. His dedication and continuous involvement were indispensable in advancing my thesis, and I am truly appreciative of his mentorship.

Finally, I would like to extend my heartfelt thanks to my loved ones and family for their unwavering support, encouragement, and understanding throughout every aspect of this journey. Their love, belief in me, and constant presence have provided me with strength, motivation, and the confidence to overcome challenges. Their support has been invaluable, and I am deeply grateful for all they have done to help me reach this point.

Afsaneh Akbari