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D8.4 – DEVELOPING RESILIENCE-ENABLING ENERGY RETROFIT INTERVENTIONS THAT WILL CONTRIBUTE TO THE CLIMATE-PROOFING OF THE BUILT ENVIRONMENT

Application to a real demo

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MULTICLIMACT

D8.4 - DEVELOPING RESILIENCE-ENABLING ENERGY RETROFIT INTERVENTIONS THAT WILL CONTRIBUTE TO THE CLIMATE-PROOFING OF THE BUILT ENVIRONMENT- APPLICATION TO A REAL DEMO

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Lead beneficiary	NCSRD
Main Authors	Athanasios Sfetsos (NCSRD), Diamando Vlachogiannis (NCSRD), Maria Gavrouzou (NCSRD), Margarita Golemi (NCSRD)
Main contributors	Lucia Barchetta (CAM), Marta Rivarola (RINA-C), Eva Raggi (RINA-C), Romina Fattoretti (CAM)
Reviewers	Celina Solari (RINA-C), Mina Moayyedi (UKA), Youssef Elomari (KTH)
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REVISION TABLE

Version	Date	What
v1.0	03/12/2024	Table of Contents (1st version)
v2.0	08/08/2025	First Draft (Partners added content to chapters -1st version)
V3.0	01/09/2025	Final version ready for quality check (all partners have added their final input)
V4.0	22/09/2025	Final version ready for submission

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ABBREVIATIONS AND ACRONYMS

ACRONYM	DESCRIPTION
AeDES	Agibilità e Danno nell'Emergenza Sismica - Usability and Damage in Seismic Emergency
CAM	Municipality of Camerino
CLE	Condizione Limite di Emergenza – Emergency Limit Condition
EPC	Energy Performance Certificate
GDPR	General Data Protection Regulation
GNDT	Gruppo Nazionale Difesa Terremoti (National Group for Earthquake Protection)
IEQ	Indoor environmental quality
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale - Italian National Institute for Environmental Protection and Research
ISTAT	Istituto Nazionale di Statistica - Italian National Institute of Statistics
NCSRD	National Center for Scientific Research "Demokritos"
NbS	Nature-based Solutions
PAI	Piano di Assetto Idrogeologico - Hydrogeological Asset Management Plan
QGIS	Quantum Geographic Information System
RDBMS	Relational Database Management System
ReLUIS	Italian Network of University Laboratories of Earthquake Engineering

EXECUTIVE SUMMARY

Deliverable D8.4 reports on Task 8.4 of the MULTICLIMACT project, which aimed to develop and apply resilience-enabling energy retrofit interventions for Camerino (Italy). The objective was to translate the solution portfolio identified in Task 2.4 into a real demonstration case, considering the specific climatic and seismic risks, building typologies, and heritage constraints of Camerino's historic urban fabric.

The work combined building-level data with hazard-specific analyses. A detailed dataset was preprocessed, normalised, and clustered using mixed-type methods (Gower distance with Agglomerative Hierarchical and K-Medoids algorithms)[1-3]. Six clusters were identified as the most meaningful typologies for both heatwave and earthquake hazards. For heatwaves, clusters reflected differences in construction period and exposure to thermal extremes, while for earthquakes they captured variations in structural form, usability classification, and component-level damages.

Based on these clusters, 31 energy interventions identified in Task 2.4 were assessed through a five-star ranking system. The evaluation considered technical feasibility, adaptation potential, and compatibility with the local heritage context. Nature-based solutions (e.g., street trees, urban parks, shading, reforestation) emerged as top-priority interventions for heatwaves, while earthquake resilience emphasised structural retrofitting, fire-resistant materials, and envelope reinforcement. The cluster-specific ranking highlighted the differentiated applicability of solutions: while measures such as insulation and cool roofs are broadly effective, others (e.g., private gardens, monitoring systems) show strong cluster dependence.

The work was carried out by NCSRD, in collaboration with RINA Consulting, and the Municipality of Camerino (CAM). At this stage, the results provide a structured framework for prioritising interventions and defining operative guidelines for Camerino's historic Centre. The guidelines address practical implementation issues, including heritage-related restrictions and spatial constraints, and recommend a balanced integration of passive, technological, and nature-based measures.

1. INTRODUCTION

This report is a deliverable of the project "MULTICLIMACT - MULTI-faceted CLIMate adaptation ACTions to improve resilience, preparedness and responsiveness of the built environment against multiple hazards at multiple scales," funded by the European Commission through the European Climate, Infrastructure and Environment Executive Agency (CINEA). As outlined in the Grant Agreement, MULTICLIMACT aims to develop an integrated framework and digital toolkit to assist public stakeholders and citizens in assessing and improving the resilience of the built environment across different scales—buildings (including cultural heritage), urban infrastructure, and territorial systems—facing a range of climatic and natural hazards. This includes the implementation of a resilience scorecard system and a suite of solutions encompassing design practices, innovative materials, and digital tools to enable informed planning, decision-making, and monitoring processes that improve both structural and social resilience.

Task 8.4 – "Resilience-enabling energy retrofit interventions aimed to contribute to the climate-proofing of the built environment at multiple scales – development for the application to a real demo case". It was part of Work Package 8, which formed part of the second phase of MULTICLIMACT. This phase is dedicated to the translation and demonstration of design and planning methods developed during the first phase into real-life conditions. Task 8.4 specifically focused on the Italian demo case in the Municipality of Camerino, aiming to identify energy and water retrofit interventions for traditional building typologies and to assess the feasibility of decentralized technological solutions—such as renewable energy systems and nature-based urban interventions—to enhance the self-sufficiency and resilience of the built environment.

The outcomes of Task 8.4 were closely linked to earlier analytical efforts carried out in Task 2.4, which provided a methodology for resilient building design and for identifying energy and water adaptation measures. Task 8.4 built upon and operationalised these recommendations, tailoring them to the local conditions of Camerino. It also prepared the ground for the practical demonstration activities foreseen in WP11. While climate hazards were a central part—particularly heatwaves, droughts, and heavy precipitation—Task 8.4 also accounted for other locally relevant threats such as seismic risk, which was critical in the historical centre of Camerino.

This deliverable captured the initial stages of Task 8.4, including the methodology for identifying building typologies, preliminary clustering analysis based on multi-parameter vulnerability, and the first insights on applicable energy and water solutions. It serves as a foundational reference for forthcoming feasibility studies and design interventions to be developed in collaboration with other project partners.

Deliverable 8.4 consists of 7 chapters organized as follows:

- Chapter 1 introduces the deliverable by outlining the objectives and expected impact of Task 8.4, the target audience, the methodological approach followed, the contribution of the involved partners, the interdependencies with other Work Packages and Tasks, and this overview of the deliverable structure.
- Chapter 2 presents the general background and context of the study by providing an overview of the local context and challenges of the Camerino demo site, describing the characteristics of the building typologies, and identifying the existing and potential water and energy solutions.
- Chapter 3 details the methodology applied for the identification and clustering of building typologies, including dataset compilation, feature selection, preprocessing, spatial patterns, and validation for both heatwave and earthquake hazards.
- Chapter 4 presents the results of the study, including the extraction of building typologies, cluster characteristics, and spatial distribution for both heatwave and earthquake vulnerability.
- Chapter 5 assesses and prioritises energy and water interventions for the identified clusters, with a dedicated focus on nature-based solutions and operative guidelines for application in Camerino's historic centre.

- Chapter 6 summarises the main findings and conclusions of Task 8.4 and outlines potential directions for future work.
- Chapter 7 lists the references used throughout the document.
- Chapter 8 provides supporting material in the annex, including supplementary data and additional analyses.

1.1. OBJECTIVES AND EXPECTED IMPACT

The objective of this deliverable is to document the methodology, progress, and preliminary outcomes of Task 8.4 entitled "Resilience-enabling energy retrofit interventions that will contribute to the climate-proofing of the built environment at multiple scales – development for the application to a real demo case," led by NCSRD in collaboration with RINA-C, CMCC, and the Municipality of Camerino (CAM).

As part of Work Package 8, which focuses on the validation of adaptation solutions and decision-support tools through local implementation, Task 8.4 translates the planning methods and design concepts developed in earlier phases (notably Task 2.4) into the real context of the Camerino demo site in Italy. The task places emphasis on:

- Integrating local characteristics of the built environment, including architectural typologies and infrastructure systems;
- Developing operative guidelines for energy retrofitting and technological interventions, such as renewable energy installations and decentralized systems;
- Supporting self-sufficiency of buildings and communities in terms of energy supply, water provision, and risk mitigation, especially in relation to climate-related and natural hazards;
- Exploring urban solutions that incorporate Nature-based Solutions (NbS) for managing climate risks at district and community scales.

The expected impact of Task 8.4 lies in generating practical, scalable insights on how traditional and modern buildings in vulnerable territories like Camerino can be retrofitted and climate-proofed through an integrated, context-sensitive approach. The work also contributes to validating MULTICLIMACT's broader framework by demonstrating multi-hazard resilience planning in a real-world setting.

1.2. PURPOSE AND TARGET GROUP

This deliverable (D8.4) is part of Task 8.4 of the Horizon Europe project MULTICLIMACT, which aims to enable climate-proofing of the built environment through integrated resilience and retrofit strategies. The purpose of this document is to present the first steps toward the development and contextualisation of resilience-enabling energy retrofit interventions in the historic centre of Camerino, Italy—the demo case selected under WP8. It focuses on the analysis of the existing building stock, the identification of vulnerabilities to climate-related and seismic hazards, and the formulation of methodological pathways for sustainable retrofitting.

The primary target groups of this deliverable include:

- **Municipal authorities and decision-makers** seeking evidence-based, site-specific guidelines for building and urban resilience.
- **Built environment professionals** (engineers, architects, and urban planners) involved in renovation and adaptation strategies.
- **Civil protection authorities** and **infrastructure operators** concerned with preparedness and self-sufficiency under multi-hazard conditions.
- **Researchers and EU project partners** contributing to or building upon the MULTICLIMACT knowledge base.

The deliverable is classified as **Public (PU)** and aims to support replication and uptake of the methodology in other heritage or vulnerable contexts.

1.3. OVERALL APPROACH

The methodology followed in Task 8.4 built upon the design principles and practices developed under WP2 and tailored them to the unique urban, historical, and climatic characteristics of Camerino (Figure 1). The approach was structured around three main pillars:

1. **Typological Analysis of the Built Environment**:
    - A data-driven assessment of the traditional building stock in Camerino was undertaken using a combination of field-survey data and statistical clustering methods.
    - Key variables included structural characteristics, age, materials, height, and observed damage levels from previous seismic events.
2. **Hazard-Specific Vulnerability Profiling**:
    - The building dataset was split according to environment — relevance to specific hazards — namely, heatwaves and earthquakes — to produce targeted vulnerability profiles.
    - These profiles served as a basis for proposing climate- and seismic-resilient retrofit measures.
3. **Integration of Energy and Urban Retrofit Concepts**:
    - The outcomes of the vulnerability analysis were fed into the development of energy retrofit scenarios and decentralised technological solutions (e.g., renewable microgrids).
    - The task also explored Nature-based Solutions (NbS) at the district scale to mitigate climate stressors such as heat and water scarcity.

The results of this deliverable will eventually be translated into **actionable design and retrofit guidelines**, tailored to the Camerino context, with the potential to scale and adapt them to similar Mediterranean and seismic-prone regions.

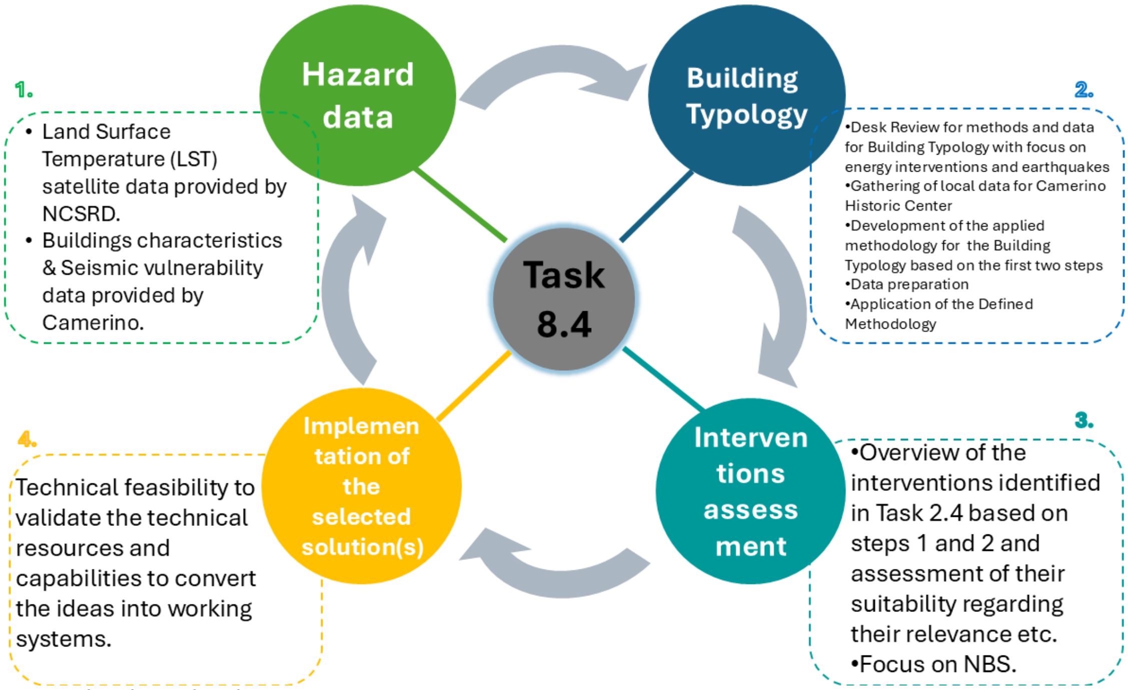

Figure 1. Flowchart of Task 8.4.

1.4. CONTRIBUTION OF THE PARTNERS

PARTNER SHORT NAME	CONTRIBUTIONS
NCSRD	Coordination of Task 8.4 and contribution to building typology and selection of Best Practices Solutions (input from T2.4) for energy and water for the Camerino historic centre.
RINA-C	Contribution to the selection of Best Practices Solutions (input from T2.4) for energy and water for Camerino historic centre.
CAM	Contribution to building typology and selection of Best Practices Solutions (input from T2.4) for energy and water for Camerino historic centre.
All Partners	Use/application of the selected energy and water solutions to perform feasibility studies for the CAMERINO building typology.

Table 1. Contributions of consortium partners to D8.4.

Co-funded by the European Union

1.5. INTERDEPENDENCIES WITH OTHER WPS AND TASKS

Task 8.4 focused on the development and contextual application of resilience-enabling energy retrofit interventions. Its implementation was directly linked to prior conceptual and design work carried out in Task 2.4 (WP2), which established foundational design practices and typological approaches for energy retrofitting traditional building stock in hazard-prone areas. In this sense, Task 8.4 acted as a developmental continuation of Task 2.4, aiming to translate best practices into real-world operability, focusing on the Italian demo case of Camerino (Figure 2).

Task 8.4 draws upon and interacts with the following tasks and work packages:

- WP2 – Task 2.4: Provided the design principles, building typology analysis, and guidelines for climate-proofing retrofits. Task 8.4 operationalized these by adapting them to the local characteristics, climate/natural risks (e.g., earthquakes and heatwaves), and energy profiles of Camerino.
- WP10 - Task 10.1: Develops and customizes the CIPCast digital platform for multi-hazard risk assessment and damage estimation at building and district scale. Task 8.4 draws on CIPCast's data integration and real-time risk prediction capabilities to inform and prioritize retrofit interventions, ensuring that resilience measures address both structural vulnerabilities and critical service disruptions.
- WP11 – Task 11.1: Task 11.1 serves as the main demonstration platform for the MULTICLIMACT framework at the building scale. It includes the testing and validation of solutions developed under Task 8.4. The building-scale resilience measures and energy retrofitting strategies formulated in this task will be installed, monitored, and assessed in real conditions. This will involve local actors such as the Municipality of Camerino and the University of Camerino. Task 11.1 thus plays a pivotal role in validating the practical impact, feasibility, and user responsiveness of the technical concepts developed under Task 8.4.
- WP15 – 15.1: Extends the demonstration and monitoring activities initiated in Task 11.1, enabling further evaluation of the performance and benefits of the energy retrofit and resilience interventions. Task 8.4 outputs are continuously assessed and refined based on real-time data and operational feedback, including the integration of digital tools such as CIPCast and the monitoring of KPIs for durability, efficiency, and user well-being.

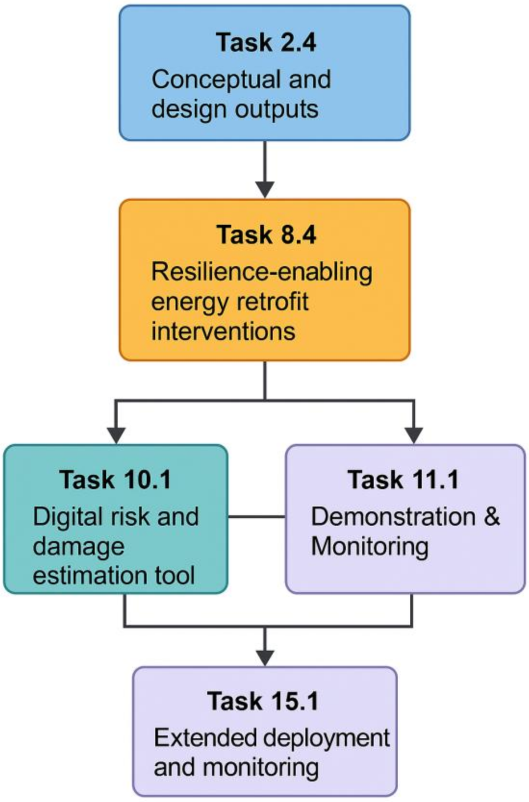

Figure 2. Visual interpretation of the interdependencies of Task 8.4 with other tasks and work packages.

In sum, Task 8.4 acts as a developmental hub within MULTICLIMACT, integrating the conceptual outputs from earlier design and climate analysis tasks with later demonstration and evaluation activities. Its centrality in the Camerino pilot allows it to bridge theory and practice, feeding essential insights into both upstream (design) and downstream (testing and replication) project components.

2. GENERAL BACKGROUND AND CONTEXT

Chapter 2 lays the foundation for the subsequent analysis by providing a detailed overview of the general background and context of the Camerino demonstration case. It opens with a comprehensive description of the local context, highlighting the geographic, demographic, and socio-economic features of Camerino, along with the key challenges posed by natural and climate hazards. The following section delves into the classification of local building typologies, combining insights from both desk-based literature review and data-driven analysis to establish a robust framework for targeted interventions. Finally, the chapter presents a summary of the energy and water solutions identified for climate resilience from Deliverable 2.4 "Planning and designing resilient housing: energy retrofit interventions that will contribute to the climate proofing of the built environment at multiple scales".

2.1. OVERVIEW OF THE LOCAL CONTEXT AND CHALLENGES

Camerino occupies a strategic position in the south-central Marche region of Italy, nestled within an elongated depression that runs from north-northwest to south-southeast between mountain ranges. The municipality extends over nearly 130 square kilometers at an elevation of 661 meters above sea level, making it a typical hill town of central Italy. With a population of approximately 6,859 inhabitants, Camerino represents a common challenge facing many Italian historic centers: maintaining vitality and services despite demographic decline.

2.1.1. TERRITORIAL STRUCTURE AND INFRASTRUCTURE NETWORKS

The town's location on a Miocene sandstone ridge between the Chienti and Potenza River valleys has shaped its development for over two millennia. This strategic position allowed control over important trans-Apennine routes, including several mountains passes that historically connected the Adriatic coast with central Italy. Today, while the SS77 highway provides the main connection to the regional transport network, the town's mountainous setting continues to present accessibility challenges that influence its economic and social dynamics.

The infrastructure network serving Camerino extends well beyond the historic center, encompassing rural roads, agricultural facilities, and scattered residential settlements that form an integral part of the territorial system. The rural road network connects 43 rural settlements (frazioni) with the main center, though many sections present geometric limitations and seasonal accessibility issues during extreme weather events. Key infrastructure nodes include the water treatment facilities serving both urban and rural areas, the electrical distribution network, and telecommunications infrastructure that shows significant coverage gaps in rural territories, limiting digital connectivity essential for economic diversification and remote work opportunities.

Agricultural infrastructure represents a critical component often overlooked in resilience planning. The territory includes extensive agricultural land, with infrastructure including irrigation systems, agricultural cooperatives facilities, and numerous farm buildings that serve both productive and residential functions. Many of these structures, built primarily in the post-war period, present vulnerabilities to both seismic and climate hazards while representing essential economic assets for rural communities.

2.1.2. HISTORIC CENTER AND BUILT HERITAGE

Despite its relatively small size, Camerino functions as an important service center for the surrounding territory. The presence of the University of Camerino, founded in 1336 and one of Europe's oldest universities, elevates the town's significance far beyond what its population might suggest. The university brings approximately 7,000 students to the town, effectively doubling its daytime population and injecting vitality into the local economy and cultural life.

The historical center of Camerino presents a remarkably well-preserved example of medieval urban planning adapted to challenging topography. Its distinctive spindle or fusiform shape reflects the natural constraints of its hilltop setting, with the medieval walls still defining the urban perimeter across approximately 35 hectares. The center stretches about 850 meters at its longest point and reaches 400 meters at its widest, creating a compact urban form that has evolved through distinct historical phases.

Archaeological and documentary evidence reveals four major periods of urban development. The earliest traces date to the Hellenistic period (4th-3rd century BCE), though little remains visible from this ancient phase. The Roman period brought more structured development, with orthogonal planning elements and substantial residential buildings. The most significant transformation occurred during the medieval period, particularly under the Da Varano signory from the 13th to 16th centuries, when the city acquired much of its current urban structure. Finally, various seismic events necessitated major reconstructions that added new architectural layers while generally respecting the mediaeval street pattern.

The historical urban organisation into three districts, or "terzieri" (Figure 3) – Sossanta, Mezzo, and Muralto – continues to influence the city's spatial structure. Each district developed its own character: Sossanta below the Cathedral served religious functions, Mezzo formed the commercial and civic heart, while Muralto housed craftsmen and defensive structures. This tripartite division created a functional specialisation that remains partially visible today.

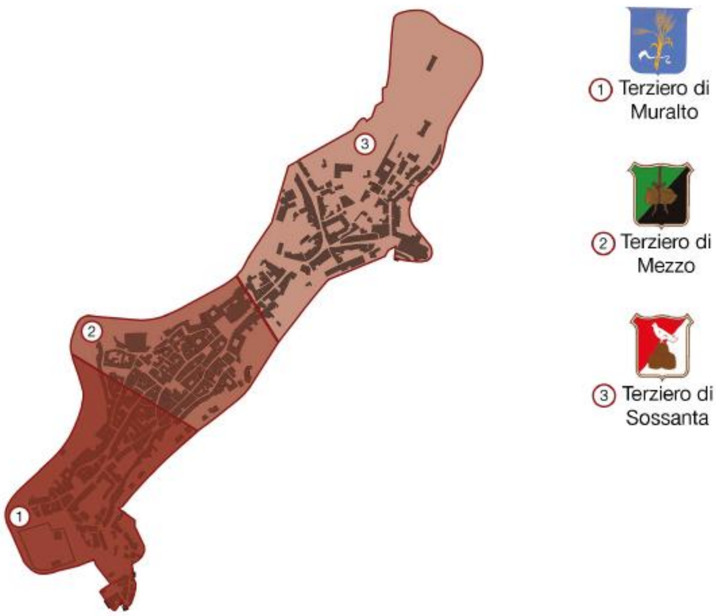

Figure 3. Historic division of the town into three districts (Terzieri).

The urban morphology centres on two perpendicular main axes that generate the primary circulation network (Figure 4), with organic medieval patterns filling the peripheral areas. Key urban nodes include Costanti Square, which functions as a crucial junction between different parts of the city, and the linear system of public spaces from Cavour Square to Garibaldi Square that forms the civic spine of the settlement.

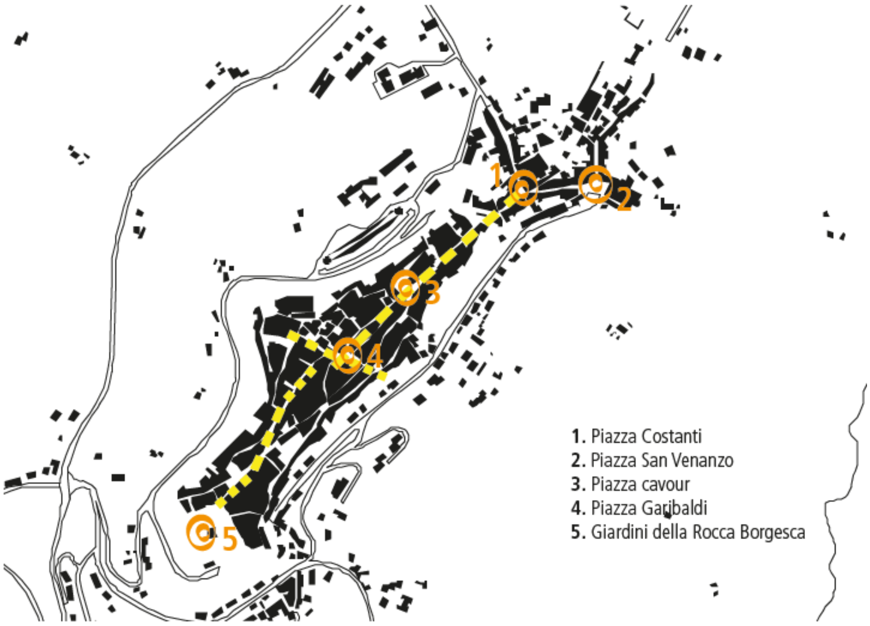

Figure 4. Main structural axes and nodes of the historic centre of Camerino.

Camerino's built heritage presents a rich tapestry of architectural types that chronicle its evolution from medieval town to modern service centre. The building stock can be categorised into four main chronological and typological groups, each reflecting different social needs and construction techniques.

Medieval structures dating from the 12th to 15th centuries comprise about 25-30% of the building stock. These include simple row houses with typical dimensions of 5-6 metres frontage and 10-12 metres depth, as well as more complex courtyard buildings formed through progressive aggregation. The cellular structure of these buildings, often featuring 6x6 metre or 9x9 metre bays with internal masonry pillars, reflects medieval construction capabilities and family-based social organisation.

Renaissance and post-Renaissance transformations, representing 35-40% of buildings, introduced more elaborate architectural elements while often maintaining medieval structural systems. During this period, wealthy families created palace residences by combining multiple medieval units, adding monumental staircases, vaulted ceilings, and regularised facades. These interventions demonstrate how economic prosperity translated into architectural ambition while respecting existing urban constraints.

The post-1799 earthquake reconstruction phase accounts for 20-25% of current buildings and introduced neoclassical design elements, structural improvements including iron tie rods, and more systematic ground-floor commercial adaptations. This period represents an early example of post-disaster planning that attempted to improve seismic performance while maintaining urban character.

Modern insertions from the 20th century, comprising 10-15% of the building stock, include some reinforced concrete structures and additions that often contrast with the historical fabric. These interventions reflect changing construction technologies and functional needs but sometimes compromise the integrity of the historical ensemble.

Construction techniques predominantly feature local sandstone masonry, with approximately 60% irregular stone masonry, 30% mixed brick-stone masonry, and 10% squared stone masonry. Wall thicknesses typically range from 50-90 centimeters at ground level, reducing to 45-60 centimeters at upper floors.

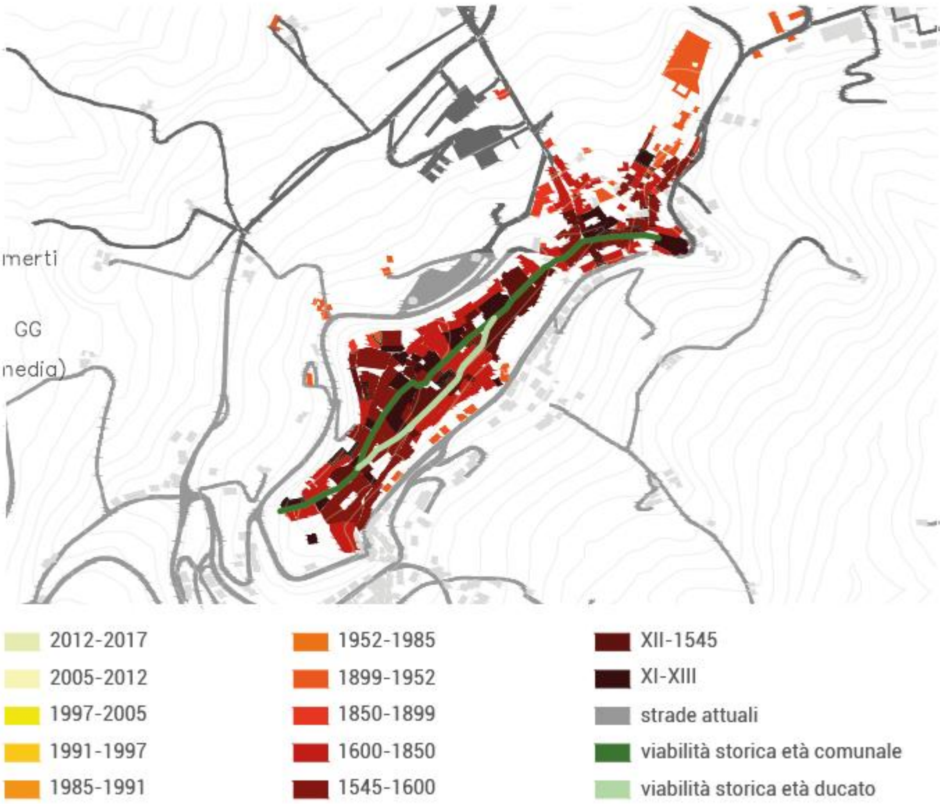

Figure 5. Construction periods of buildings in Camerino's historic centre.

2.1.3. RURAL TERRITORIES AND TRADITIONAL BUILDING TYPOLOGIES

Beyond the historic center, Camerino's rural territories encompass diverse settlement patterns and building typologies that present unique challenges and opportunities for resilience building. The rural built environment includes numerous individual buildings distributed across multiple settlements, ranging from small clusters to larger villages[4]. These settlements reflect different historical periods and functions, from medieval fortified villages to 19th-century agricultural colonies and 20th-century rural expansions.

Traditional rural building typologies can be classified into five main categories:

- Historic Rural Villages (Castelli): Medieval fortified settlements feature clustered stone buildings organized around central courtyards or small squares. These structures, typically multi-storey with thick masonry walls, present similar seismic vulnerabilities to the historic center but with limited access for emergency services and reduced maintenance due to population decline.
- Agricultural Complexes (Case Coloniche): Traditional farmsteads scattered across the territory combine residential and productive functions in integrated complexes. The main houses, built primarily in the 18th-19th centuries, feature characteristic architectural elements including external staircases, loggias, and attached barns. These buildings often house multiple families and maintain active agricultural functions, though many require structural improvements and energy efficiency upgrades.
- Rural Churches and Community Buildings: The territory includes numerous rural churches, parish halls, and community centers that serve as focal points for local communities. These buildings, dating from the medieval period to the 19th century, present particular challenges

due to their cultural significance, structural vulnerabilities, and essential role in maintaining community cohesion in dispersed settlements.

- Modern Rural Residential Buildings: Post-war residential construction in rural areas includes both individual houses and small residential developments. Built primarily in the second half of the 20th century using reinforced concrete or mixed masonry systems, these buildings generally present lower seismic vulnerability but often lack energy efficiency measures and may require infrastructure upgrades to support modern connectivity and services.
- Agricultural and Industrial Buildings: The rural territory includes numerous agricultural facilities (livestock buildings, storage facilities, processing centers) and small industrial structures. While often less architecturally significant, these buildings represent essential economic infrastructure and employment sources for rural communities.

2.1.4. DEMOGRAPHIC DYNAMICS AND COMMUNITY VULNERABILITIES

Camerino's demographic trajectory exemplifies the resilience challenges facing Italian historic hill towns, where population decline intersects with institutional assets in complex ways. The 7.8% population loss between 2001 and 2021 mirrors widespread rural depopulation across central Italy but signals deeper vulnerabilities when combined with accelerated aging. With an aging index of 321,8 [5]- well above the regional average of 226,4 - Camerino faces a critical demographic imbalance that threatens community vitality and economic sustainability. This demographic imbalance particularly affects rural areas where traditional extended family networks provided resilience against economic and environmental shocks. The loss of young adults reduces both economic vitality and the capacity for physical adaptation measures, as rural communities increasingly lack the human resources necessary for infrastructure maintenance and emergency response.

These trends demand targeted resilience strategies that leverage Camerino's unique strengths while addressing demographic vulnerabilities. The university and administrative functions represent crucial anchors that can attract younger populations and maintain economic activity, but their effectiveness depends on adapting to demographic realities. Building resilience requires interventions that both slow demographic decline - through improved services, digital connectivity, and economic opportunities - and help the community adapt to an older population structure through age-friendly infrastructure, intergenerational programming, and care systems that support aging in place while maintaining community cohesion.

2.1.5. ECONOMIC STRUCTURE AND TERRITORIAL INTEGRATION

Camerino’s economy is strongly service-oriented. According to ISTAT, over 78% of the local workforce is employed in the tertiary sector, the highest share among municipalities in the Marche region [6]. Within this framework, the University of Camerino represents the primary economic engine, directly employing more than 1,000 staff members and indirectly sustaining a service economy based on student presence. Thousands of students bring seasonal vitality, supporting restaurants, retail, rental housing, and other local services [7].

The role of tourism remains relatively limited compared to the city’s cultural potential, while manufacturing and agriculture play minor roles, mostly represented by small-scale enterprises and family-run farms. At the regional level, around 73% of employment is in services, 23% in industry, and 5% in agriculture [8], and Camerino broadly reflects this structure, though with an even greater dependence on education and public services.

The 2016-2017 earthquake sequence severely disrupted this already fragile economic ecosystem. The extensive damage to the historical center forced the closure of 40% of commercial activities and resulted in estimated economic losses of €150 million. Many businesses relocated outside the historical center or closed permanently, accelerating economic decline. The displacement of 2,000 residents – nearly 30% of the population – further undermined the customer base for remaining businesses, creating a negative spiral that reconstruction efforts are still working to reverse.

2.1.6. MULTI-HAZARD ENVIRONMENT AND TERRITORIAL VULNERABILITIES

Camerino faces a complex array of natural hazards dominated by seismic risk but increasingly influenced by climate change impacts. Understanding this multi-hazard environment is essential for developing appropriate adaptation and mitigation strategies for the historical center. Seismic hazards represent the primary threat to Camerino. The town sits in Seismic Zone 2, indicating medium-high seismicity with reference peak ground acceleration between 0.15 and 0.25 g.

The historical record reveals a pattern of devastating earthquakes: the 1279 event reached intensity IX-X on the Mercalli scale, the 1799 earthquake caused widespread destruction at intensity VIII-IX, and the 1997 Umbria-Marche sequence caused significant damage. The recent 2016-2017 Central Italy sequence demonstrated the ongoing threat, with the main shock reaching magnitude 6.5.

Geological hazards compound the seismic risk. Approximately 32% of the municipal territory is classified as having medium-high landslide susceptibility (P2-P3 in the PAI classification [9]. The eastern escarpment below the historical centre presents rockfall hazards, while areas with sediment cover exceeding 10 metres face differential settlement risks. These geological conditions not only pose direct threats but also amplify seismic effects through site-specific responses.

Climate-related hazards are intensifying due to ongoing climate change. Based on data from ISPRA and the Regional Multi-Risk Functional Centre, Camerino experiences increasingly extreme weather events. Extreme precipitation events show a concerning trend, with an increase in events exceeding 50 mm in 24 hours compared to the 1961-1990 baseline. The September 15, 2022 event, which delivered 90 mm in just 3 hours, exemplifies the new intensity of rainfall that overwhelms historical drainage systems. The maximum recorded daily precipitation of 149 mm in November 2013 indicates the potential for catastrophic flooding in vulnerable areas [10].

Extreme temperatures are increasingly frequent and intense. Data from the official meteorological station of Camerino [10] for 2015–2025 indicate maximum values up to 37.5°C (2 August 2017), with further peaks of 36.1°C (July 2023) and 36.0°C (July 2021 and June 2022). The data confirm marked interannual variability, with warm years (2017, 2022, 2023) alternating with colder periods, pointing to increasing instability of the local climate. Snow events remain significant, with the design snow load set at 1.50 kN/m^2 for Camerino's elevation. Recent significant events include the February 2012 accumulation exceeding 1 metre and the January 2017 event that deposited 60 cm in 48 hours. Such events pose risks to historical roof structures not designed for these loads.

While the elevated historical centre avoids direct riverine flood risk, localised pluvial flooding occurs during extreme rainfall events due to insufficient drainage capacity. The September 2022 and May 2019 events caused localised flooding, highlighting the vulnerability of the historical drainage infrastructure designed for a different climate regime.

The built environment of Camerino's historical centre faces interconnected vulnerabilities stemming from inherent structural weaknesses, earthquake damage, infrastructure deficiencies, and emerging climate stresses. These challenges require integrated approaches that consider both immediate safety needs and long-term resilience.

Structural vulnerabilities pervade the building stock. Critical deficiencies affect the majority of buildings: 85% lack effective wall-to-wall connections, 75% have inadequate wall-to-floor connections, and 60% feature thrusting roofs that push outward on walls during seismic events. Modifications over centuries have compromised structural integrity, with 70% of buildings showing openings that interrupt the "masonry box" behaviour essential for seismic resistance.

The post-2016 damage assessment documented through AeDES forms revealed the extent of recent earthquake impacts. Only 15% of buildings remained fully usable (Category A), while 37% were unsafe (Category E) and 10% faced partial or total collapse (Category F). Damage patterns showed 40% of buildings experience in-plane shear failure, 35% out-of-plane overturning mechanisms, and 25% combined failure modes. This damage reflects both the earthquake intensity and pre-existing vulnerabilities.

Infrastructure systems suffer from age and deferred maintenance. The water network, with 40% of pipes predating 1980, experiences high leakage rates that waste resources and potentially undermine foundations. Emergency accessibility remains critically constrained, with 2.3 km of routes narrower than 3.5 metres impeding emergency vehicle access. The electrical and telecommunications networks show vulnerabilities at 12 critical nodes identified through network analysis.

Climate-related challenges increasingly stress the historical building stock. The urban heat island effect raises temperatures 2-3°C above the surrounding countryside during summer heat waves, stressing both residents and building materials. Drainage systems designed for 30-year return periods prove inadequate for current extreme precipitation events. Many historical roofs are under-designed for current snow loads. Freeze-thaw cycles have increased since the 1990s, accelerating masonry deterioration through moisture infiltration and expansion.

Addressing Camerino's vulnerabilities requires a sophisticated approach that balances multiple objectives: ensuring life safety, preserving cultural heritage, maintaining economic viability, and building climate resilience. The intervention strategy developed through this research employs a multi-criteria framework that prioritises actions based on technical urgency and cultural-social importance.

Technical interventions must respect the historical fabric while achieving acceptable safety levels. For masonry buildings, local mechanism prevention using steel tie rods can prevent out-of-plane collapse while remaining largely reversible. Masonry consolidation through hydraulic lime injection improves cohesion without introducing incompatible materials. Floor stiffening using diagonal steel bracing or cross-laminated timber overlays enhances diaphragm action. Where differential settlement threatens stability, micropiles provide foundation support with minimal disruption to archaeological layers.

Climate adaptation measures increasingly factor into intervention planning. Green infrastructure solutions, including permeable paving, help manage stormwater while maintaining historical character. Building envelope improvements must balance energy efficiency with moisture management in historical masonry – a particular challenge requiring careful material selection and detailing. Drainage system upgrades to 50-year return period standards protect both buildings and urban spaces from increasing precipitation extremes.

The performance objectives reflect a pragmatic approach to historical building safety. Rather than requiring full compliance with new construction standards, interventions target 60% of new building performance for life safety, limiting interstorey drift to 0.3% for damage limitation, and ensuring immediate occupancy for strategic buildings after a 475-year seismic event. Climate resilience objectives aim to maintain internal comfort conditions under a 2°C warming scenario while preserving historical fabric.

Implementation challenges include coordinating interventions across building aggregates where multiple owners must cooperate, securing adequate funding for comprehensive interventions, maintaining heritage values while meeting safety requirements, and minimizing disruption to remaining residents and businesses during long construction periods. The integration of seismic strengthening with energy efficiency improvements offers opportunities to leverage multiple funding sources while achieving co-benefits.

Camerino's reconstruction and resilience building efforts operate within a complex multi-level governance framework that both enables and constrains intervention possibilities. Understanding this context is essential for identifying opportunities and barriers to implementing the proposed prioritization framework.

At the national level, Italy's regulatory framework provides sophisticated tools for historical center intervention. The NTC 2018 seismic design code includes specific provisions for existing masonry buildings, recognizing that historical structures cannot meet new construction standards. Circular 7/2019 [11] provides detailed guidance for assessing and strengthening existing masonry, while [12] establishes guidelines specifically for heritage buildings. The Cultural Heritage Code (D.Lgs 42/2004) [13] ensures protection of historical values but can complicate intervention approval processes. The recent National Climate Adaptation Plan [14] begins to integrate climate considerations into heritage management, though implementation guidelines remain under development.

Regional instruments in Marche provide additional layers of regulation and support. Regional Law 22/2011 [15] adapts —application national building codes to local conditions and historical building types. The post-2016 Special Reconstruction Framework streamlines some procedures and provides enhanced funding for integrated interventions. The Regional Climate Adaptation Plan [16] represents an important step toward addressing climate risks, though specific measures for historical centers need further development. The regional microzonation program has produced detailed seismic hazard maps essential for site-specific intervention design.

At the municipal level, Camerino has developed several planning instruments that guide reconstruction efforts. The Historical Center Framework Plan provides detailed intervention categories for different building types and urban areas. The identification and mapping of structural aggregates facilitate coordinated intervention planning. The Emergency Limit Condition (CLE) analysis identifies critical infrastructure and escape routes that must remain functional after earthquakes. However, the integration of these various plans remains challenging, and climate adaptation considerations are not yet fully incorporated into local planning instruments.

2.2. BUILDING TYPOLOGY

Understanding and classifying building typologies is essential for developing targeted climate-resilient retrofit strategies. A building typology refers to the systematic classification of buildings based on shared architectural, structural, and functional characteristics—such as construction period, number of storeys, structural system, façade type, and layout. These typological attributes enable tailored interventions for improving energy efficiency, enhancing seismic resilience, and ensuring thermal comfort across different contexts.

The need for establishing building typologies has become increasingly urgent due to the vulnerabilities of European building stock to climate/natural hazards such as heatwaves, earthquakes, and flooding. Much of this stock was constructed prior to modern energy performance and hazard-resilience standards, leaving it exposed to both chronic and acute climate risks [17, 18]. Typological classifications allow technical experts and decision-makers to identify at-risk building groups and prioritize interventions that align with structural characteristics, historical context, and retrofit feasibility.

Building typologies support a range of sectors and objectives:

- Targeted retrofitting: Retrofit needs and solutions differ significantly across building types. For instance, pre-1945 masonry multifamily buildings often require a different approach than post-2000 reinforced-concrete structures. Understanding typology allows interventions to be fine-tuned to each building’s vulnerability and energy behavior.
- Refined risk assessment: Typological data improves hazard modelling by enhancing the precision of risk assessments. Empirical studies have shown that structural damage patterns during hazards like earthquakes or floods correlate strongly with typological categories [19].
- Policy and planning guidance: Building typologies are embedded in national energy strategies, influencing energy performance certificate (EPC) systems, retrofit incentive schemes, and zoning laws. The JRC’s 2014 overview of building typologies in Europe highlights their central role in implementing long-term renovation strategies.

Building typologies have long supported risk-informed planning and hazard-specific assessments. In seismic engineering, typologies are used to estimate likely damage patterns and guide retrofitting needs across unreinforced masonry buildings or reinforced concrete frames. Similarly, in the context of energy retrofits, typologies have been leveraged to assess thermal performance under climate stressors. Ascione et al.(2015)[20] demonstrated how Mediterranean housing typologies with distinct envelope configurations benefit from optimized insulation thickness and cool roof coatings, maximizing energy savings while minimizing overheating risks.

Typologies are also instrumental for policy development and urban planning. The European TABULA and EPISCOPE projects, referenced by the JRC (2014) [18], developed national residential building typologies to support long-term renovation strategies and harmonized retrofit planning. These tools inform Energy Performance Certificates (EPCs), financial incentives, and national energy efficiency roadmaps under the Renovation Wave initiative. Fan and Xia(2017)[21] reinforced the value of typology in designing efficient envelope and PV retrofits for older apartment blocks. By tailoring the model to specific characteristics of ~50-year-old structures, they demonstrated how performance gains and return on investment can be optimized through typology-based strategies.

From a methodological perspective, building typology supports both top-down (desk-based) and bottom-up (data-driven) approaches. The former relies on existing classifications from literature and institutional sources, while the latter employs computational techniques—such as clustering algorithms—to extract structural patterns from large datasets. This dual methodology ensures robustness and adaptability, especially when tailoring strategies for specific local contexts.

In MULTICLIMACT Task 8.4, the typological study is based on a combination of a desk review of relevant literature and policy frameworks, and a data-driven clustering analysis using local building data from Camerino's historic center. This twofold methodology ensures alignment with European best practices while grounding the typology in Camerino's unique architectural, seismic, and climatic context.

The resulting typology enables:

- Scenario modelling for energy and water resilience
- Prioritized strengthening of seismically vulnerable typologies
- Development of hazard-specific and scalable retrofit guidelines
- Enhanced communication and engagement with local stakeholders

In practical terms, building typologies serve across various domains:

- Energy retrofits: Envelope upgrades, insulation, and passive cooling strategies are matched to typological features to optimize energy performance without compromising heritage value.
- Seismic resilience: Typologies allow estimation of expected structural failure patterns under seismic stress, aiding prioritization of reinforcement efforts.
- Urban planning: Planners use typologies to tailor zoning policies, emergency response plans, and funding allocation for renovation.
- Monitoring and modelling tools: Typologies are integrated into models and databases—such as EPC registries or GIS-based hazard simulations—to project impacts and test adaptation scenarios.

By leveraging the typological framework, MULTICLIMACT enables a more granular, scalable, and locally anchored understanding of building vulnerability and retrofit needs. This ensures that Camerino's built heritage can evolve in a climate-resilient and sustainable manner.

2.2.1. DESK REVIEW

A comprehensive desk review was performed to gather and analyze state-of-the-art methodologies and results related to building typologies, vulnerability assessments, and retrofit scenarios across various contexts and hazard types. By systematically reviewing recent studies, clustering techniques, classification systems, and digital tools, we aimed to identify the most relevant approaches, variables, and findings applicable to the Camerino demo case and to the broader objectives of Task 8.4.

Wu et al.(2022)[22] introduced a clustering-based approach to identify heat-prone neighborhood typologies in European cities with temperate climates. Using K-means clustering on parameters such as floor area ratio, shape factor, street orientation, and green space, they derived four main neighborhood types that support targeted adaptation interventions for urban heat. Martínez-Rocamora et al.(2024)[2] applied clustering techniques—including Ward, PAM-Ward, and PAM algorithms—to cadastral data in order to define typologies relevant to energy retrofitting. Variables such as location, construction period, building type, and number of floors were used to determine clusters, facilitating the identification of retrofit needs and priorities at scale. Martínez-Rocamora et al.(2024)[2] used hierarchical (Ward) and partitional (PAMWard, PAM) clustering on cadastral data—incorporating variables like construction year, number of floors, building type, and façade characteristics—to generate high-resolution typologies for energy retrofitting.

Dascalaki et al.(2011)[23] developed a harmonized classification for residential building typologies in Greece, based on construction period, building size, and climate zone. This structure enabled the assessment of 24 distinct building types with regard to energy performance, supporting massive evaluation of conservation measures. Meyers-Angulo et al.(2023)[24], Firmansyah et al.(2024)[25] advanced the classification of buildings by seismic vulnerability using both traditional clustering (Cluster-ANN) and convolutional neural networks (CNNs). These approaches incorporate features such as number of storeys, building height, type, and vertical irregularity, demonstrating the power of both statistical and image-based methods in rapid, city-scale vulnerability assessment. Their findings support the use of advanced analytics and AI in supporting disaster risk reduction and resilience planning.

Silva et al.(2022)[26], Landolfo et al.(2022)[27] contributed frameworks for classifying the European building stock with respect to both technological and typological classes, considering vulnerability to multiple hazards (seismic and climatic). Their work supports the development of accurate building technologies maps, integrating structural characteristics, energy performance, and hazard exposure. Ibrahim et al.(2021)[28] focused on heritage residential buildings, combining rule-based GIS analysis and expert-driven validation to develop retrofitting matrices balancing conservation with energy efficiency. Tocchi et al.(2022)[29] provided regional-based exposure models to improve seismic risk assessment, emphasizing the integration of local building typologies, census data, and construction details. Zhang et al.(2023)[30] further extended automated identification using UAV imagery and deep learning to distinguish building structural types, validating the application of innovative remote sensing and AI tools for vulnerability assessment.

The reviewed literature demonstrates a convergence of advanced clustering, statistical, and AI-driven approaches for typology identification and vulnerability assessment. The adoption of these techniques within Task 8.4 ensures that interventions for the Camerino demo case are evidence-based, tailored to local risk profiles, and compatible with the best practices in both energy retrofitting and disaster resilience. Moreover, the comparative analysis of methods and findings allows for the harmonization of building data and facilitates the transferability of results to similar historic and hazard-prone urban contexts.

2.3. ENERGY & WATER SOLUTIONS

The identification of energy and water solutions in Deliverable 2.4 [31] constituted a foundational step in defining a multi-scalar strategy for enhancing the climate resilience of the built environment. These solutions were selected based on their potential to reduce exposure and vulnerability to multiple hazards, improve energy and water efficiency, and foster adaptive capacity through both technological and nature-based interventions. The outcomes of Task 2.4 directly informed the site-specific analysis and feasibility assessment conducted within Task 8.4, which focused on the application of these measures in the historic center of Camerino.

Energy-related solutions identified in Task 2.4 included a range of passive and active interventions aimed at reducing thermal stress, enhancing energy autonomy, and supporting sustainable renovation practices. These ranged from cool roofs and ventilated façades to geothermal heat pumps, photovoltaic panels, and battery storage systems. Of particular interest to the implementation in Camerino were those solutions that could be integrated in low-invasive ways into heritage buildings or shared across building clusters to enable community-level resilience.

ENERGY SOLUTIONS

1. Balcony/private garden
2. Adopted public spaces

3. Amenity areas
4. Parks
5. Street trees
6. Reforestation
7. Cool roofs and ventilated roofs
8. Shading devices
9. Adequate insulation
10. Natural ventilation
11. Fire-resistant building materials
12. Natural daylighting
13. Building Monitoring System
14. Sensors
15. Renewable energy
16. Energy storage
17. Demand and response programs
18. Energy communities
19. Light-coloured and reflective materials
20. Passive ventilation through thermal chimneys
21. Materials with high thermal mass
22. Active cooling ventilation
23. Geocooling and heat pumps
24. Passive dampers
25. Jacketing of concrete frame elements
26. Electrical and mechanical systems and utilities above flood level
27. The Expanded EM-DAT disaster database to the European level (eEM-DAT)
28. Myclimateservices.eu
29. Overtopping BReakwater for Energy Conversion (OBREC)
30. QoAir
31. Unified Fire Protection Units and System (UFPUS)

Water-related solutions selected in Task 2.4 addressed both extremes of the water cycle: water scarcity and water excess. These include measures for rainwater harvesting and reuse, green roofs and permeable pavements to increase infiltration and reduce runoff, flood barriers, and slope stabilisation techniques suitable for hillside urban settings. Nature-based Solutions (NbS), such as bioswales and riparian buffers, were highlighted for their multifunctional benefits in both urban and peri-urban contexts.

WATER SOLUTIONS

1. Urban wetlands
2. Mangroves, dunes, and healthy reef systems
3. Lamination tanks
4. Rainwater collection tanks
5. Raised structures and/or raised entry threshold
6. Emergency irrigation of surrounding landscaping linked with rainwater collection system
7. Water-resistant materials and moisture-resistant materials
8. Impact-resistant roofing materials

9. Window/services/fixtures protections
10. Early warning systems
11. Flood barriers
12. High placement of electrician, ventilation and heating systems
13. Drainage corridors
14. Slope stabilization
15. Bioswales
16. Greywater recycling
17. Favor aerodynamic shapes
18. Lowest liveable floor elevated above ground level
19. Effective roof drainage system
20. Hip-roof (with slopes of 30˚)
21. Sustainable urban drainage system (SuDS)
22. Pervious soils
23. Buffer zones around the building
24. Indoor water efficiency installation
25. Water-resistant insulation
26. Groundwater by solar photovoltaic (PV) pumping system
27. Taps and Showerheads
28. Household Appliances
29. 3D Printing of Coastal Protection Reefs
30. Infosequia
31. ArboDroughtStress
32. Smart blue-green roof system
33. Bluebloqs
34. Toolkit Method
35. NOAQ Boxwall
36. Tubebarrier

In Task 8.4, these pre-selected solutions were assessed for their technical and spatial feasibility in the Camerino context, considering the local building typologies, exposure to climatic and geological hazards, and availability of local resources. The linkage between Deliverable 2.4 and the activities in Task 8.4 ensured continuity between strategic planning and operational implementation, supporting the development of resilience-enabling interventions that are aligned with both the climatic challenges and the socio-cultural fabric of the territory.

3. METHODOLOGY AND IMPLEMENTATION

Chapter 3 outlines the methodology and implementation process applied to the Camerino demo case, providing the foundation for the clustering and typological analysis. Section 3.1 describes the overall workflow for the identification of building typologies, highlighting the sequence of data loading, feature selection, normalisation, distance computation, clustering, and validation. Section 3.2 presents the datasets employed in the study, combining satellite-derived land surface temperature data for heatwave exposure assessment with the detailed *AeDES* database on building stock and post-earthquake conditions. Section 3.3 details the application of the methodology to Camerino's historic centre, with separate clustering procedures developed for heatwaves and earthquakes. Each procedure includes feature selection, preprocessing, spatial exploration, clustering algorithms, and validation indices, ensuring robust and hazard-specific groupings.

3.1. METHODOLOGY FOR THE IDENTIFICATION OF BUILDING TYPOLOGY

The following workflow describes the comprehensive process implemented for clustering the Camerino building dataset according to both heatwave and earthquake hazard parameters. All data analysis and modelling were performed using Python 3.11[32], exploiting a suite of scientific and geospatial libraries. Mixed-type building data were preprocessed before being analysed using the Gower distance metric [1] to appropriately handle heterogeneous feature types. Clustering was then conducted using both Agglomerative Hierarchical Clustering [3] and K-Medoids algorithms [33], both of which support the use of precomputed dissimilarity matrices. Internal cluster validation employed the silhouette score [34] and Dunn index [35] to identify optimal solutions and ensure interpretability. This workflow (Figure 6) enabled the integration of spatial, typological, and hazard-related attributes to derive meaningful building groups tailored to climate and seismic risk assessment.

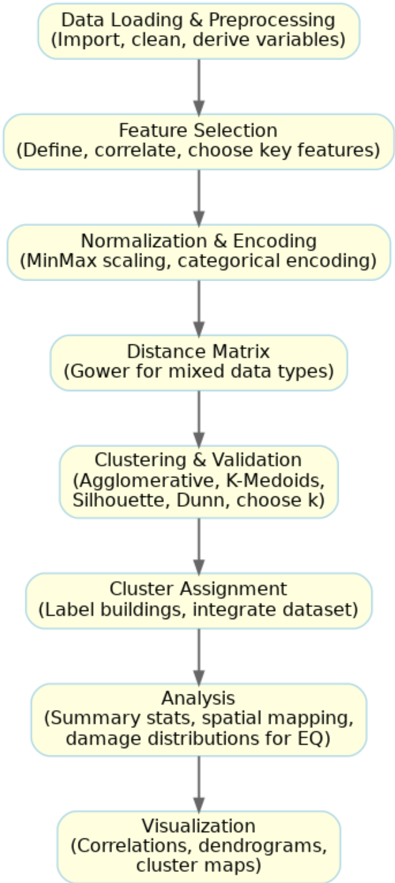

Figure 6. Building typology methodology flowchart.

More specifically, the following steps were performed:

- **Data Loading & Preprocessing**

The first step involved importing and loading the building dataset from Excel, which contained all relevant features for analysis. Where necessary, derived variables were computed, such as composite damage scores for structural components. The dataset was then cleaned to remove inconsistencies and handle missing values, ensuring that only reliable information was included in the clustering process.

- **Feature Definition & Selection**

  Candidate feature sets were defined separately for each hazard (heatwaves and earthquakes) to capture the specific characteristics most relevant to vulnerability. A correlation analysis was conducted to explore relationships between variables and identify redundancy. Based on this, we selected a subset of non-redundant and physically meaningful features, ensuring that the clustering would be driven by variables that truly reflect building characteristics and hazard exposure.

- **Data Normalisation environment - environment - & Transformation**

  To prepare the selected variables for analysis, continuous and ordinal features were normalised using MinMax scaling, placing them on a comparable range between 0 and 1. Nominal and categorical features were encoded appropriately so that they could be integrated alongside numerical data. These transformations ensured that all variables were represented in a consistent format suitable for clustering and distance computation.

- **Distance Matrix Computation**

Because the dataset included a mix of numerical, ordinal, and nominal variables, we employed the Gower distance metric. This method allows the calculation of pairwise dissimilarities across mixed data types, ensuring that each type of variable contributes appropriately to the clustering.

- **Cluster Analysis & Validation**

  Clustering was then performed using algorithms capable of handling mixed-type data, specifically Hierarchical (Agglomerative) clustering and K-Medoids, both applied to the precomputed Gower distance matrices. To evaluate the quality of the clustering, internal validation indices such as the Silhouette score and the Dunn index were calculated. These measures guided the determination of the optimal number of clusters (k), balancing compactness and separation of the resulting groups.
- **Cluster Assignment**

  Based on the chosen method and optimal cluster number, each building in the dataset was assigned to a cluster. These cluster labels were integrated back into the main dataset, allowing further interpretation and comparison of results across different building groups.
- **Statistical & Spatial Analysis**

  For each cluster, summary statistics (mean, median, minimum, maximum, and standard deviation) were computed to describe the distribution of features. Spatial analysis was also performed, mapping the distribution of clusters and key variables across Camerino's urban fabric. For earthquake-related clustering, the analysis was extended to include cluster-specific distributions of structural damage types and levels, offering a more detailed understanding of vulnerability patterns.
- **Visualisation**

  Finally, a range of visualisations supported both validation and interpretation. These included feature distributions, correlation matrices, silhouette and Dunn indices, dendrograms, and spatial cluster maps. Maps were generated not only for clusters but also for each key feature, enabling the identification of distinct geographic patterns and their relation to hazard vulnerability.

3.2. DATASETS FOR CAMERINO DEMO CASE

In this study, two main types of datasets were utilised to support the vulnerability and clustering analysis for the Camerino demo case. First, for risk assessment, we employed satellite-derived land surface temperature data based on Landsat 8 imagery (Figure 7) to quantify heat island exposure [36]. This dataset offers estimates of land surface temperature at a 30x30 metre spatial resolution, with a 16-day temporal frequency covering the period from 2013 to 2021. While it provides valuable insights into spatial and temporal temperature patterns, it is important to note that some limitations exist due to potential data gaps on cloudy days, which may affect the completeness and accuracy of the exposure assessment. Furthermore, the distance of buildings from parks was calculated via GIS software to decide if it is a heatwave-contributing factor for the Camerino case study. Second, we used the detailed Camerino Aedes database, which contains comprehensive information on the local building stock. This includes structural attributes, usage, construction period, and additional building characteristics essential for typology classification and hazard analysis.

Co-funded by
the European Union

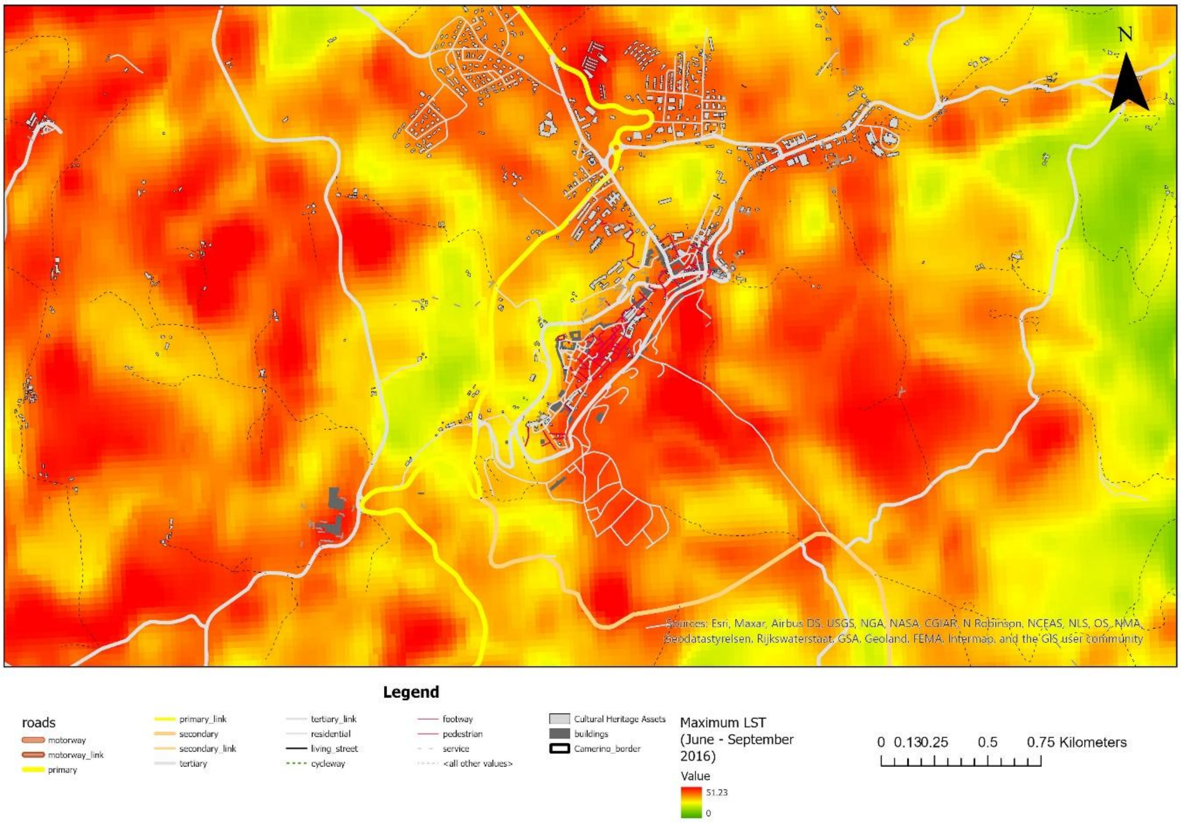

Figure 7. Land Surface Temperature (LST) for the area of Camerino.

Following the 2016-2017 Central Italy earthquake sequence, a comprehensive database was developed to systematically organise and analyse the post-earthquake damage assessment data collected through AeDES forms (Agibilità e Danno nell'Emergenza Sismica - Usability and Damage in Seismic Emergency). This database represents a crucial component of the vulnerability assessment framework, providing a large amount of data at the building scale.

The AeDES form, standardised at the national level and developed by the Department of Civil Protection in collaboration with ReLUIS (Italian Network of University Laboratories of Earthquake Engineering), serves as the primary tool for rapid post-earthquake assessment of ordinary buildings. The digitalisation and systematic analysis of these forms through a dedicated database structure enables the transformation of field observations into actionable intelligence for reconstruction planning and resilience building.

The database was constructed using Microsoft Access, chosen for its ability to manage relational data structures while remaining accessible to municipal technical staff without specialised database training. The relational database management system (RDBMS) approach allows for the storage of complex, interconnected data in multiple tables, with each record containing distinct fields that capture the multifaceted nature of building conditions and damage patterns.

The database architecture reflects the structure of the AeDES form itself, which collects information across multiple domains:

- Building identification and characteristics: Each building unit is assigned a unique identifier that links to the municipal cadastral system, enabling integration with existing administrative databases. Basic parameters recorded include the number of floors, construction period, primary use (residential, commercial, mixed), structural typology (masonry, reinforced concrete, mixed systems), and aggregation characteristics (isolated building, end unit, intermediate unit within aggregate).

- Structural system details: The database captures detailed information about vertical structures (masonry type, quality and thickness), horizontal structures (floor types ranging from timber beams to reinforced concrete slabs), roof configurations, and foundation systems where visible or documented. This structural characterization proves essential for understanding damage patterns and planning appropriate interventions.
- Damage assessment data: Section 4 of the AeDES form, which documents damage levels and extent, receives particular attention in the database structure. The system records four damage levels for structural components:
    - D0 (no damage)
    - D1 (slight damage)
    - D2-D3 (moderate to heavy damage)
    - D4-D5 (very heavy damage to collapse)

  Critically, the database also captures damage extent for each component, classified as affecting less than 1/3, between 1/3 and 2/3, or more than 2/3 of the element. This granular recording of both damage severity and extent enables nuanced understanding of building conditions.
- Usability outcomes: The final usability judgement is stored with categories ranging from A (usable) through F (unusable due to external risk), along with any temporary safety measures implemented and recommendations for immediate interventions. For Camerino, the distribution of these outcomes revealed that only 15% of buildings remained fully usable (Category A), while 37% were deemed unsafe (Category E).

The true power of the database emerges through its integration with QGIS, an open-source geographic information system. Each database record links to the spatial data through unique building identifiers, enabling comprehensive spatial analysis and visualisation.

The integration process employs the "join" function in QGIS, connecting the attribute tables of the cadastral base cartography with the AeDES database tables. This linkage creates a comprehensive geodatabase where each building polygon contains not only geometric information but also the full spectrum of structural characteristics, damage assessments, and usability outcomes.

This systematic approach to data management transforms the emergency response tool (AeDES forms) into a comprehensive knowledge base that supports long-term resilience planning for Camerino's historical centre. The database not only captures the immediate post-earthquake situation but also provides the empirical foundation for validating vulnerability assessment methodologies and prioritising interventions that balance safety requirements with heritage preservation needs.

The data structure is designed for a collection of information at the building scale (granularity) and concerns masonry buildings.

The following set of tables (Tables 2–6) presents the proposed structure of the database derived from the AeDES forms and the integration with GIS layers. Each table groups fields according to the corresponding section of the survey form, ensuring consistency between post-earthquake data collection and the subsequent vulnerability/loss modelling.

- Table 2. *Section 1 - Building identification (AeDES form – section 2 + GIS informations)*. – Building identification introduces general descriptors of each record, such as name, georeferencing and additional notes, which allow the linkage with cadastral and GIS information.
- Building geometry details the main dimensional characteristics of the structure (number of storeys, basements, average heights, surface ranges, and construction/renovation period).
- Table 4 – Building typology defines the prevailing and secondary structural systems (vertical and horizontal), including the presence of mixed systems, isolated columns, strengthening interventions and roof type.
- Table 5 – Site morphology records information on site setting (crest, slope, plain) and foundation conditions.

- Table 6. *Section 5 – 2016 Seismic Damage (AeDES form - section 4-5*). – 2016 Seismic Damage describes the level and extent of damage observed in structural and non-structural components after the 2016 earthquake, following the coding system of the AeDES Sections 4-5. This information is fundamental for calibrating vulnerability functions and for validating loss estimation models.

For each field, the tables report:

- Alias: short name used in the database.
- Content: type of variable (text, integer - number, real value - number, coded classes).
- Note: explanatory description, clarifying the coding system and its meaning for vulnerability/loss models.

FIELD	ALIAS	CONTENT	NOTE
A1	Name	Text	Identification
A2	Georeferencing	Shapefile GIS	Georeferencing
A3	Additional notes	Text	Notes on the considered building

Table 2. Section 1 - Building identification (AeDES form - section 2 + GIS informations).

FIELD	ALIAS	CONTENT	NOTE
B1	Nr Storeys	Integer	Number of storeys (including basements)
B2	Nr Basements	Integer	Number of basements
B3	Average storey height [m]	Integer (1..4)	Average storey height 1 = <2.5 m 2= 2,50-3,49 m 3= 3,5-5,00 m 4= >5,00 m
B4	Average storey surface [m]	Integer (1...16)	Average storey surface 1= >50 m^2 2= 50-69 m^2 3= 70-99 m^2 4= 100-129 m^2 5= 130-169 m^2 6= 170-229 m^2 7= 230-299 m^2 8= 300-399 m^2 9= 400-499 m^2 10= 500-649 m^2 11= 650-899 m^2 12= 900-1199 m^2 13= 1200-1599 m^2 14= 1600-2199 m^2 15= 2200-3000 m^2

			16= >3000 m²
B5	Construction/renovation period	Integer (1..8)	Period of construction or period relative to last important renovation 1=<1919 2=1919-1945 3=1946-1961 4=1962-1971 5=1972-1981 6=1982-1991 7=1992-2001 8=>2002
B6	Nr storeys above ground	Integer	Number of storeys above ground

Table 3. Section 2 - Building Geometry (AeDES form - section 2).

FIELD	ALIAS	CONTENT	NOTE
C0-1	Structure Typology T1 [%]	Real (0-100)	Percentage of the prevailing typology of vertical/horizontal structures. The following fields contain information about the building typology according to AEDEs form (post-earthquake survey). *Reference document:* https://www.eeri.org/wp-content/uploads/Italy/EUR%2022868%20(2007)%20Field%20Manual%20for%20post-earthquake%20damage%20assessment.pdf
C0-2	T1-Vertical Structures	Integer (1,..,5)	Vertical Structures (prevailing typology) 1=unknown 2=Irregular layout or bad quality/without tie rods or tie beams 3=Irregular layout or bad quality/with tie rods or tie beams 4=Regular layout and good quality/ without tie rods or tie beams 5=Regular layout and good quality/with tie rods or tie beams
C0-3	T1-Horizontal Structures	Integer (1,…,6)	Horizontal structures (prevailing typology) 1=Unknown 2=Vaults without tie rods 3=Vaults with tie rods 4=Beams with flexible slab 5=Beams with semirigid slab

			6=Beams with rigid slab)
C0-4	Structure Typology T2 [%]	Real (0-100)	Percentage of the secondary typology (derived as 100-C0-1) of vertical/horizontal structures
C0-5	T2-Vertical Structures	Integer (1,..,5)	Vertical Structures (secondary typology) 1=unknown 2=Irregular layout or bad quality/without tie rods or tie beams 3=Irregular layout or bad quality/with tie rods or tie beams 4=Regular layout and good quality/ without tie rods or tie beams 5=Regular layout and good quality/with tie rods or tie beams
C0-6	T2-Horizontal Structures	Integer (1,..,6)	Horizontal structures (secondary typology) 1=Unknown 2=Vaults without tie rods 3=Vaults with tie rods 4=Beams with flexible slab 5=Beams with semirigid slab 6=Beams with rigid slab)
C0-7	Isolated columns	integer (0,1)	Presence of isolated columns 0=no, 1=yes
C0-8	Mixed structures	integer (1,..,3)	Presence of a mixed structure typology 1=frame over masonry 2=masonry over frame 3=masonry and frame in parallel
C0-9	Strengthening	Integer (1,..,3)	Presence of strengthened masonry 1=injections or unreinforced plasters 2=reinforced masonry of reinforced plasters 3=other or unknown strengthening
C0-10	Roof	Integer (1,..,4)	Roof 1=thrusting heavy 2=non thrusting heavy 3=thrusting light 4=non thrusting light

Table 4. Section 3 - Building typology (AeDES form - section 3).

FIELD	ALIAS	CONTENT	NOTE
E1	Site Morphology	Integer (1,..,4)	Site morphology 1=crest

			2=sleep slope 3=mid slope 4=plan
E2	Foundations	Integer (1,..,4)	Damage to the foundations 1=Absent 2=produced by earthquake 3=worsened 4=pre-existent

Table 5. Section 4 - Site morphology (AeDES form - section 7).

FIELD	ALIAS	CONTENT	NOTE
F1-1	Damage Vertical Structures	Integer (0..333)	Damage to the structural components: vertical structures Code consisting of 3 integers: The first position (hundreds) describes the extension of very heavy damage. The second position (tens) describes the extension of medium severe damage. The third one (units) describes the extension of slight damage. Extension is described by the following code: 0= no damage or negligible damage 1=extension >2/3 2=1/3<extension <2/3 3=extension <1/3 (ordered as in Aeeds form) e.g., 2. 002 (or = slight damage with extension between 1/3 and 2/3 110 = very heavy damage with extension < 1/3 and medium damage with extension < 1/3
F1-2	Damage Floors	Integer (0,333)	Damage to the structural components: floors Score as F1-1
F1-3	Damage Stairs	Integer (0,333)	Damage to the structural components: stairs Score as F1-1
F1-4	Damage Roof	Integer (0,333)	Damage to the structural components: roof Score as F1-1
F1-5	Damage Partition	Integer (0,333)	Damage to the structural components: infill-partitions Score as F1-1
F1-6	Pre-existing Damage	Integer (0,333)	Damage to the structural components: Pre-existing damage Score as F1-1

F2-1	Damage Coverings	Integer (0,1)	Damage to the non structural components: falling of plaster,coverings, false ceilings 0=absent 1=present
F2-2	Damage Tiles Chimneys	Integer (0,1)	Damage to the non structural components: falling of tiles, chimneys Score as F2-1
F2-3	Damage Eaves	Integer (0,1)	Damage to the non structural components: falling of eaves, parapets Score as F2-1
F2-4	Damage Objects	Integer (0,1)	Damage to the non structural components: falling of internal or external objects Score as F2-1
F2-5	Damage Hydraulic	Integer (0,1)	Damage to the non structural components: damage to hydraulic or sewage systems Score as F2-1
F2-6	Damage Electric/gas	Integer (0,1)	Damage to the non structural components: damage to electrical or gas systems Score as F2-1
F13	Usability Classification	integer (1,...,6)	Usability classification 1=usable building 2= usable with countermeasures (temporarily unusable) 3=partially unusable 4=requiring more detailed investigation (temporarily unusable) 5=unusable 6=unusable for external risk

Table 6. Section 5 - 2016 Seismic Damage (AeDES form - section 4-5).

3.3. BUILDING TYPOLOGY FOR CAMERINO DEMO CASE

This section details the systematic approach used to classify and analyse building typologies in Camerino's historic centre, tailored to both heatwave and earthquake hazards. The methodology is structured into two main parts, each corresponding to a specific hazard (heatwave & earthquake), and includes dedicated steps for feature selection, data preprocessing, clustering, validation, and spatial analysis.

3.3.1. HEATWAVES' ANALYSIS

This analysis presents the analysis and results of the building typology clustering focused on heatwave vulnerability in the historic centre of Camerino. Using a mixed-type dataset, Gower-based hierarchical and KMedoids clustering methods were applied. Cluster validation and spatial mapping were performed to identify patterns of vulnerability across the urban fabric.

3.3.1.1. FEATURE SELECTION

During the data preprocessing stage, a significant number of variables from the Camerino Aedes database were excluded from the clustering analysis due to the presence of missing values. Clustering algorithms—particularly those that rely on distance or similarity calculations—require complete data for all selected features, as missing values cannot be directly accommodated in most standard implementations. Attempts to impute or estimate missing values for highly incomplete variables can introduce bias and reduce the reliability of clustering results. To maintain the validity and interpretability of the groupings, only features with sufficient data completeness were retained for the analysis, while variables with extensive gaps were omitted from the final feature set.

Full list of heatwave-related features used:

- ARCH_DB.B1 Nr storeys (Numerical) (originally titled in Aedes database: Nr storeys)
- ARCH_DB.B6 Nr storeys above ground (ordinal) (originally titled in Aedes database: Nr storeys above ground)
- ARCH_DB.B3 Average storey height (Ordinal) (originally titled in Aedes database: Average storey height [m])
- ARCH_DB.B5 Construction/renovation period (Ordinal) (originally titled in Aedes database: Construction/renovation period)
- temp_mean (Numerical) (LST dataset)
- HubDist_Parks (Numerical)

Feature Selection and Correlation Analysis

To assess the suitability and independence of the candidate features for the heatwave clustering analysis, we performed a correlation analysis using Pearson's correlation coefficient. The correlation matrix (Figure 8) illustrates the pairwise relationships among the initial set of features. The following heatmap presents the correlation matrix for all candidate features considered for heatwave-related clustering in the Camerino building dataset:

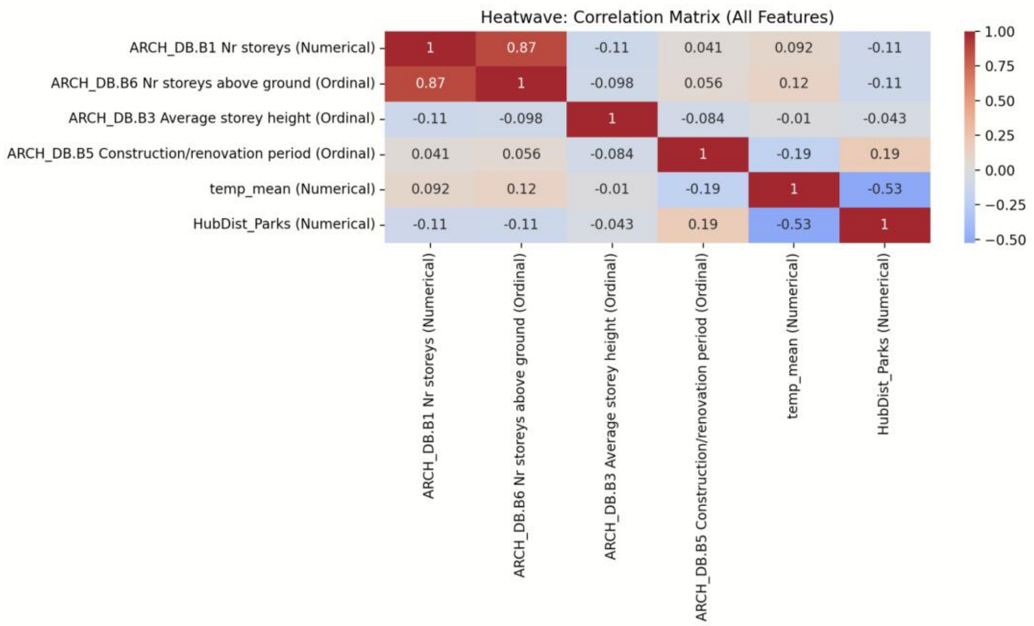

Figure 8. Heatwave - Correlation Matrix (All Features).

The selection of the three final features—mean temperature (temp_mean) and construction/renovation period (ARCH_DB.B5 Construction/renovation period)—was made based on the following considerations:

- **High Correlation:** ARCH_DB.B1 Nr storeys' and 'ARCH_DB.B6 Nr storeys above ground' were highly correlated (r = 0.87). To avoid redundancy and multicollinearity, only 'Nr storeys' was retained.
- **Limited Relevance:** 'ARCH_DB.B3 Average storey height' was found to be largely explained by the number of storeys and contributed limited unique information to the hazard, thus it was excluded.
- **Contextual Bias and Lack of Physical Meaning:** 'HubDist_Parks' demonstrated a negative correlation with mean temperature (r = -0.53), which is counterintuitive—one would expect proximity to parks to moderate temperatures, not increase them. However, in the specific case of Camerino, this relationship is likely an artifact: the town is surrounded by cropped fields and the presence or absence of parks does not accurately reflect temperature mitigation. The spatial distribution of temperature also shows only slightly lower temperatures near parks. Given this, the variable was excluded from the final clustering.

These considerations ensured the clustering focused on features both statistically valid and physically meaningful for heatwave vulnerability in Camerino.

Surviving features after selection:

- ARCH_DB.B5 Construction/renovation period (Ordinal)
- temp_mean (Numerical)

Histogram analysis was performed to explore the distribution of key features prior to clustering. By visualizing how variables such as mean temperature and construction period are spread across the dataset, we were able to identify dominant patterns (e.g., concentration of buildings in older age classes or exposure to higher temperatures), detect imbalances in the data, and confirm the suitability of these features for clustering. Figure 9 illustrates the frequency distribution of mean land surface temperatures across the Camerino dataset. Most buildings are exposed to relatively high temperatures, with the largest concentration between 43°C and 4°C. This skew towards higher values underlines the significance of thermal stress in the historic centre and confirms the importance of including this parameter in the heatwave clustering analysis.

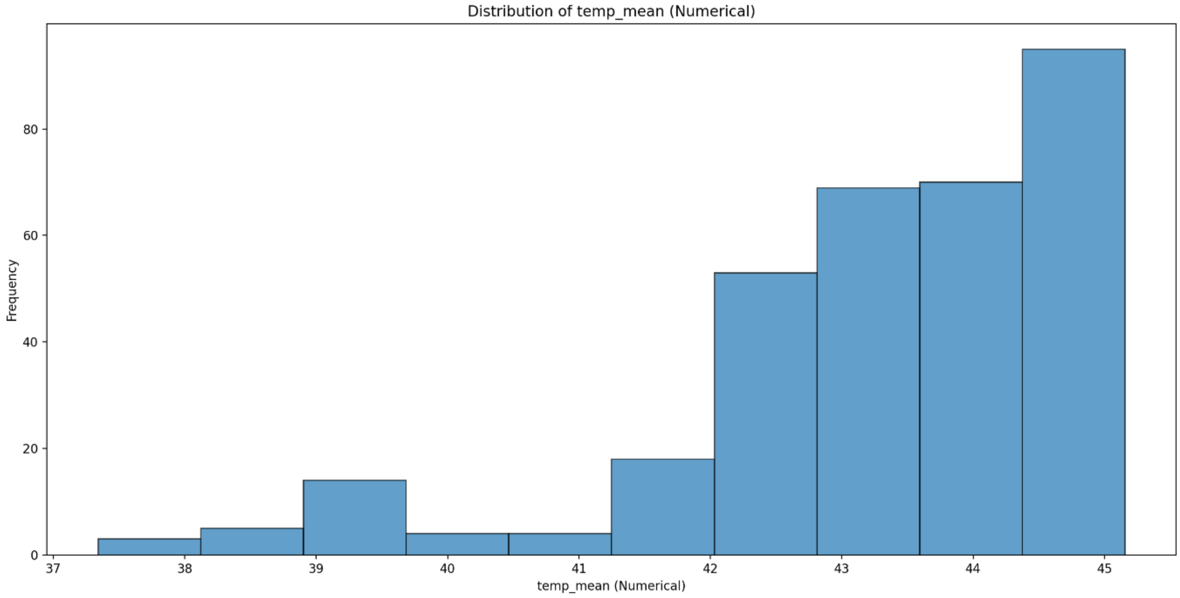

Figure 9. Frequency distribution of temp_mean.

Figure 10 shows the distribution of building construction/renovation periods. The majority of the stock falls within the earliest category (pre-1919), reflecting the historical character of Camerino's urban fabric. More recent construction periods are represented in much smaller proportions. This dominance of older buildings indicates a high relevance of age-related vulnerability, justifying the inclusion of this variable in the clustering procedure.

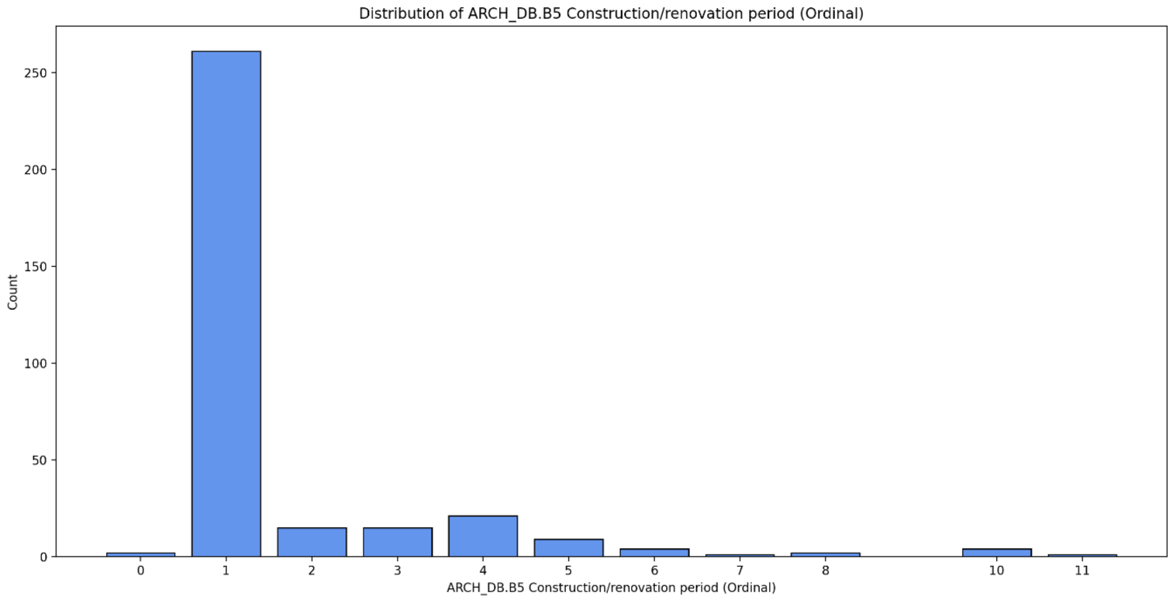

Figure 10. Frequency distribution of construction/renovation period.

3.3.1.2. PREPROCESSING & SPATIAL PATTERNS

All features were normalised using MinMax scaling to [0,1]. The spatial distribution of each feature was mapped to explore geographic patterns. Figure 11 shows the geographic spread of building ages in Camerino's historic centre. Older structures (darker tones) dominate the central fabric, reflecting the town's historic heritage, whereas more recent constructions (lighter tones) appear mainly at the edges or in reconstructed areas. This visualisation is critical to confirm how historical layering influences vulnerability, since older buildings are generally more exposed to both seismic and heatwave risks.

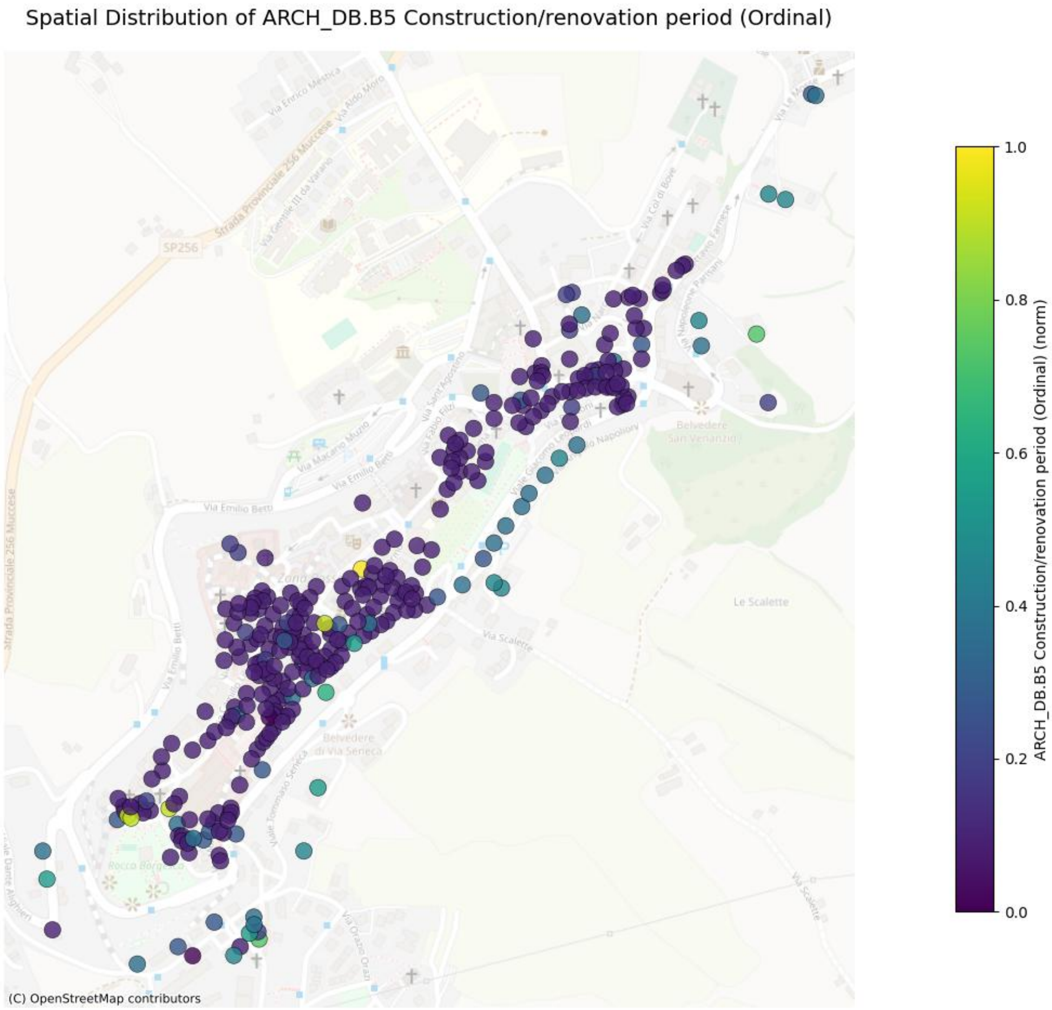

Figure 11. Spatial Distribution of ARCH_DB.B5 construction/ renovation period (Normalised).

The distribution of distances highlights how building proximity to parks varies across the city, as depicted in the application Figure 12¤. Peripheral neighbourhoods, especially in the southern and western zones, are closer to green areas (lighter tones), while the dense historic core shows greater distances (darker tones), indicating limited natural cooling capacity. This step was important because green spaces are a key moderating factor in heatwave exposure, and the map allowed us to visually test whether this variable provided meaningful differentiation across the study area. It also helped identify contextual biases (e.g., the limited role of parks in Camerino compared to open agricultural land), which guided the final decision to exclude this feature from clustering.

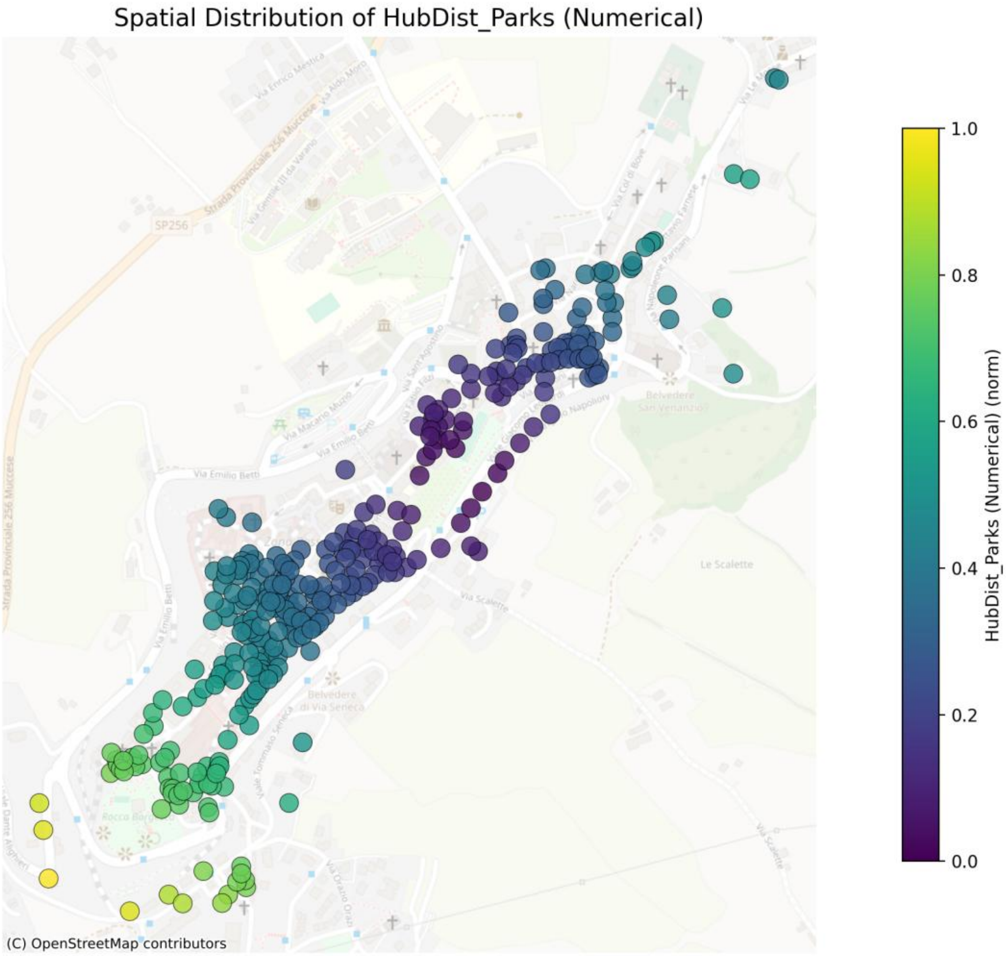

Figure 12. Spatial Distribution of HubDist_Parks (Normalized).

Figure 13 reflects spatial variations in land surface temperature derived from LST satellite data. Hotspots (yellow) are concentrated in the urban core, while cooler zones (blue/green) appear at the periphery and in less densely built areas. Visualizing this parameter allowed us to identify localized urban heat island effects, aligning with expectations from urban form and confirming the physical relevance of this variable for the heatwave clustering.

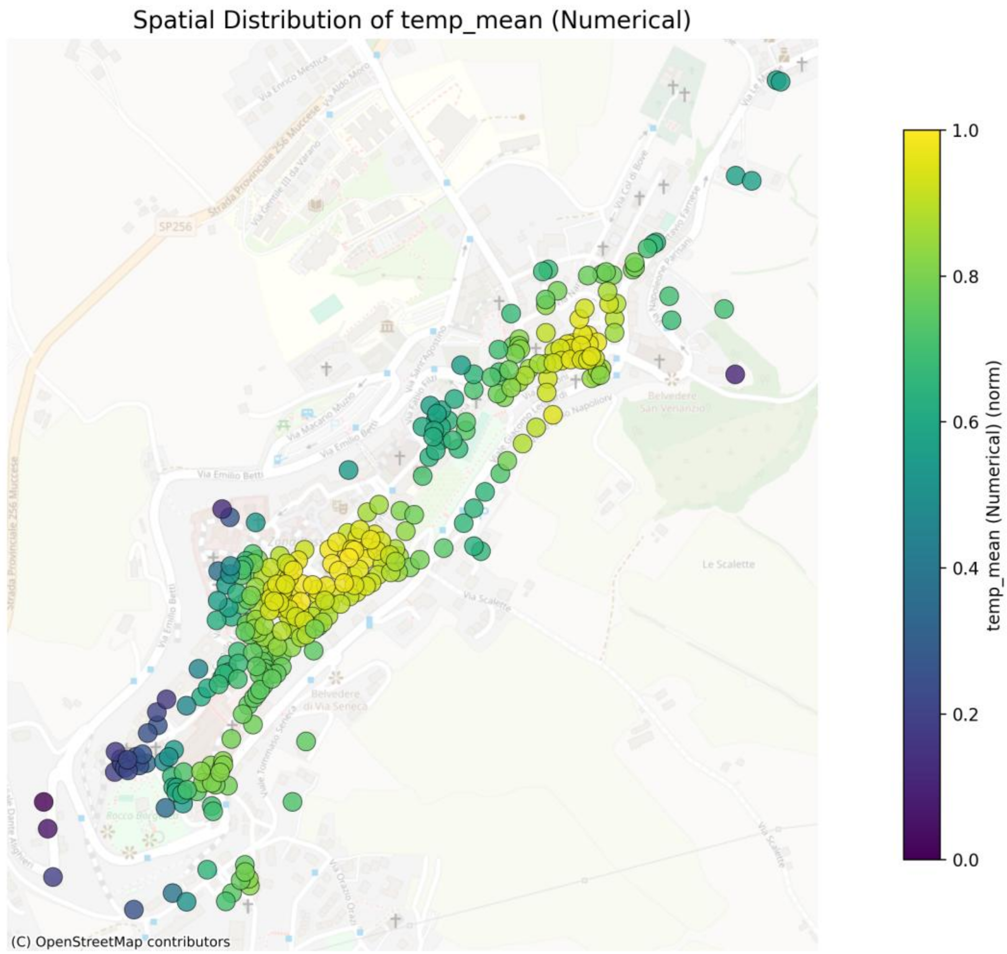

Figure 13. Spatial Distribution of temp_mean (Normalised)

The distribution of building heights indicates clusters of taller structures in parts of the central area and predominantly low-rise buildings in peripheral neighbourhoods. Although this visualisation confirmed that the dataset reflected Camerino's known urban profile, further correlation analysis revealed strong redundancy between the number of storeys and other variables (e.g., average storey height and storeys above ground). As a result, this feature was excluded from the final clustering set. Nevertheless, mapping was an important step to validate the dataset and to confirm the urban morphology patterns before narrowing down the variables.

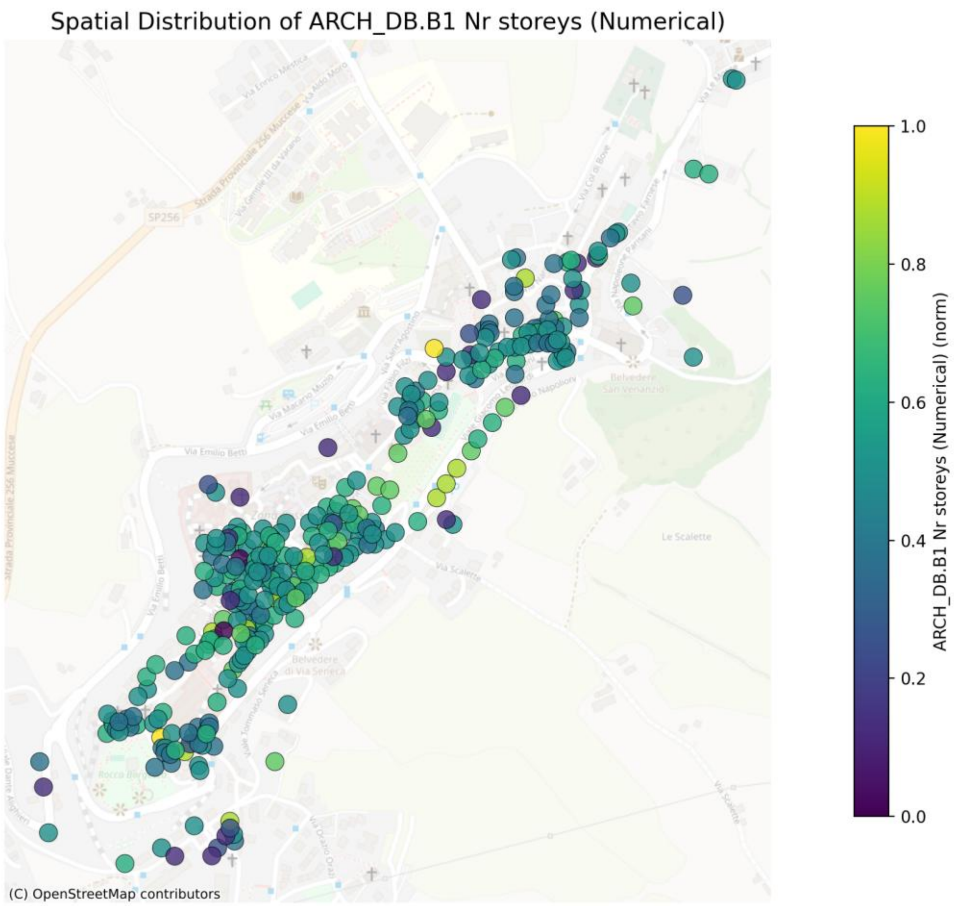

Figure 14. Spatial Distribution of ARCH_DB.B1 Nr storeys (Normalized).

Figure 15 shows that most buildings have relatively uniform average storey heights (green/blue tones), with occasional taller structures (yellow) scattered throughout. While the variation is less pronounced than in the number of storeys, mapping this parameter helped confirm its spatial consistency and provided a check against outliers. The visualisation showed that average storey height contributed little additional information beyond building height, which supported its exclusion during feature selection.

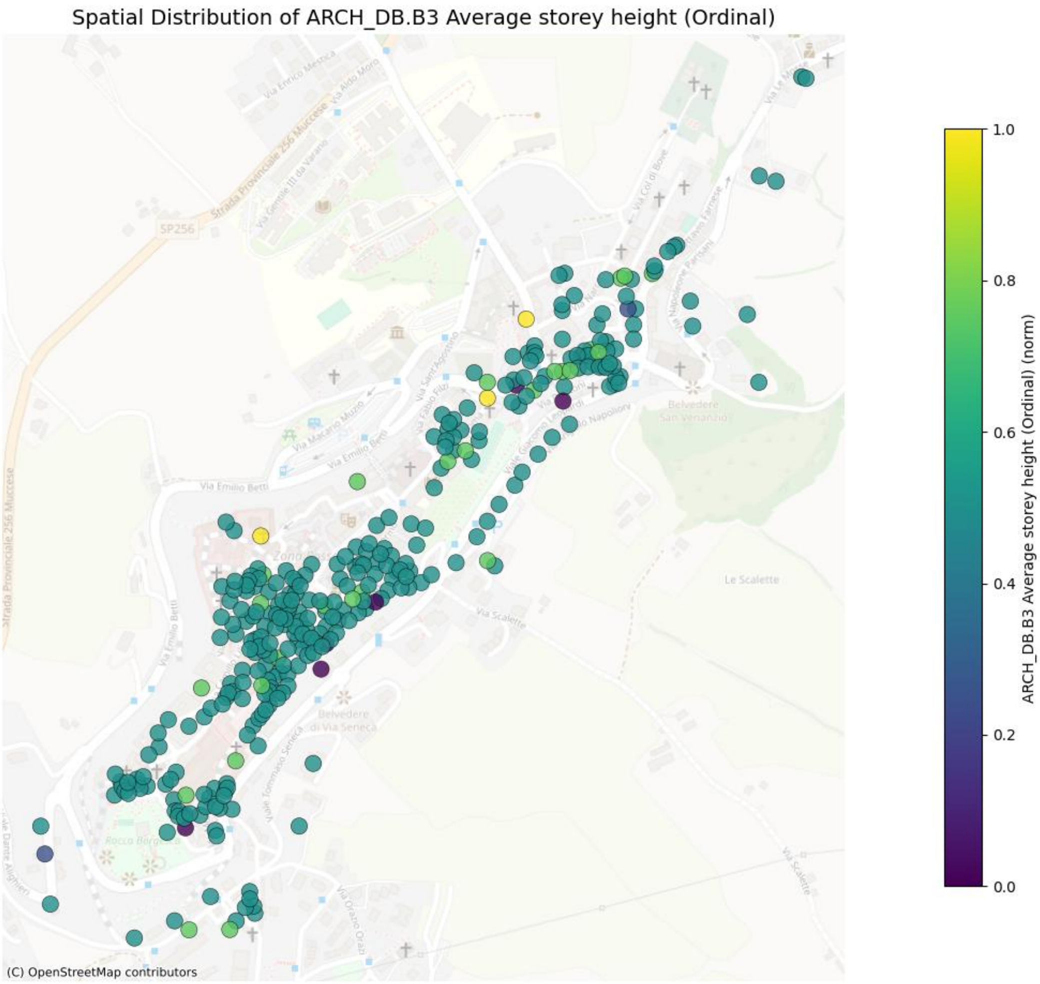

Figure 15. Spatial Distribution of ARCH_DB.B3 Average storey height (Normalised).

3.3.1.3. CLUSTERING ALGORITHMS & VALIDATION

To address the mixed-type nature of the dataset, comprising both numerical and categorical (ordinal/nominal) variables, we adopted the **Gower distance metric** for clustering. Gower distance is specifically designed for datasets containing mixed data types, as it computes pairwise dissimilarities while respecting the scaling and qualitative differences among variable types. This property made it an ideal choice for our context, where traditional Euclidean distance would be inappropriate due to the presence of categorical variables.

Clustering was performed using both **Agglomerative Hierarchical Clustering** and **K-Medoids** algorithms, both of which accept precomputed Gower distance matrices. Hierarchical clustering also allowed us to generate dendrograms for visualisation of the cluster structure and for flexible selection of cluster numbers.

To determine the optimal number of clusters (**k**) and to evaluate the clustering quality, we employed two key cluster validation indices:

- **Silhouette Score**: Measures the coherence of individual objects within clusters, taking values between -1 and 1. Higher silhouette scores indicate more distinct and well-separated clusters. We computed silhouette scores for each tested value of k to assess clustering performance.

- **Dunn Index**: Assesses clustering quality by quantifying the ratio of minimal inter-cluster distance to maximal intra-cluster distance. Higher Dunn index values signify more compact and better-separated clusters.

Dendrograms produced from hierarchical clustering provided a visual summary of the clustering structure, helping us to interpret how the data naturally group together. The dendrograms enabled us to observe the hierarchy of merges and to experiment with different cut heights, effectively allowing the comparison of different numbers of clusters (k).

In selecting the final number of clusters, we considered:

- **Consistency across methods**: We compared results from different clustering algorithms to ensure robustness of the cluster structure.
- **Maxima in silhouette score and Dunn index**: Preference was given to values of k that simultaneously maximized these indices, indicating both cohesive and well-separated clusters.
- **Visual inspection of dendrograms**: We identified "natural" cut points where large vertical gaps between merges (i.e., the "max gap" method) indicated a substantial jump in dissimilarity, suggesting a meaningful cluster separation.
- **Visual inspection of different k's spatial maps**: we visually inspected the spatial distribution of clusters for different values of k. By examining the resulting maps across a range of cluster numbers, we ensured that the selected solution not only satisfied internal metrics but also captured distinct and interpretable spatial patterns relevant to vulnerability in Camerino. This comparative map analysis helped inform our final choice of k.

By combining quantitative validation indices with qualitative insights from dendrograms, we identified the most stable and interpretable cluster solution for the heatwave hazard typology. Gower Agglomerative hierarchical and KMedoids clustering were tested for k=2 to k=10 clusters. Figure 16 compares silhouette scores across different values of *k* for Agglomerative and K-Medoids clustering using Gower distance. Agglomerative clustering consistently achieved higher silhouette values, indicating better-defined and more coherent clusters compared to K-Medoids. The scores decrease gradually as *k* increases but remain relatively high and stable between *k=4* and *k=6*, suggesting this range provides the most meaningful cluster structures.

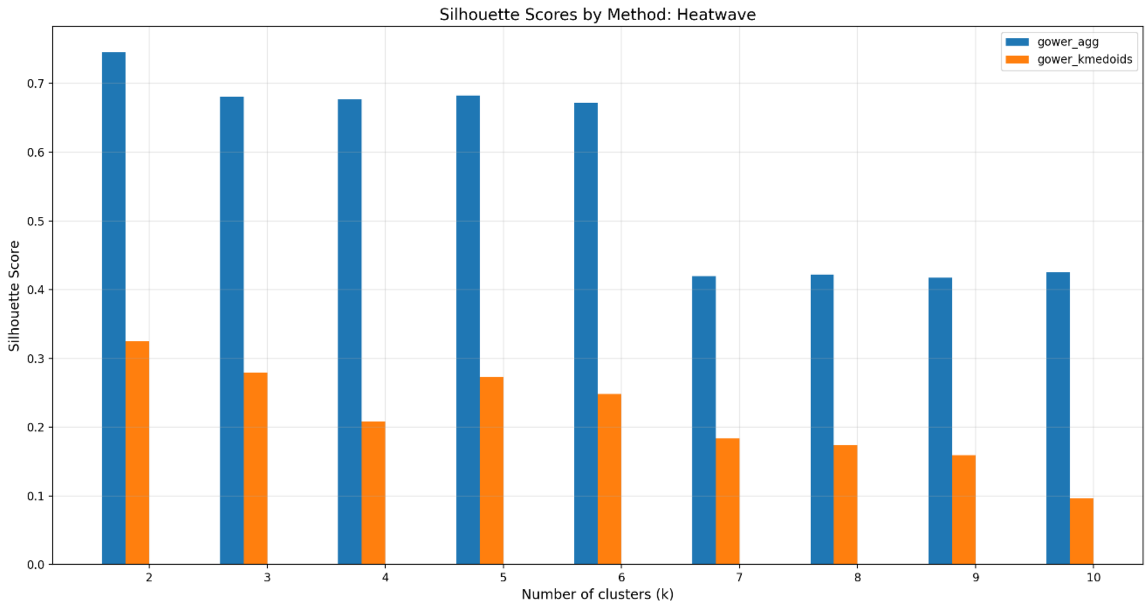

Figure 16. Silhouette Scores by Method.

The Dunn index results (Figure 17) reinforce the silhouette score findings. Agglomerative clustering produced consistently higher Dunn values than K-Medoids, highlighting more compact clusters with greater separation. The index shows local peaks at *k=2* and *k=6*, indicating that these cluster numbers provide robust and interpretable solutions.

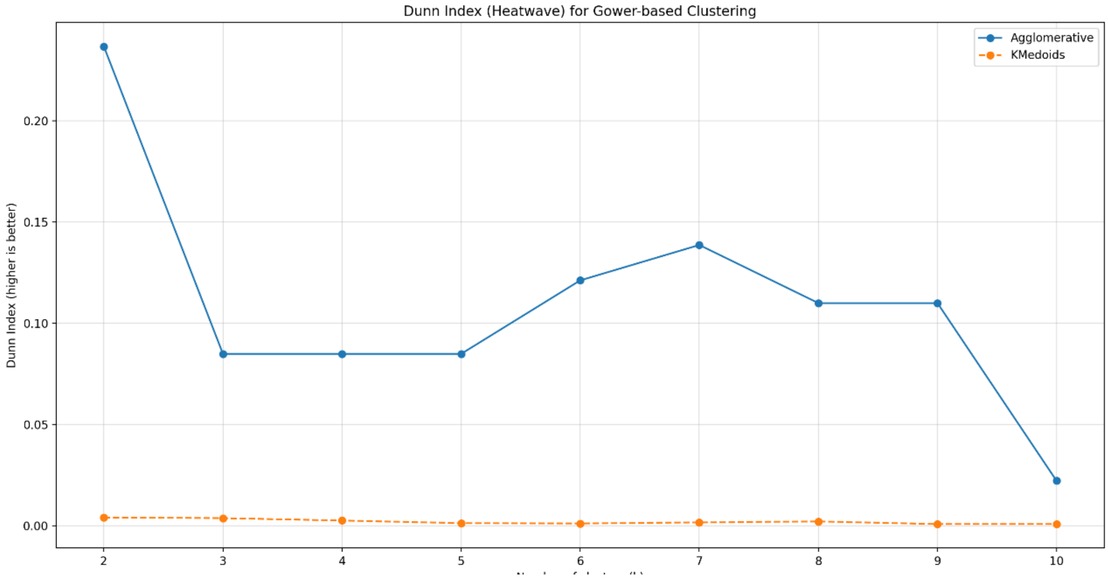

Figure 17. Dunn Index for Gower-based Clustering.

The dendrogram (Figure 18) shows the hierarchical clustering structure, illustrating how buildings merge into clusters at increasing dissimilarity levels. Red dashed lines mark alternative cuts corresponding to different numbers of clusters. Clear structural breaks are visible at *k=2*, *k=4*, and *k=6*, with *k=6* offering a balanced trade-off between detail and interpretability.

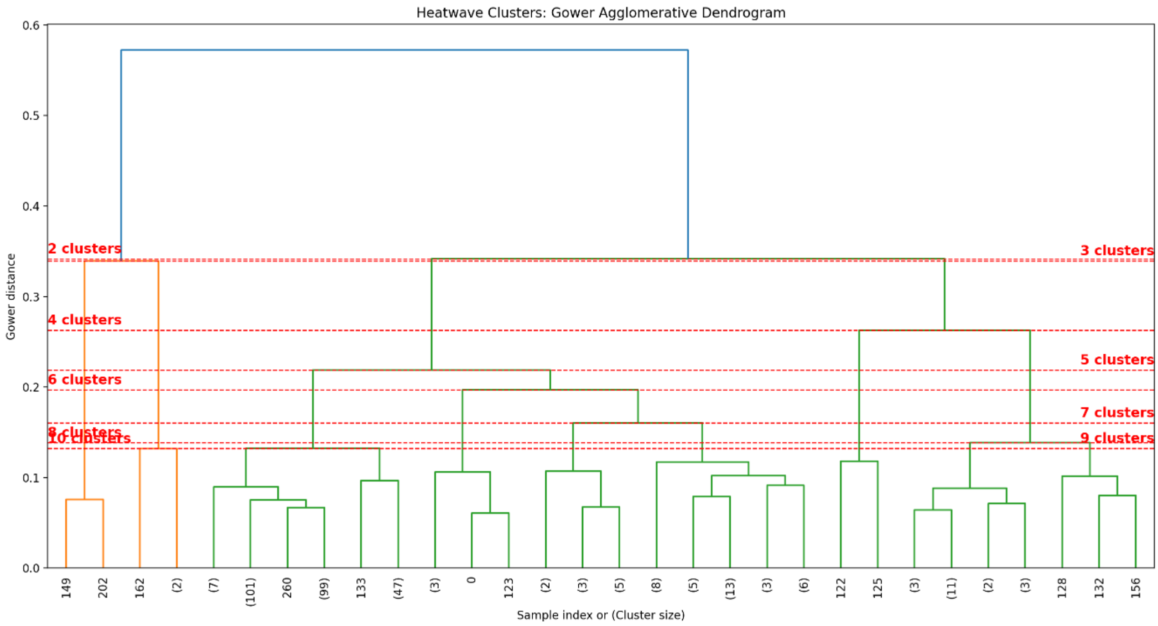

Figure 18. Gower Agglomerative Dendrogram

Figure 19 illustrates the relationship between the number of clusters (*k*) and the cut height of the dendrogram using Gower distance. Each step represents a merge in the hierarchical clustering process, with red markers indicating the cluster counts obtained at different cut levels. Distinct plateaus correspond to stable clustering solutions, suggesting that certain values of *k* (notably *k=2*, *k=4*, and *k=6*) are more meaningful than others. Among these, *k=6* provides the best compromise, capturing sufficient differentiation among building groups while avoiding over-fragmentation of the dataset. This stability aligns with the results of the silhouette score and Dunn index, reinforcing the robustness of the six-cluster solution for heatwave-related building typology analysis.

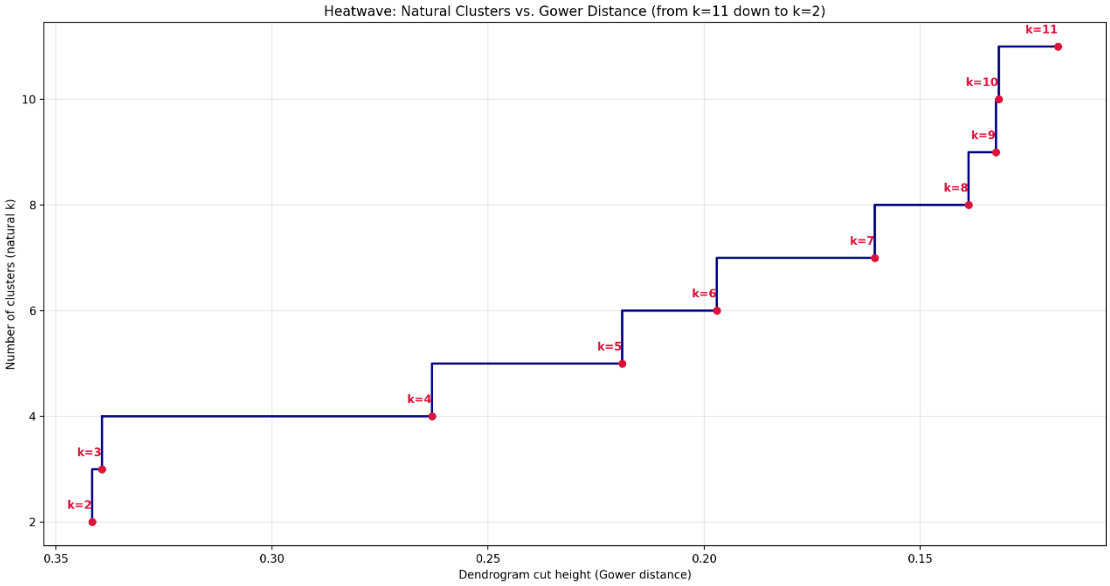

Figure 19. Clusters vs. Gower Distance.

The cluster validation results guided the selection of the optimal number of clusters. Silhouette scores indicated that Agglomerative clustering consistently outperformed K-Medoids, with relatively high values across several candidate solutions. The Dunn index further confirmed the superiority of Agglomerative clustering, with the most stable results observed at lower values of k. The dendrogram analysis revealed clear natural separations, particularly at k=2, k=4, and k=6. Among these, the solution with **k=6 clusters** was selected, as it provided the best balance between internal validation metrics and interpretability of spatial and typological patterns.

3.3.2. EARTHQUAKES' ANALYSIS

This analysis presents the methodology and results of unsupervised clustering on building data from Camerino, focusing on earthquake hazard. Clusters are matched with 31 energy and adaptation solutions using a 5-star ranking matrix. The analysis supports targeted interventions for resilience. Building features (number of storeys, construction period, usability) were clustered using Gower distance and Agglomerative/KMedoids methods. Validation via silhouette and Dunn indices, with results visualised in spatial maps and dendrograms

3.3.2.1. FEATURE SELECTION

As reported earlier, during the data preprocessing stage, a number of variables from the Camerino Aedes database were excluded from the clustering analysis due to the absence of some values.

Full list of earthquake-related features used:

- ARCH_DB.B1 Nr storeys (Numerical) (originally titled in Aedes database: Nr storeys)
- ARCH_DB.B5 Construction/renovation period (Ordinal) (originally titled in Aedes database: Construction/renovation period)

- ARCH_DB.F3 Usability Classification (Ordinal) (originally titled in Aedes database: Usability Classification)

To ensure that the variables used for earthquake-related clustering were both independent and relevant, we conducted a correlation analysis using Pearson's correlation coefficient. The correlation matrix (Figure 20) illustrates the pairwise relationships among the key candidate features—number of storeys, construction/renovation period, and usability classification—for the Camerino building dataset.

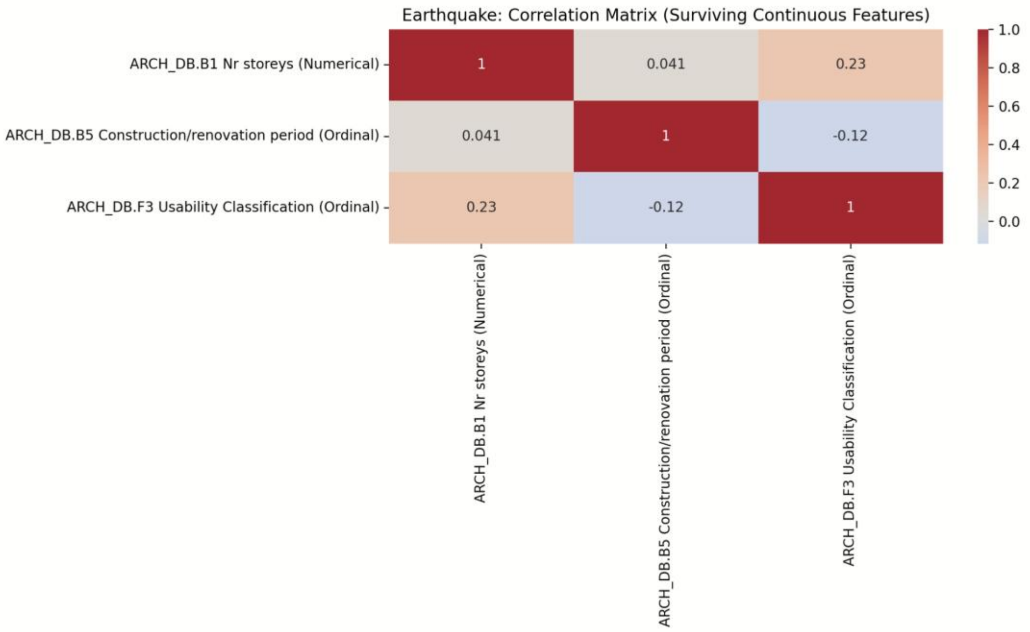

Figure 20. Correlation matrix.

As shown in the heatmap, the selected variables demonstrated low to moderate correlations (maximum $|r| \approx 0.23$), indicating a lack of strong redundancy or multicollinearity among them. This justified their concurrent use in the clustering procedure, as each feature captures a distinct aspect of building characteristics relevant for seismic vulnerability. Specifically, the following three variables were retained for clustering:

- ARCH_DB.B1 Nr storeys (Numerical)
- ARCH_DB.B5 Construction/renovation period (Ordinal)
- ARCH_DB.F3 Usability Classification (Ordinal)

Frequency distributions were again analyzed for earthquake-related features to understand their variability and dominance in the dataset and to ensure consistency with the heatwave analysis. This step also confirms the representativeness of key variables before clustering. It is important to highlight that *construction/renovation period (ARCH_DB.B5)* (Figure 10) is a common variable used in both the heatwave and earthquake clustering procedures. Its inclusion in both hazard contexts reflects its dual role: influencing thermal behavior (e.g., insulation, materials) as well as structural vulnerability to seismic loads. Figure 21 shows the frequency distribution of the number of storeys across the Camerino building stock. Most buildings have 3 to 5 storeys, with a clear peak at 4, reflecting the dominant typology in the historic center.

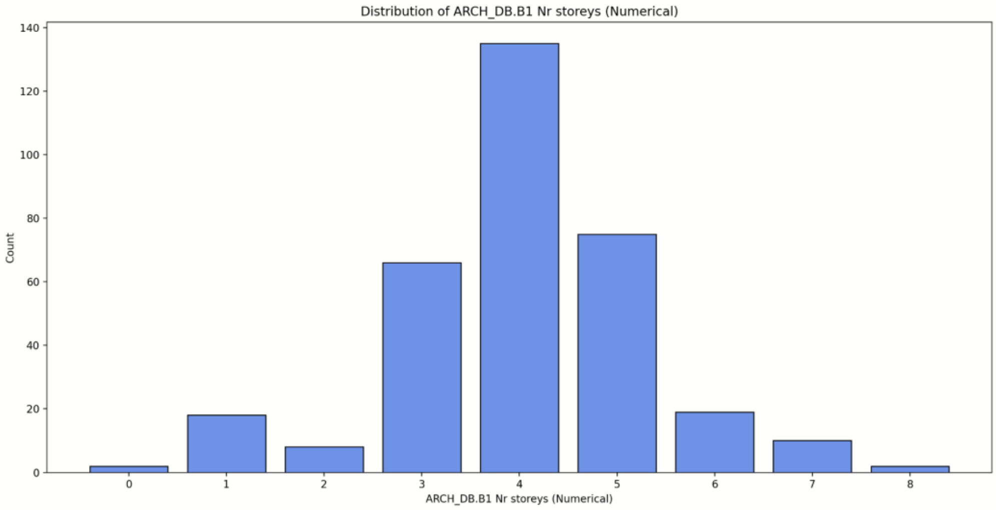

Figure 21. Frequency distribution of ARCH_DB.B1 Nr storeys (Numerical).

Figure 22 shows the distribution of buildings according to the usability classification assigned in the AeDES forms following the 2016–2017 seismic events. The categories capture whether a building is fully usable, temporarily unusable with countermeasures, partially unusable, or entirely unusable due to structural or external risks. The frequency distribution shows a clear concentration of buildings in the most severe usability class (Category 5 – unusable), reflecting the extensive structural damage sustained across Camerino's historic centre. In contrast, relatively few buildings remain fully usable (Category 1), with intermediate categories also represented to a lesser degree.

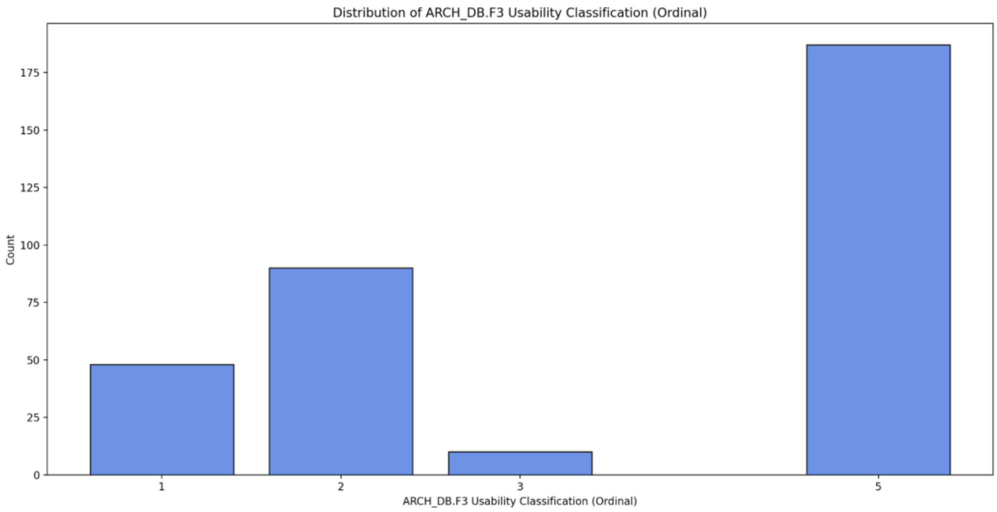

Figure 22. Frequency distribution of ARCH_DB.F3 Usability Classification (Ordinal).

3.3.2.2. PREPROCESSING & SPATIAL PATTERNS

All features were normalised using MinMax scaling to [0,1]. The spatial distribution of each feature was mapped to explore geographic patterns. It is important to note that the other earthquake-related input variables—*number of storeys* (ARCH_DB.B1) (Figure 14) and *construction/renovation period* (ARCH_DB.B5) (Figure 11)—were already illustrated and discussed in the heatwave analysis section. Therefore, they are not repeated here. As noted in 3.3.1, the number of storeys distribution showed that most buildings are three to five storeys high, a factor that increases seismic vulnerability due to higher structural loads and potential resonance effects. Similarly, the construction/renovation period was dominated by pre-1919 masonry buildings, which are particularly fragile under earthquake loading due to their age, materials, and construction practices.

Figure 23 presents the spatial distribution of the usability classification across Camerino's historic center. The visualisation highlights areas where buildings were deemed unusable or severely compromised (yellow points), which cluster heavily in the central and southern parts of the town. In contrast, darker tones indicate buildings classified as usable or only requiring countermeasures, which appear more scattered and less concentrated.

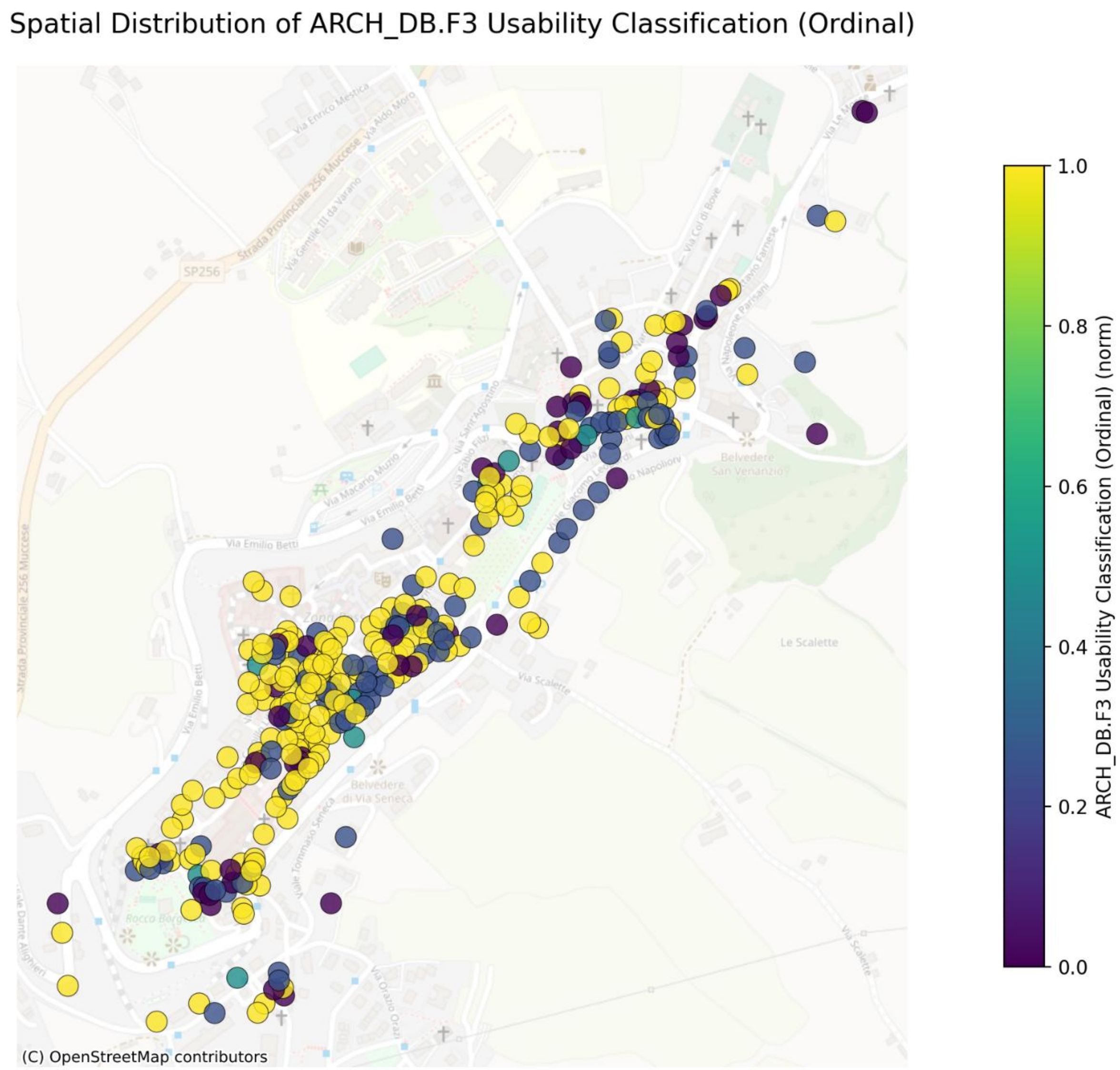

Figure 23. Spatial distribution of ARCH_DB.F3 Usability Classification (Ordinal).

3.3.2.3. CLUSTERING ALGORITHMS & VALIDATION

Similar to the heatwave analysis, the earthquake-related clustering addressed the mixed-type nature of the dataset by employing the Gower distance metric, which is well suited for handling numerical, ordinal, and nominal variables within a unified framework. Clustering was carried out using Agglomerative Hierarchical Clustering and K-Medoids, both capable of operating on precomputed

Gower distance matrices. Validation of the clustering solutions was performed using two internal indices: the Silhouette Score, which measures the coherence and separation of clusters, and the Dunn Index, which assesses compactness relative to inter-cluster distances. Dendrograms generated by the hierarchical method provided an additional visual tool for exploring the structure of the data and selecting natural cut points. As in the heatwave case, the final choice of the number of clusters (k) was informed by a combination of validation indices, consistency across methods, and visual inspection of spatial distributions, ensuring that the resulting groups were both statistically robust and meaningful in terms of seismic vulnerability patterns.

The silhouette score results (Figure 24) demonstrate that Agglomerative clustering consistently outperformed K-Medoids for the earthquake dataset. The highest silhouette value was observed at *k=2* (0.70), indicating highly compact and well-separated groups. While scores declined gradually for higher values of *k*, they remained within an acceptable range up to *k=8*. The absence of valid K-Medoids scores reflects the difficulty of applying this method when ordinal and nominal features dominate, reinforcing Agglomerative clustering as the most reliable approach in this case.

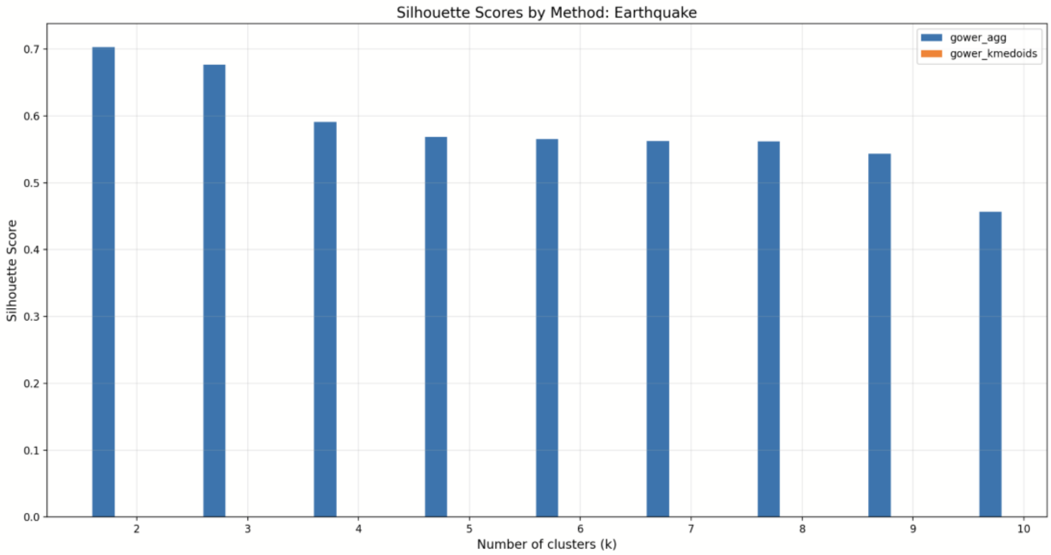

Figure 24. Silhouette scores by method.

The Dunn index analysis (Figure 25) further confirms these patterns. The metric peaked at *k=2* (0.30), highlighting the strong compactness and separation of the dataset at this level. However, as *k* increases, values decrease, reaching a relatively stable plateau between *k=5-6* (around 0.10). While the Dunn index indicates diminishing returns in terms of statistical separation beyond *k=2*, it also shows that solutions up to *k=6* maintain sufficient internal coherence to be meaningful. This trade-off between statistical optimisation and practical interpretability underpins the choice of *k=6*, ensuring both robustness and detail in identifying earthquake-related typologies.

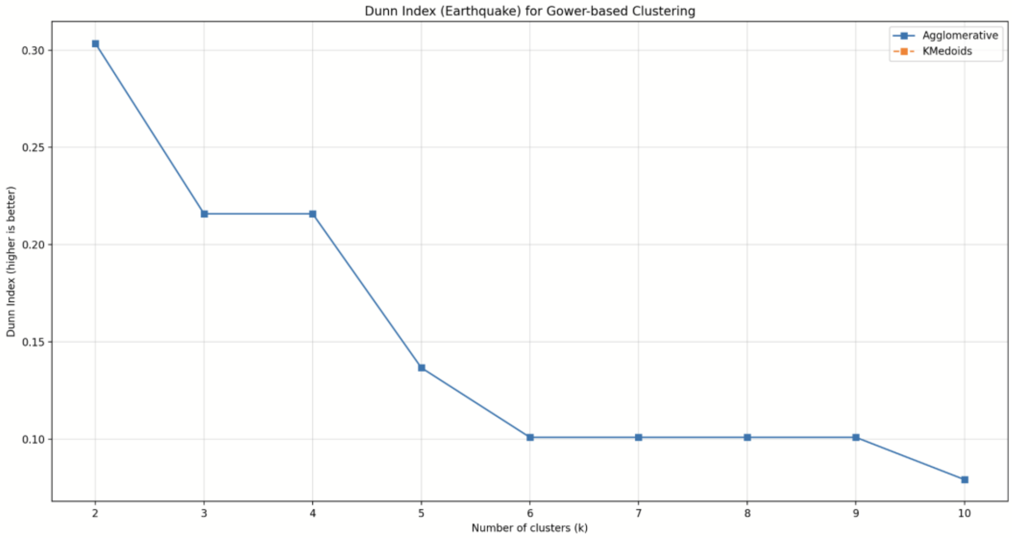

Figure 25. Dunn index by k.

The dendrogram (Figure 26) provides a visual overview of the hierarchical relationships between buildings under the earthquake feature set. Clear merging patterns can be observed at different cut levels, with distinct partitions visible at *k=2, 3, 4,* and *6*. The choice of *k=6* allows for the retention of structural diversity across Camerino's urban fabric, enabling the identification of more nuanced groupings compared to the very coarse separation at *k=2*. Importantly, the dendrogram illustrates that while lower cluster solutions offer stronger statistical validation, higher partitions reveal meaningful distinctions among building groups that align with known typological and vulnerability characteristics.

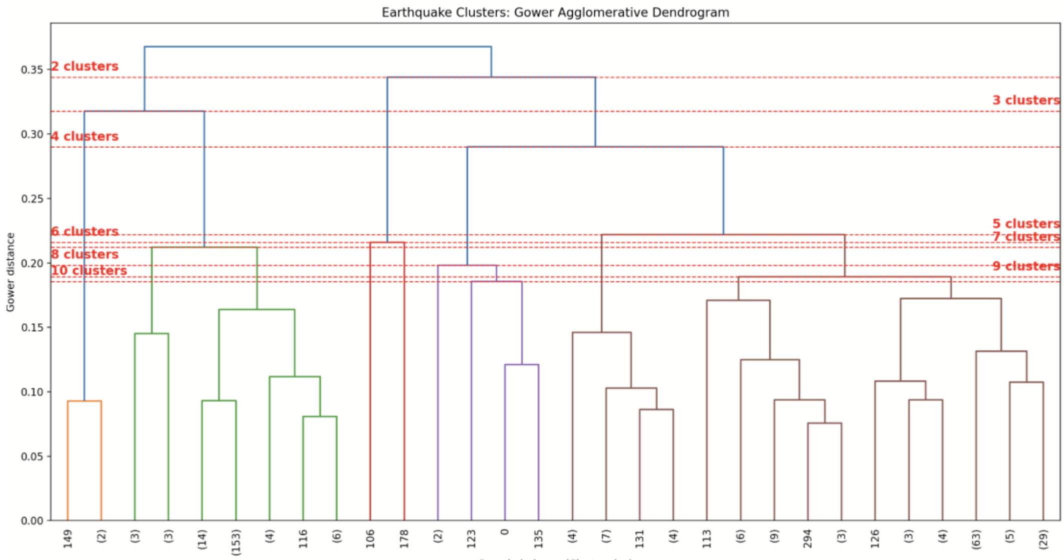

Figure 26. Annotated dendrogram (Agglomerative, Gower).

Figure 27 highlights the evolution of clusters as the cut height changes in the dendrogram. The stepwise pattern shows stable "plateaus" at *k=2-6*, each representing a potential clustering solution with reasonable interpretability. Beyond *k=6*, the breaks become progressively smaller and less meaningful, reflecting fragmentation rather than clear typological differences. The decision to adopt *k=6* provides a balance between statistical metrics and practical insight: it preserves key differences in usability, storey count, and construction period while avoiding over-simplification of Camerino’s building stock.

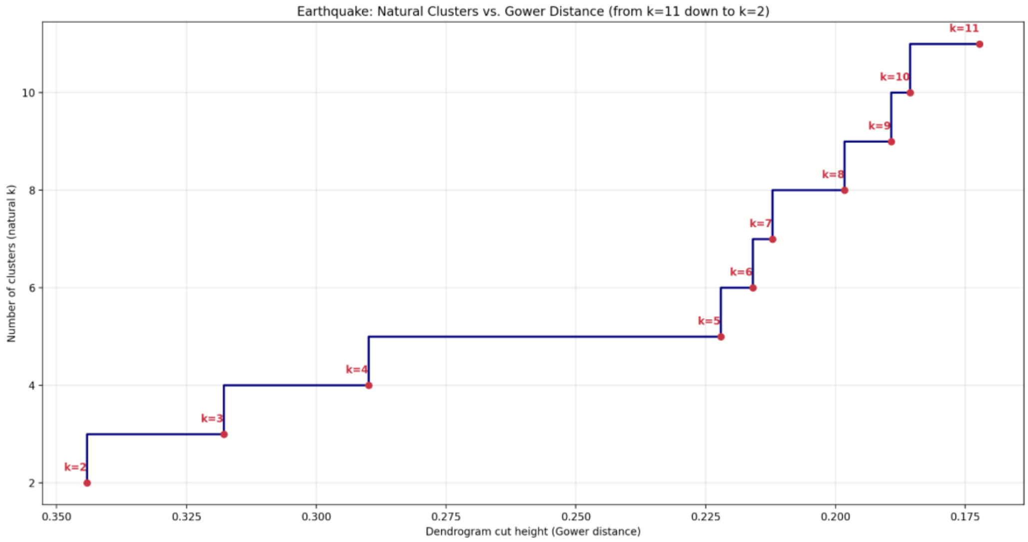

Figure 27. Natural clusters vs. Gower distance.

4. RESULTS

Chapter 4 presents the extraction of building typologies for the Camerino demo case under both heatwave and earthquake hazards. For heatwaves, six building groups were identified, characterized by differences in construction period and exposure to land-surface temperature, highlighting how building age and urban location shape vulnerability to extreme heat. For earthquakes, six clusters were also derived, but the analysis went further by examining cluster-specific distributions of structural and nominal damages. This additional step provided a deeper understanding of how different building types respond to seismic events, linking usability outcomes with observed damage patterns. Overall, the chapter establishes a comprehensive typological framework that captures hazard-specific vulnerabilities while emphasizing the structural and temporal factors that condition resilience across Camerino's historic urban fabric.

4.1. BUILDING TYPOLOGY EXTRACTION FOR HEATWAVE

The heatwave-related clustering identified six distinct building groups in Camerino, based on construction/renovation period and land surface temperature exposure. By combining typological and climatic attributes, the analysis highlights how buildings of different ages are distributed across zones of varying thermal stress. The resulting clusters distinguish very new constructions in the hottest areas, older structures concentrated in warm to hot zones, and mid-20th century or intermediate-age buildings often located in comparatively cooler parts of the city. This classification provides a structured basis for assessing heatwave vulnerability and tailoring adaptation measures to the specific characteristics of each cluster.

Table 7 presents the normalized descriptive statistics for the two key variables used in the heatwave clustering: construction/renovation period and mean temperature. Clear patterns emerge across the six clusters. Clusters 1 and 2 correspond to the newest buildings (normalized values close to 1), but they differ sharply in temperature exposure, with Cluster 1 located in the hottest zones (mean ≈ 0.94) and Cluster 2 in moderately warm areas (mean ≈ 0.31). In contrast, Clusters 3 and 6 represent the oldest buildings (normalized values close to 0.1), with Cluster 3 concentrated in the hottest parts of Camerino (mean ≈ 0.81) and Cluster 6 in moderately warm contexts (mean ≈ 0.24). Clusters 4 and 5 capture mid-20th century and intermediate-age buildings, showing more variability in construction periods (means ≈ 0.38–0.45) and spanning both hot (Cluster 4, mean ≈ 0.74) and cooler (Cluster 5, mean ≈ 0.03) urban zones. These results emphasize the combined role of age and thermal environment in shaping building cluster characteristics.

NORMALIZED	ARCH_DB.B5 CONSTRUCTION/RENOVATION PERIOD (ORDINAL)					TEMP_MEAN (NUMERICAL)				
Nr of clusters	mean	median	std	min	max	mean	median	std	min	max
1	0.955	0.955	0.064	0.909	1.000	0.939	0.939	0.043	0.909	0.970
2	0.909	0.909	0.000	0.909	0.909	0.306	0.224	0.152	0.212	0.482
3	0.093	0.091	0.017	0.000	0.182	0.814	0.826	0.129	0.456	1.000
4	0.376	0.364	0.120	0.182	0.727	0.742	0.727	0.114	0.549	0.972
5	0.455	0.455	0.129	0.364	0.545	0.027	0.027	0.039	0.000	0.055
6	0.140	0.091	0.078	0.091	0.364	0.239	0.224	0.072	0.099	0.381

Table 7. Statistical summary of normalized heatwave-related variables.

Table 8 summarizes the raw values of the construction period and mean temperature across the six heatwave clusters. The results confirm the patterns observed in the normalized table: Clusters 1 and 2 consist of very recent buildings (post-2002), but differ in exposure, with Cluster 1 in the hottest areas (≈44.7 °C) and Cluster 2 in moderately warm ones (≈39.7 °C). Cluster 3 includes the oldest buildings (pre-1919/1945) also exposed to high heat, while Cluster 4 groups mid-20th century buildings with similar thermal conditions. Cluster 5, representing 1970s–1980s constructions, appears in the coolest zones (≈37.6 °C), and Cluster 6 contains older buildings under moderate heat.

RAW	ARCH_DB.B5 CONSTRUCTION/RENOVATION PERIOD (ORDINAL)					TEMP_MEAN (NUMERICAL)				
Nr of clusters	mean	median	std	min	max	mean	median	std	min	max
1	10.500	10.500	0.707	10.000	11.000	44.680	44.680	0.336	44.443	44.918
2	10.000	10.000	0.000	10.000	10.000	39.732	39.090	1.191	39.000	41.106
3	1.020	1.000	0.187	0.000	2.000	43.704	43.795	1.011	40.901	45.154
4	4.140	4.000	1.325	2.000	8.000	43.138	43.017	0.891	41.627	44.932
5	5.000	5.000	1.414	4.000	6.000	37.552	37.552	0.301	37.339	37.765
6	1.545	1.000	0.858	1.000	4.000	39.209	39.090	0.561	38.115	40.314

Table 8. Statistical summary of raw values of heatwave-related variables.

The overall distribution of heatwave clusters in Camerino is shown (Figure 28), with six groups (k=6) identified through hierarchical clustering. Clusters vary significantly in size, from only a few buildings to several hundred, and exhibit distinct spatial patterns across the historic center and surrounding areas. Cluster 1 (Figure 29) includes only two buildings, both situated in the historic core. These are very new buildings (post-2002) located in zones with the highest mean temperatures, highlighting their exposure despite their limited number. Cluster 2 (Figure 30) contains three new buildings (post-2002), concentrated in the southern part of Camerino. These structures are exposed to moderately warm conditions compared to other clusters, forming a very small but distinct grouping. Cluster 3 (Figure 31) is the largest group, comprising 256 buildings spread throughout the urban area. It consists mainly of very old structures (pre-1919 to pre-1945), many of which are located in some of the hottest parts of Camerino, making this the most widespread and significant cluster in terms of vulnerability. Cluster 4 (Figure 32) includes 50 mid-20th century buildings (1962–1971), broadly distributed across the town. These buildings are often found in areas with elevated temperatures, underlining the role of this typology in shaping heatwave risk. Cluster 5 (Figure 33) is a very small group of only two buildings, dating from 1972–1981. Both are situated in the cooler zones of the city, making this cluster unique as it links intermediate-age construction with relatively low thermal exposure. Finally, Cluster 6 (Figure 34) comprises 22 buildings of older typologies (mostly pre-1945), located mainly in the southwestern part of Camerino. They are positioned in moderately warm areas, forming a medium-sized cluster with both historic and environmental relevance.

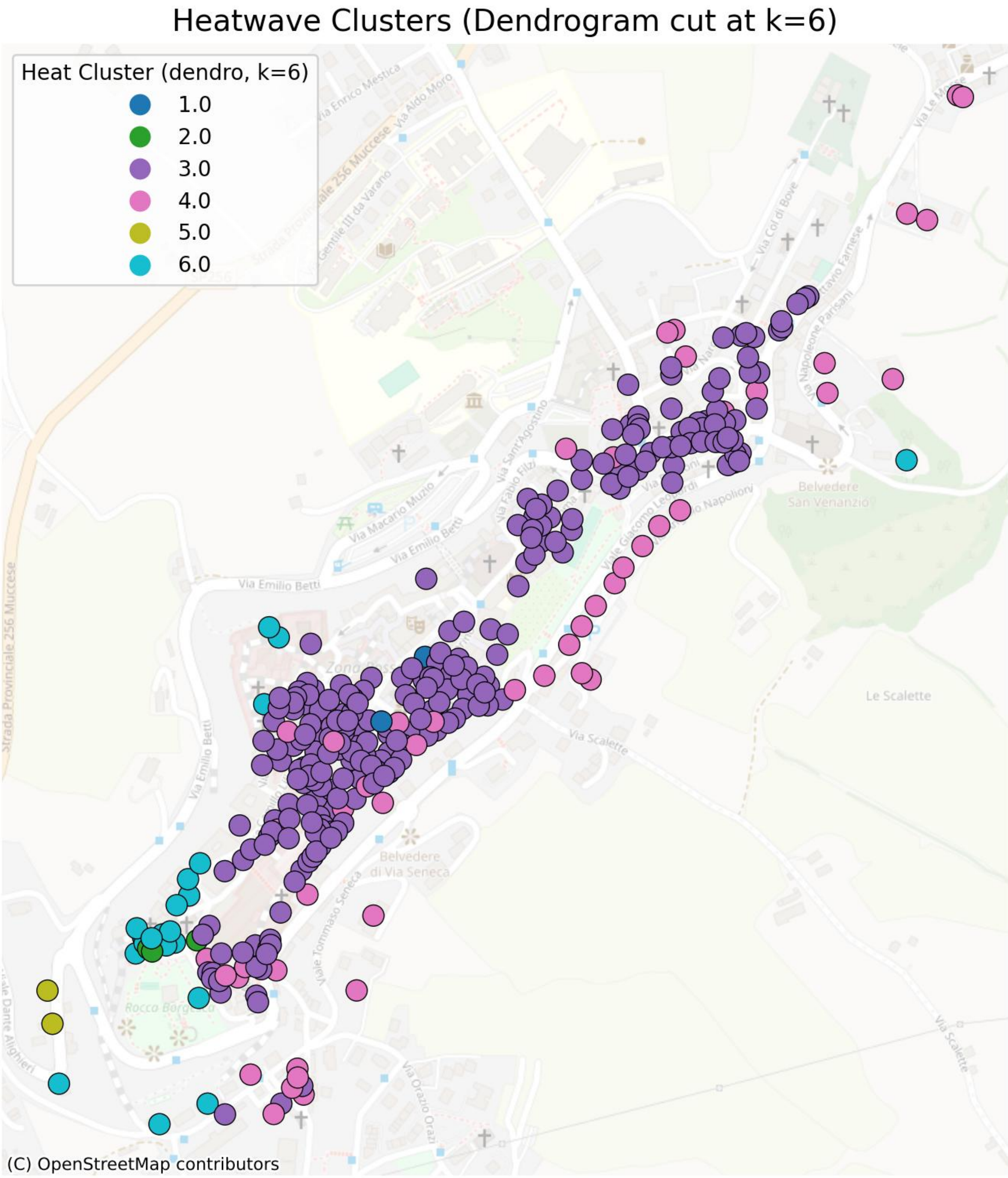

Figure 28. Spatial distribution of clusters.

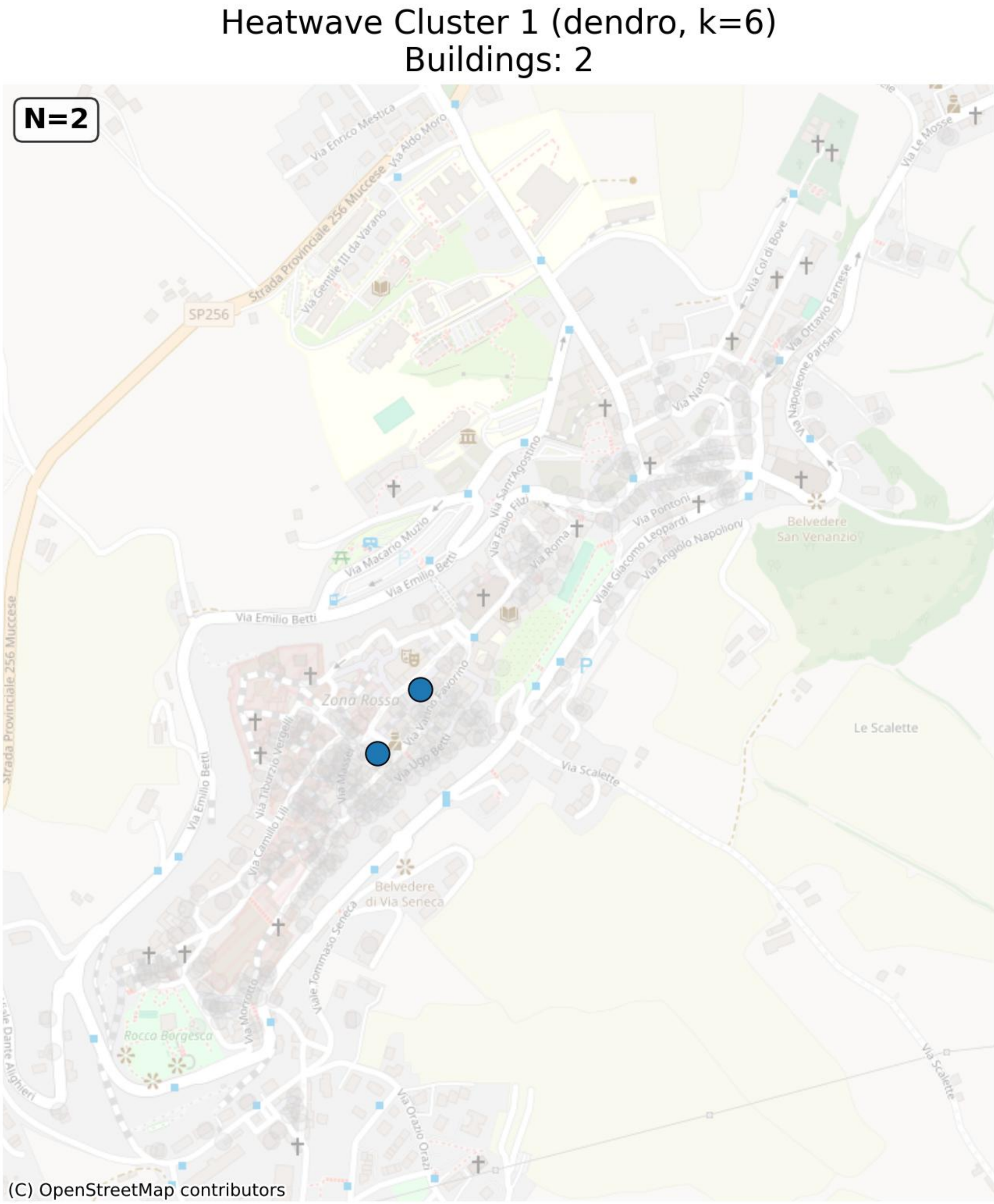

Figure 29. Spatial distribution of cluster k=1.

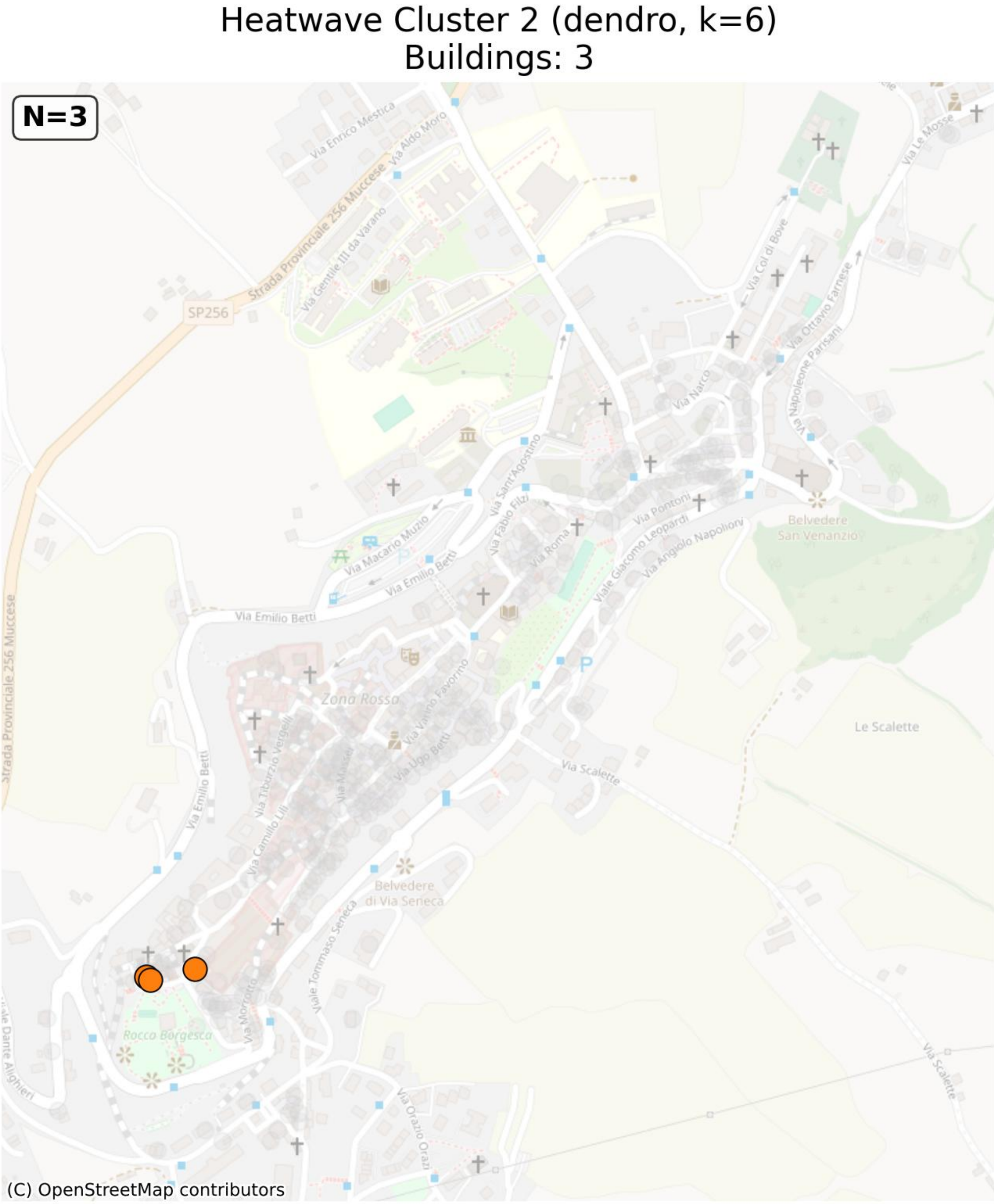

Figure 30. Spatial distribution of cluster k=2.

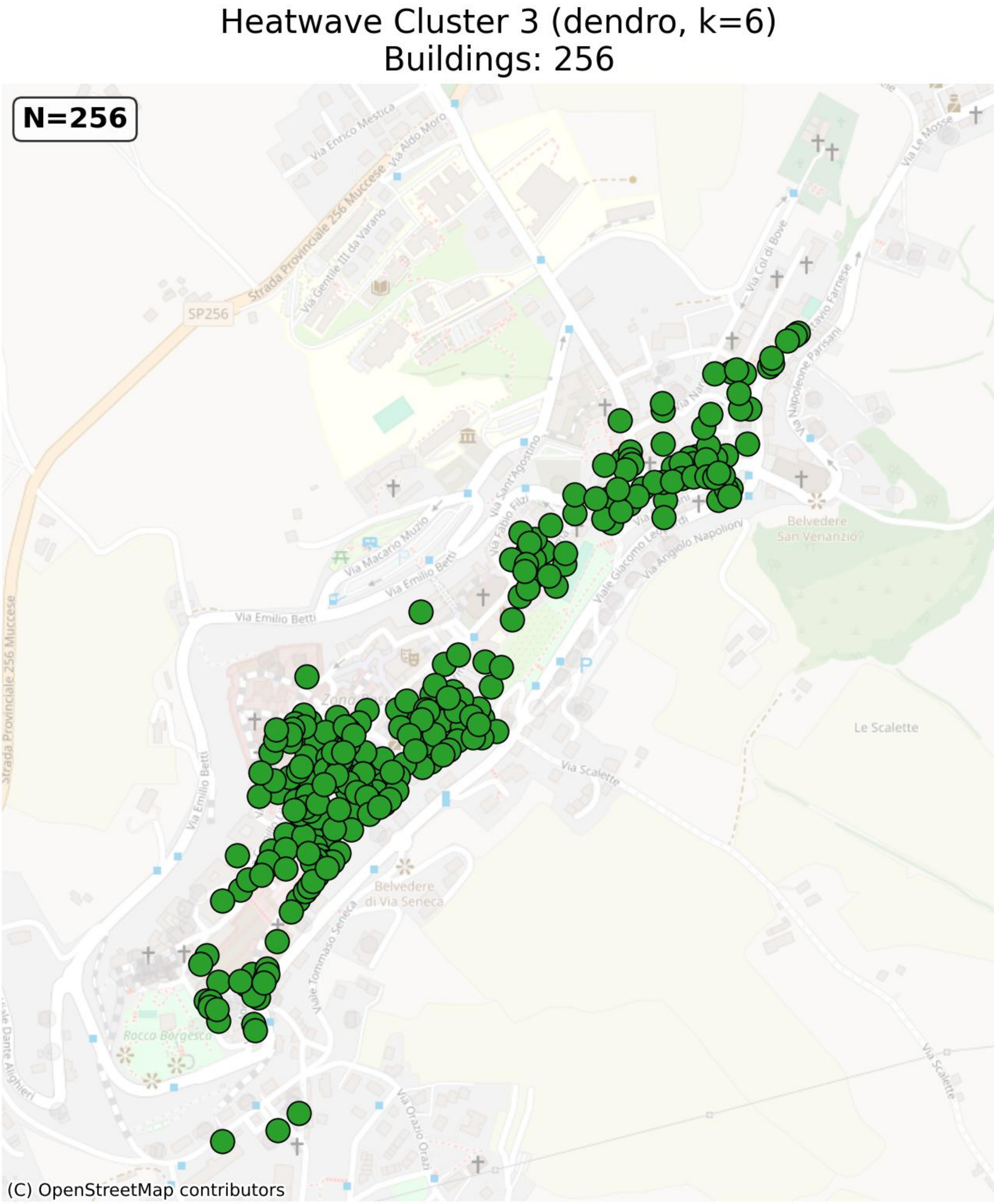

Figure 31. Spatial distribution of cluster k=3.

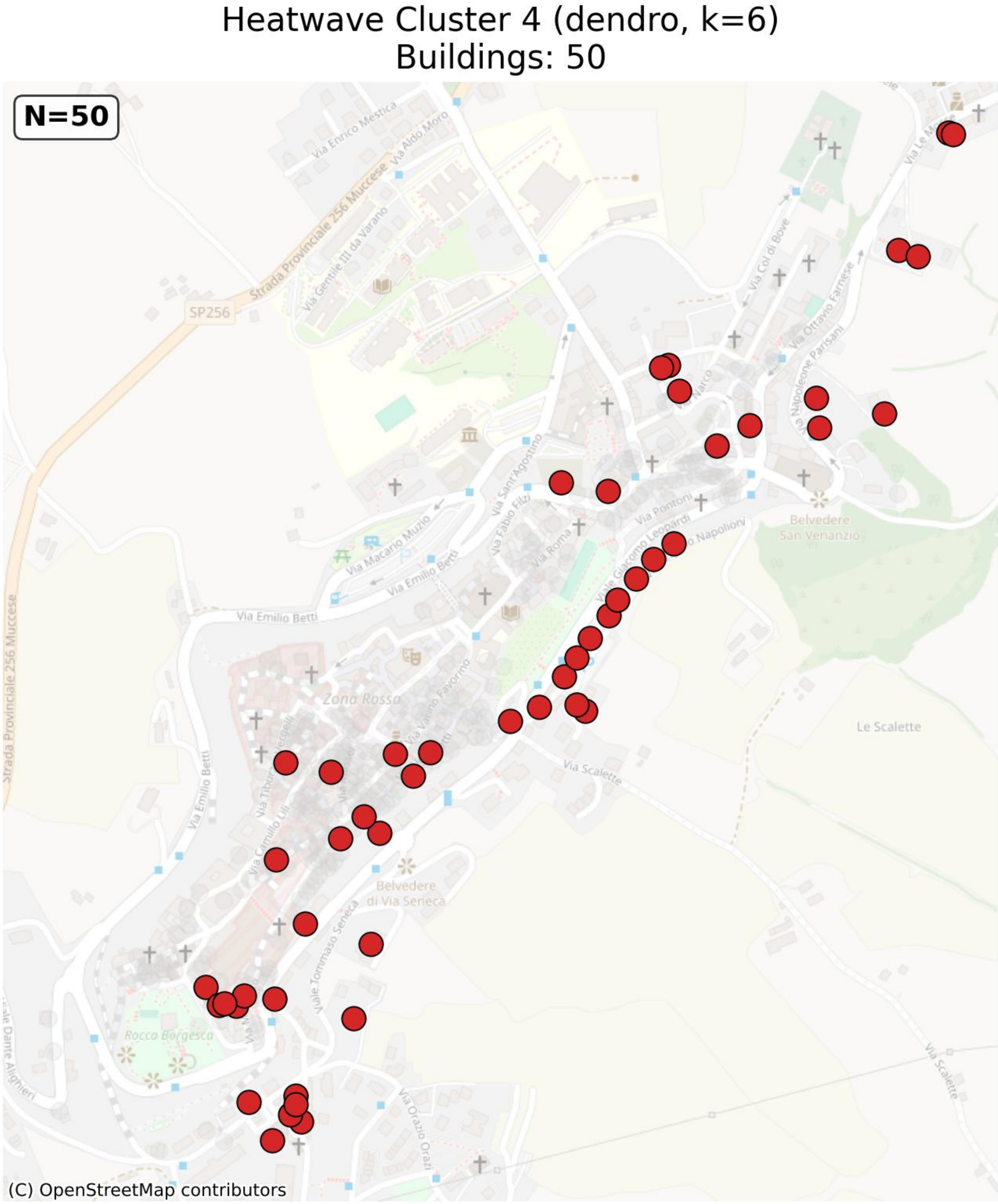

Figure 32. Spatial distribution of cluster k=4.

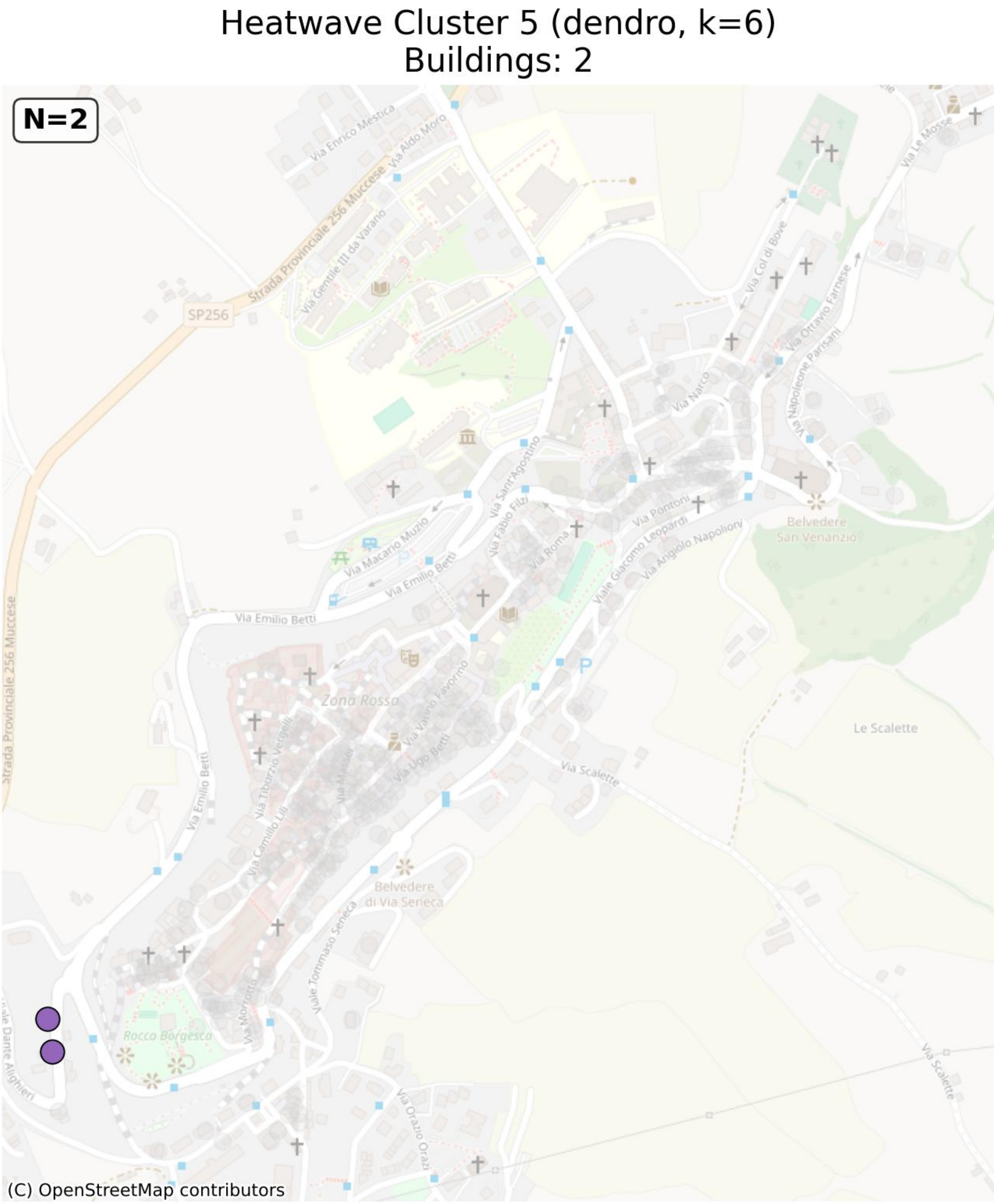

Figure 33. Spatial distribution of cluster k=5.

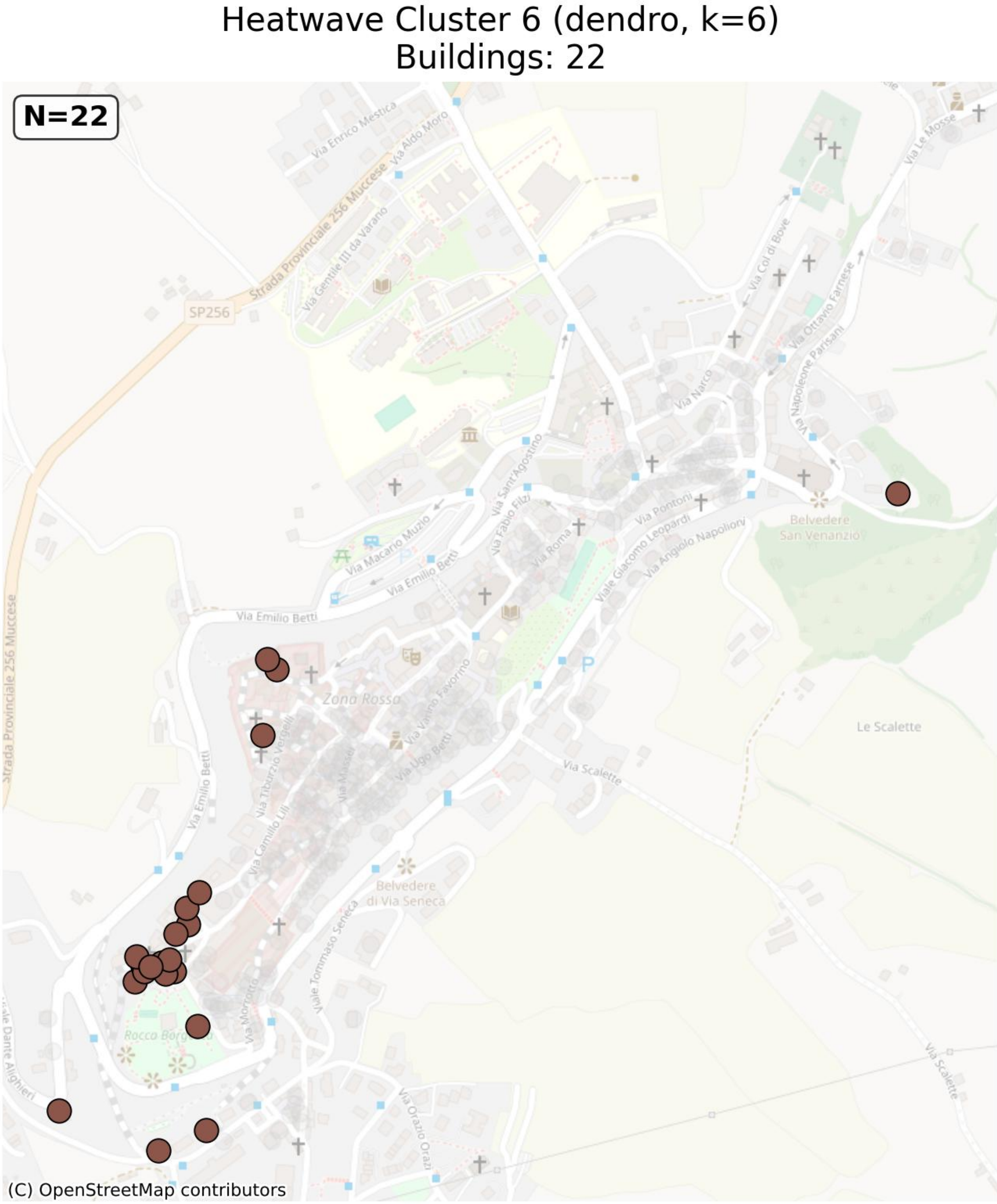

Figure 34. Spatial distribution of cluster k=6.

4.1.1. CLUSTER CHARACTERISTICS

The clustering analysis identified six distinct building groups in Camerino, each with specific typological and thermal exposure characteristics under heatwave conditions. Below, we summarise each cluster's key construction periods, average exposure to mean summer temperatures, and their relative vulnerability to heat stress.

Cluster 1 consists of very new buildings (post-2002; mean construction period index ≈10.5) located in the hottest parts of Camerino, with average peak temperatures around 44.7°C. Despite their modern construction, their placement in zones of extreme heat renders them highly exposed, underscoring the importance of cooling interventions even in newer stock.

Cluster 2 also represents new, post-2002 buildings (mean index = 10), but situated in moderately warm areas (mean ≈39.7°C). These buildings form a small group that highlights how even recent construction can have relatively low thermal exposure when positioned in cooler zones of the city.

Cluster 3 captures the oldest buildings in Camerino (mean ≈1; pre-1919 to early 1940s), many of which are concentrated in dense urban fabric. Despite their age, these structures are found in some of the hottest microclimates (mean ≈43.7°C), making them highly vulnerable given both their thermal load and potential structural fragility.

Cluster 4 comprises mid-20th-century buildings (1962-1971; mean ≈4.1), broadly distributed across the city. With average temperatures around 43.1°C, they face significant heat exposure, reflecting the widespread vulnerability of this construction period when combined with urban density and limited passive cooling features.

Cluster 5 contains a very small group of intermediate-age buildings (1972–1981; mean = 5), uniquely situated in the coolest parts of Camerino (mean ≈37.6°C). While small in size, this cluster highlights the influence of microclimatic conditions in mitigating exposure even for older typologies.

Cluster 6 represents another group of older buildings (mean ≈1.5; pre-1945), located in moderately warm areas (mean ≈39.2°C). Although not as severely exposed as Cluster 1 or 3, they still face notable risks due to their age and limited thermal resilience.

In summary, the clustering reveals clear typological and spatial trends: the most vulnerable groups are the very new and very old buildings located in Camerino's hottest zones (Clusters 1 and 3), while intermediate or moderately exposed buildings (Clusters 2, 5, and 6) benefit somewhat from location or climatic conditions. Mid-20th-century stock (Cluster 4) remains highly exposed due to both its construction period and positioning in warm microclimates. Overall, the results underline the dual influence of building age and geographic placement in determining heatwave vulnerability.

4.2. BUILDING TYPOLOGY EXTRACTION FOR EARTHQUAKE

For the earthquake hazard, the clustering analysis was extended to include both structural and non-structural building characteristics, enabling a detailed assessment of seismic vulnerability within Camerino's historic fabric. Six clusters were identified, each representing distinct typological profiles defined by variables such as number of storeys, construction/renovation period, and usability classification. Unlike the heatwave analysis, this step incorporated a broader range of information, with particular emphasis on recorded earthquake-induced damage to structural components.

Table 9 presents the statistical summary of normalised earthquake-related variables across the six identified clusters. The values, scaled between 0 and 1, allow a direct comparison of building characteristics regardless of their original measurement units. The number of storeys shows clear differentiation, with Cluster 3 representing the tallest buildings (mean ≈ 0.812) and Cluster 5 the lowest (mean ≈ 0.132). The construction/renovation period highlights the contrast between newer buildings, such as Cluster 1 (mean ≈ 0.939, corresponding to post-2002), and much older stock in Clusters 2, 5, and 6 (means around 0.12–0.17, corresponding to pre-1945). Usability classification further distinguishes clusters: while Cluster 1 buildings appear fully unusable (mean = 1.0), older single-storey buildings in Cluster 5 record much lower values (mean ≈ 0.063), indicating higher levels of retained usability.

NORMALIZED	ARCH_DB.B1 NR STOREYS (NUMERICAL)	ARCH_DB.B5 CONSTRUCTION/RENOVATION PERIOD (ORDINAL)	ARCH_DB.F3 USABILITY CLASSIFICATION (ORDINAL)

Nr of clusters	mean	median	std	min	max	mean	median	std	min	max	mean	median	std	min	max
1	0.5	0.5	0.125	0.375	0.625	0.939	0.909	0.052	0.909	1	1	1	0	1	1
2	0.529	0.5	0.148	0	1	0.122	0.090	0.085	0.090	0.545	1	1	0	1	1
3	0.812	0.812	0.265	0.625	1	0.5	0.5	0.192	0.363	0.636	0.5	0.5	0	0.5	0.5
4	0.375	0.375	0.125	0.25	0.5	0.727	0.727	0.222	0.363	0.909	0.2	0.25	0.111	0	0.25
5	0.132	0.125	0.055	0	0.25	0.170	0.090	0.147	0	0.545	0.0625	0	0.111	0	0.25
6	0.511	0.5	0.126	0.25	0.875	0.147	0.090	0.116	0	0.545	0.196	0.25	0.136	0	0.5

Table 9. Statistical summary of normalized earthquake-related variables.

Table 10 presents the statistical summary of raw values for the earthquake-related variables used in clustering. The results highlight clear typological differences between clusters. For example, Cluster 1 represents relatively new mid-rise buildings (mean 4 storeys, post-2002) with a usability classification of 5 (unusable), while Cluster 2 captures older buildings (mean ≈ 1.3; pre-1919 to pre-1945) that are also largely unusable. Cluster 3 stands out as the tallest group (mean 6.5 storeys, built around 1972–1981) with intermediate usability, whereas Cluster 5 represents very low-rise, pre-1945 buildings (mean ≈ 1 storey) with generally better usability outcomes. The raw values provide an interpretable link to real construction periods and usability classes, complementing the normalised results by showing the same typological trends in absolute terms.

RAW	ARCH_DB.B1 (NUMERICAL) NR STOREYS					ARCH_DB.B5 CONSTRUCTION/RENOVATION PERIOD (ORDINAL)					ARCH_DB.F3 USABILITY CLASSIFICATION (ORDINAL)				
Nr of clusters	mean	median	std	min	max	mean	median	std	min	max	mean	median	std	min	max
1	4.000	4.000	1.000	3.000	5.000	10.333	10.000	0.577	10.000	11.000	5.000	5.000	0.000	5.000	5.000
2	4.234	4.000	1.190	0.000	8.000	1.348	1.000	0.946	1.000	6.000	5.000	5.000	0.000	5.000	5.000
3	6.500	6.500	2.121	5.000	8.000	5.500	5.500	2.121	4.000	7.000	3.000	3.000	0.000	3.000	3.000
4	3.000	3.000	1.000	2.000	4.000	8.000	8.000	2.449	4.000	10.000	1.800	2.000	0.447	1.000	2.000
5	1.063	1.000	0.443	0.000	2.000	1.875	1.000	1.628	0.000	6.000	1.250	1.000	0.447	1.000	2.000
6	4.088	4.000	1.008	2.000	7.000	1.624	1.000	1.287	0.000	6.000	1.784	2.000	0.547	1.000	3.000

Table 10. Statistical summary of raw values of heatwave-related variables.

Figure 35 shows the overall spatial distribution of the six identified earthquake clusters across Camerino. Each cluster is represented with a distinct colour, illustrating how different building typologies and damage profiles are distributed throughout the historic center and surrounding areas. The visualization highlights concentrations of certain clusters in specific zones, reflecting localized structural vulnerabilities. Cluster 1 (Figure 36) contains only three buildings, mostly located in the southern part of the city. Despite its small size, the group is typologically distinct, capturing specific cases of post-2002 mid-rise buildings that performed poorly during seismic events. Cluster 2 (Figure 37) is by far the largest cluster, with 184 buildings concentrated across Camerino's core. It predominantly consists of very old, pre-1919 mid-rise buildings, which were among the most severely impacted in terms of both usability loss and structural/nominal damages. The widespread distribution confirms the systemic vulnerability of the historic building stock to seismic hazards. Cluster 3 (Figure

38) is a very small group of only two buildings, corresponding to the tallest structures (6–7 storeys) from the 1970s–1980s. These buildings experienced universal but low-extension structural damage, making this cluster highly distinctive but limited in scope. Cluster 4 (Figure 39) includes five low- to mid-rise post-2002 buildings, scattered across the city. Unlike Cluster 1, many of these buildings retained usability or required only minor countermeasures after the earthquake, showing improved resilience. Cluster 5 (Figure 40) comprises 16 predominantly single-storey, pre-1919 buildings that proved highly resilient to seismic impacts. Located in different parts of Camerino, these historic low-rise structures remained largely usable after the earthquake, experiencing only limited damage. Cluster 6 (Figure 41) is the second largest group, with 125 pre-1919 mid-rise buildings distributed broadly across Camerino. While moderately more robust than Cluster 2, these buildings still showed susceptibility to medium and heavy structural damages, though often at lower extensions. Their spatial spread emphasizes the prevalence of older mid-rise structures that remain partially vulnerable but not uniformly fragile.

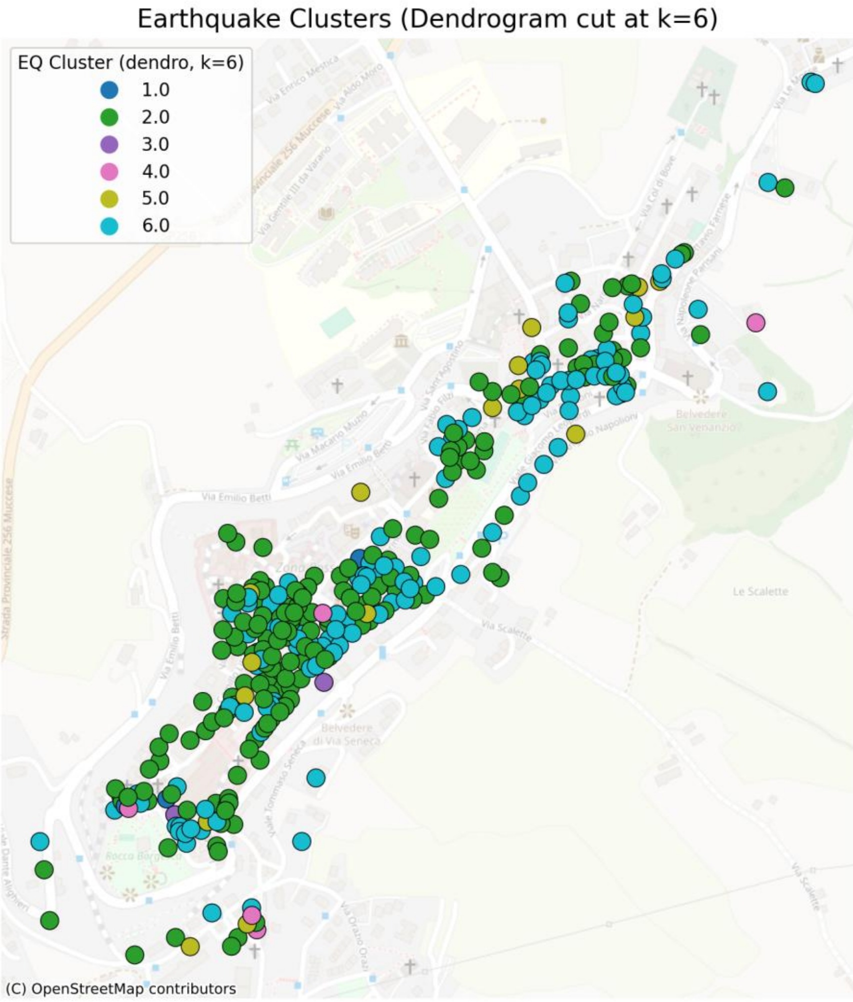

Figure 35. Spatial distribution of clusters.

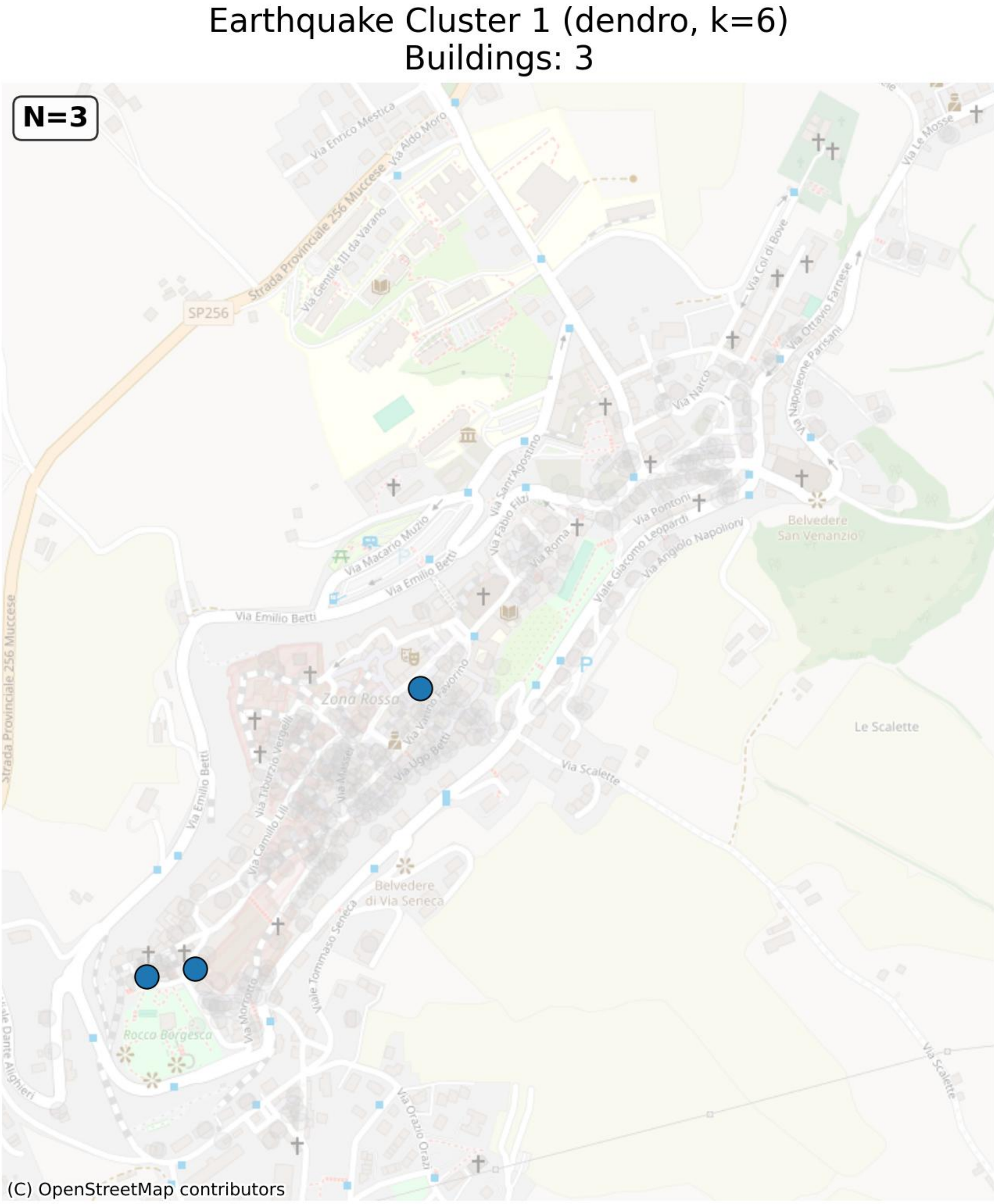

Figure 36. Spatial distribution of cluster k=1.

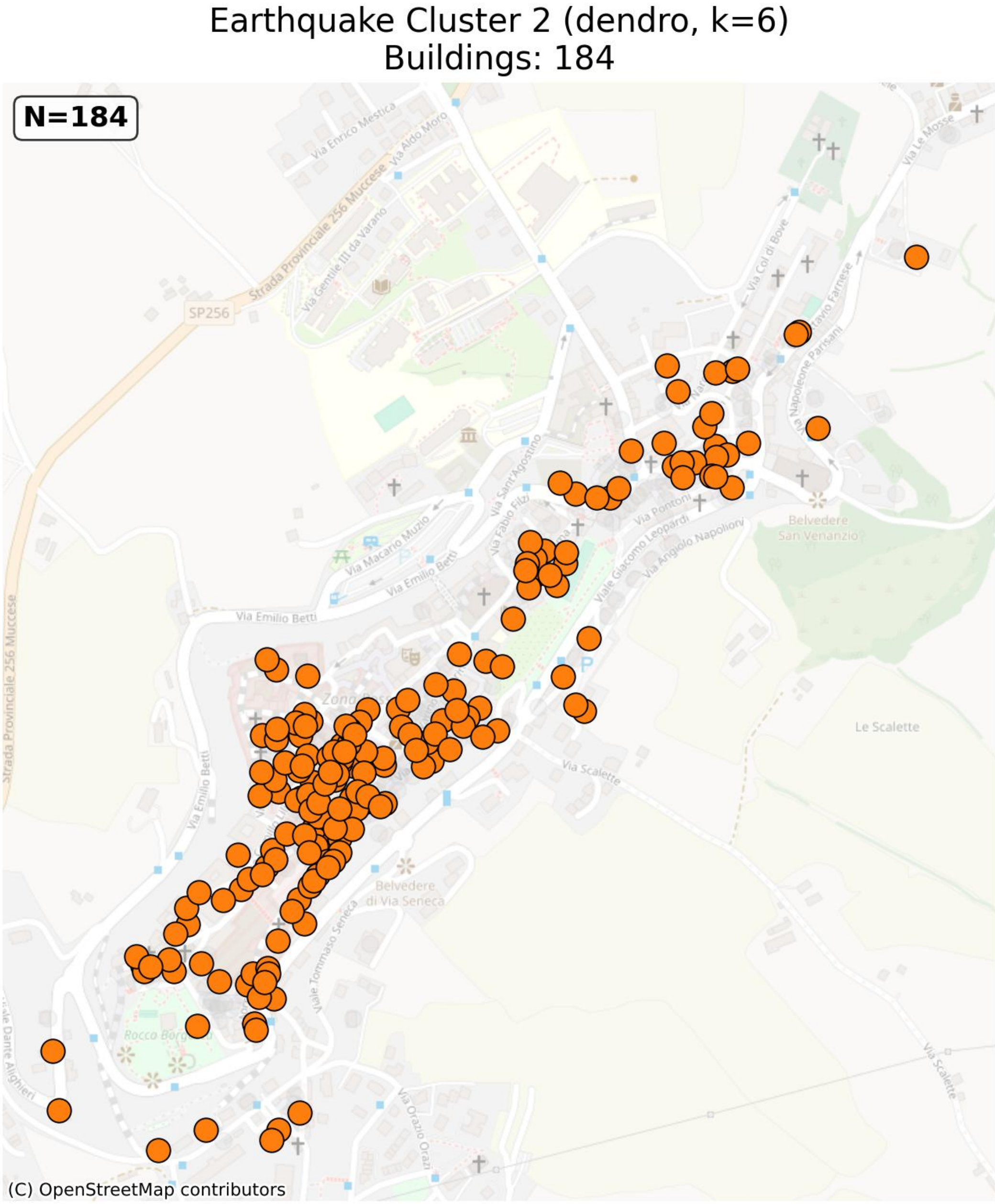

Figure 37. Spatial distribution of cluster k=2.

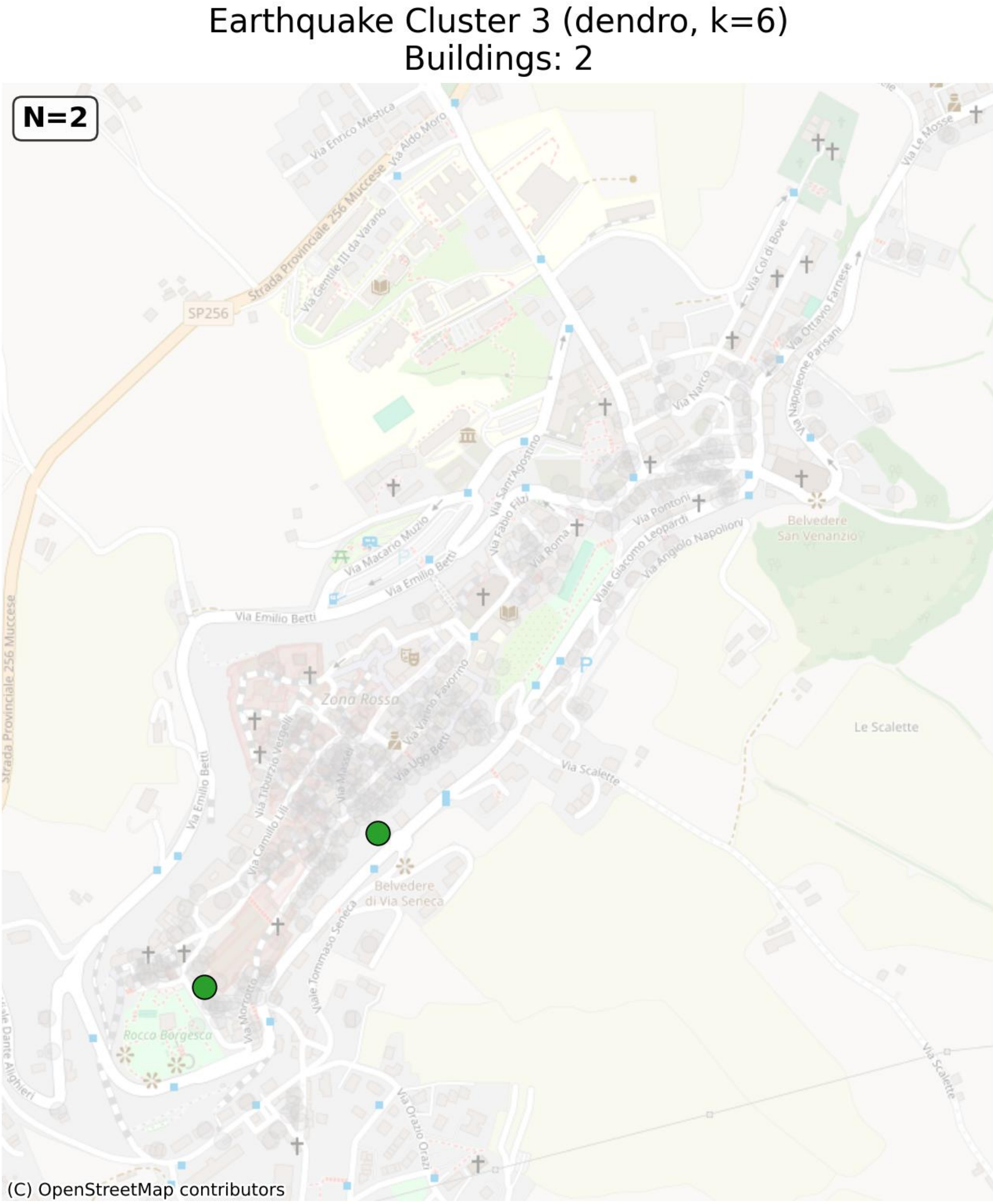

Figure 38. Spatial distribution of cluster k=3.

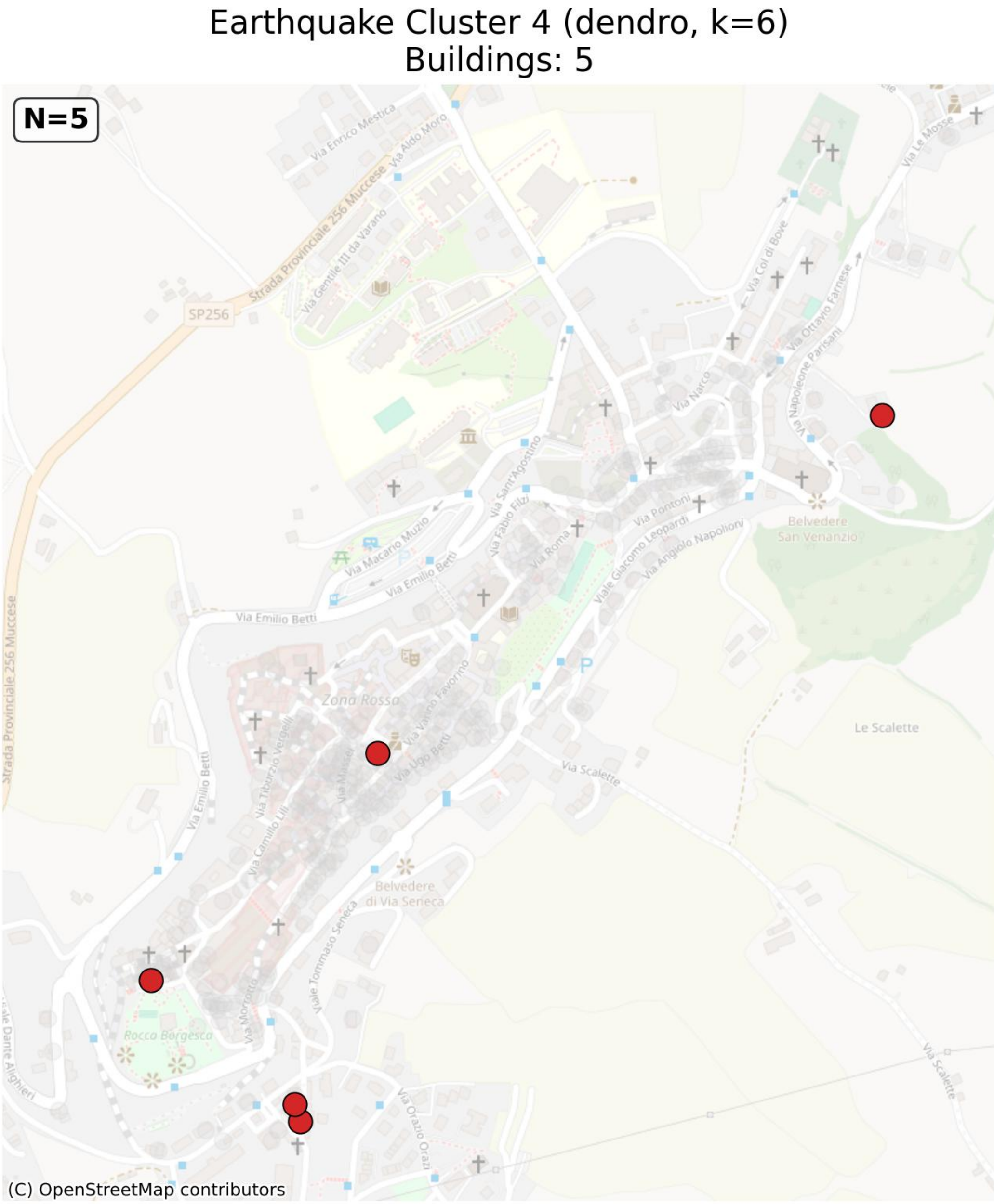

Figure 39. Spatial distribution of cluster k=4.

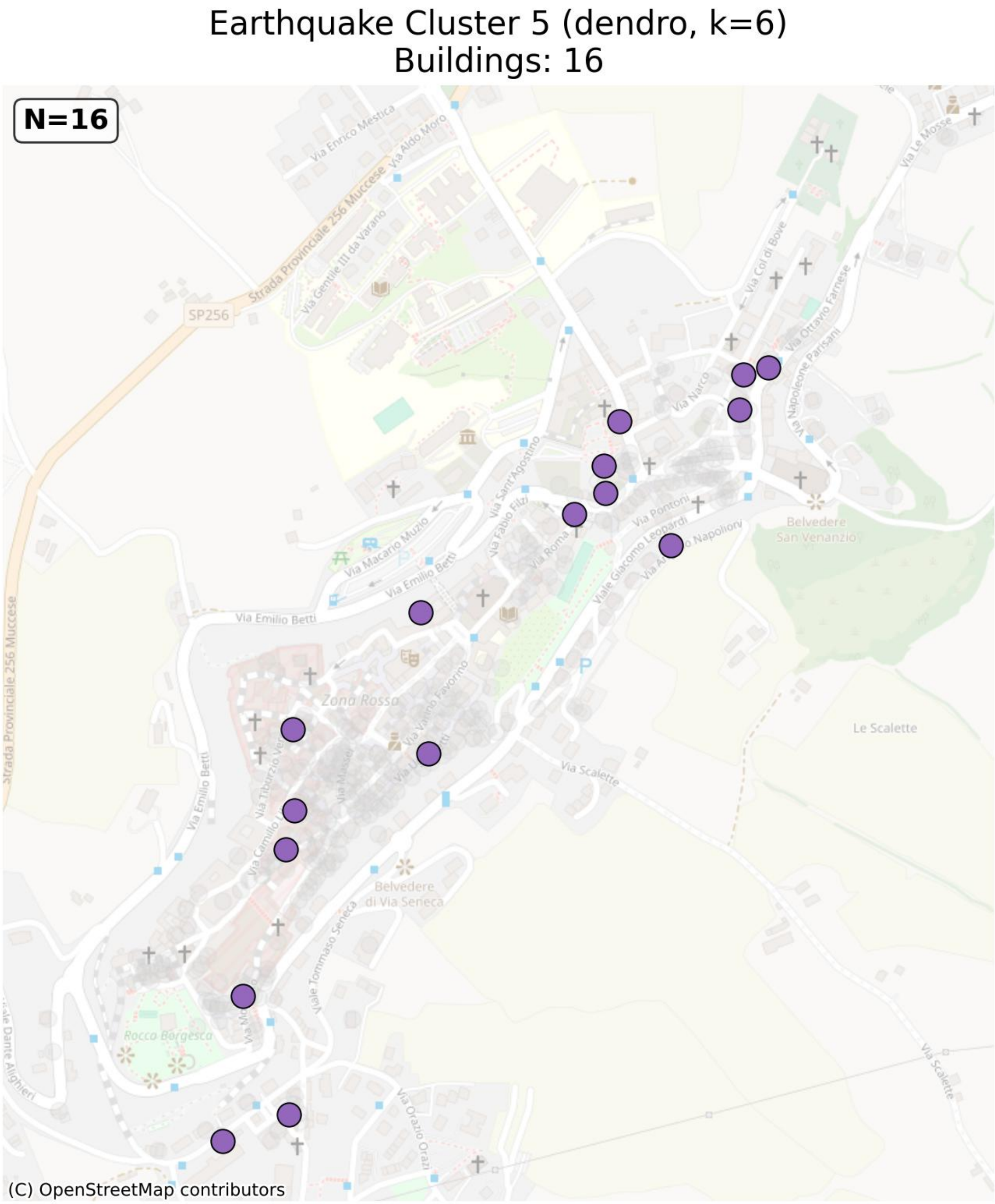

Figure 40. Spatial distribution of cluster k=5.

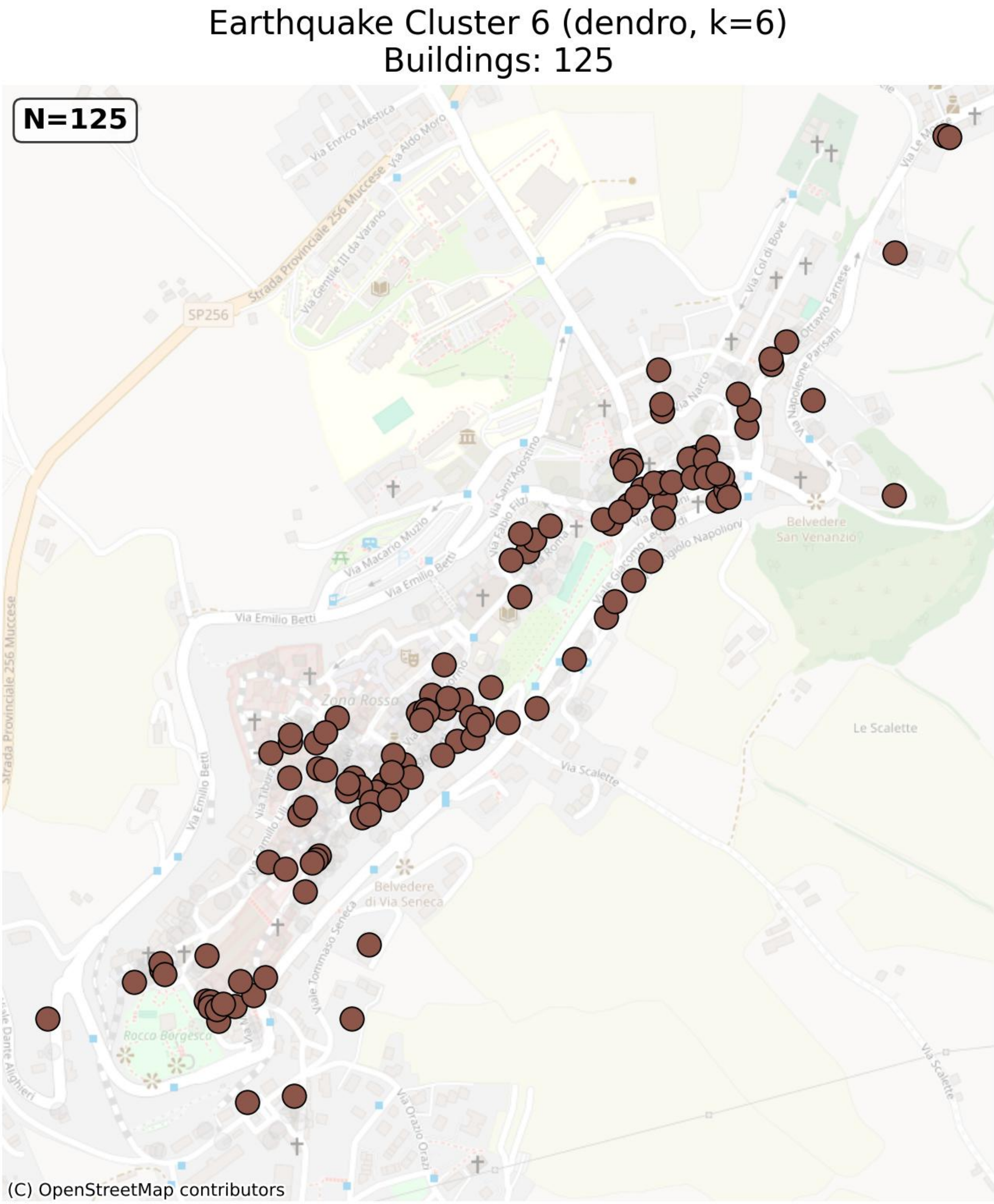

Figure 41. Spatial distribution of cluster k=6.

4.2.1. CLUSTER CHARACTERISTICS

The clustering analysis identified six distinct building groups in Camerino, each with specific typological and damage characteristics following seismic events. Below, we summarize each cluster's key structural features, usability, construction period, and a detailed profile of earthquake-induced damages, both in terms of direct component damage and secondary effects (coverings, chimneys, etc.).

Cluster 1 consists of mid-rise buildings (mean of 4 storeys) built after 2002, all of which were rendered unusable following the earthquake. This group, though small, is characterised by a high vulnerability to both nominal and structural damages. All buildings experienced damage to their coverings, and a third also suffered damage to building objects. With respect to structural components, about two-thirds of buildings exhibited no or negligible slight damage to vertical structures, but one-third showed slight damage affecting less than a third of the component. Notably, two-thirds of buildings in this cluster also had very heavy damage (again affecting less than one –third of the component). Patterns for floors, stairs, roof, partitions, and pre-existing elements were similar: a majority with no damage, but substantial minorities exhibiting slight or very heavy damage. Overall, these post-2002 buildings proved unexpectedly fragile, with extensive yet typically localised damage leading to total loss of usability.

Cluster 2 encompasses a large group of mid-rise buildings constructed prior to 1919, almost all of which were also classified as unusable post-earthquake. This cluster exhibits the broadest range and highest extent of both nominal and structural damages. Over 90% of buildings had damaged coverings, nearly half suffered damage to building objects, and 42% had tile or chimney damage. For vertical structures, just over 70% showed no slight damage, but there were significant percentages of buildings with medium and very heavy damage: over 10% and 21%, respectively, had medium or very heavy damage with notable extension, and about 40% had very heavy damage affecting up to one -third of the component. Across all other structural components, medium and heavy damage was much more frequent than in other clusters, affecting substantial portions of the buildings. This cluster represents the most vulnerable typology, with both high damage rates and damage extensions—confirming that older mid-rise buildings are at greatest risk.

Cluster 3 is a very small and distinct group, consisting of the tallest buildings in the dataset (average 6.5 storeys) built between 1972 and 1981, and generally classified as partially unusable. Half of these buildings suffered covering damage, but nominal damage to chimneys, eaves, and building systems were absent. Structurally, all buildings in this cluster experienced slight, medium, and very heavy damage to vertical structures, but always with limited extension (less than a third of the element). Similar patterns hold for floors, stairs, roofs, partitions, and pre-existing components: 100% of buildings showed damage, but exclusively at the lowest extension category. While these buildings suffered universal structural damage, the affected area within each component was typically small.

Cluster 4 comprises a small number of low- to mid-rise buildings constructed after 2002, the majority of which remained usable or usable with minor countermeasures after the earthquake. This group showed the lowest rates of nominal damage after Cluster 3: only 20% of buildings experienced damage to coverings and tiles/chimneys, with negligible incidence elsewhere. Structurally, 40% of buildings had no slight damage to vertical structures, while 20% experienced moderate and heavy damage (again, mostly with limited extension). The remaining components generally had high proportions of undamaged buildings (80–100%), with only a minority experiencing slight, medium, or very heavy damage at low extension. Overall, these new buildings performed better than the other post-2002 group (Cluster 1), demonstrating improved resilience but still with some localised weaknesses.

Cluster 5 is typified by very old (pre-1919), single-storey buildings which, despite their age, remained overwhelmingly usable after the earthquake. Only a small number of buildings in this group suffered nominal damage to coverings or building objects (19% each). Most buildings showed no damage to vertical structures and other components; when damage was present, it was almost always slight, medium, or very heavy but limited to small portions of the component. This cluster represents the most resilient typology in the sample—historic, low-rise buildings with very little earthquake-induced impairment.

Cluster 6 includes a large collection of old (pre-1919), mid-rise buildings, which generally retained usability or required only minor restrictions post-earthquake. This cluster had a moderate incidence of nominal damage—about 65% had coverings damaged, while smaller percentages experienced issues with chimneys, eaves, objects, and building systems. Structurally, the majority of buildings in all components were undamaged or only slightly damaged, but a notable minority experienced medium or very heavy damage at modest extensions. Thus, while these buildings were more robust than the unusable clusters, they still exhibited some susceptibility to structural and nominal damages.

In summary, the clustering reveals clear typological trends: post-2002 mid-rise buildings (Cluster 1) and old mid-rise buildings (Cluster 2) are the most vulnerable, exhibiting high rates and extensions of damage and rendered largely unusable. In contrast, the oldest single-storey (Cluster 5) and a portion of old mid-rise buildings (Cluster 6) showed remarkable resilience, remaining usable and sustaining limited structural and nominal damage. Tall, modern buildings (Cluster 3) displayed a unique pattern of universal but low-extension damage, while newer, low/mid-rise structures (Cluster 4) generally performed well, with only isolated damage events. The overall picture underscores the critical influence of both building age and form on earthquake damage and usability in the historic urban fabric of Camerino.

4.2.2. CLUSTER-SPECIFIC DISTRIBUTIONS OF DAMAGE LEVELS

In addition to the core clustering analysis, we also examined the distribution of earthquake-induced damage types and severity levels within each building cluster. For every identified cluster, the frequencies and extents of nominal (e.g., coverings, chimneys) and structural damages (e.g., vertical structures, floors, stairs, roof, partitions, pre-existing conditions) were calculated. This allowed us to profile the typical damage patterns associated with each building typology and provided a more detailed understanding of cluster-specific vulnerability. These results directly support the prioritisation of retrofit interventions and highlight which building groups are most at risk from seismic events in Camerino.

Variables used for cluster-specific damage assessment (per cluster):

Structural Damage Variables (by component & damage level)

- Vertical Structures (originally titled in Aedes database: Damage Vertical Structures):
  - F1-1 Very Heavy Damage Vertical Structures (Ordinal)
  - F1-1 Medium Damage Vertical Structures (Ordinal)
  - F1-1 Slight Damage Vertical Structures (Ordinal)
- Floors (originally titled in Aedes database: Damage Floors):
  - F1-2 Very Heavy Damage Floors (Ordinal)
  - F1-2 Medium Damage Floors (Ordinal)
  - F1-2 Slight Damage Floors (Ordinal)
- Stairs (originally titled in Aedes database: Damage Stairs):
  - F1-3 Very Heavy Damage Stairs (Ordinal)
  - F1-3 Medium Damage Stairs (Ordinal)
  - F1-3 Slight Damage Stairs (Ordinal)
- Roof (originally titled in Aedes database: Damage Roof):
  - F1-4 Very Heavy Damage Roof (Ordinal)
  - F1-4 Medium Damage Roof (Ordinal)
  - F1-4 Slight Damage Roof (Ordinal)
- Partition (originally titled in Aedes database: Damage Partition):
  - F1-5 Very Heavy Damage Partition (Ordinal)
  - F1-5 Medium Damage Partition (Ordinal)
  - F1-5 Slight Damage Partition (Ordinal)
- Pre-existing (originally titled in Aedes database: Pre-existing Damage):
  - F1-6 Pre-existing Very Heavy Damage (Ordinal)
  - F1-6 Pre-existing Medium Damage (Ordinal)
  - F1-6 Pre-existing Slight Damage (Ordinal)

Nominal Damage Variables

- ARCH_DB.F2-1 Damage Coverings (Nominal) (originally titled in Aedes database: Damage Coverings)
- ARCH_DB.F2-2 Damage Tiles Chimneys (Nominal) (originally titled in Aedes database: Damage Tiles Chimneys)
- ARCH_DB.F2-3 Damage Eaves (Nominal) (originally titled in Aedes database: Damage Eaves)
- ARCH_DB.F2-4 Damage Objects (Nominal) (originally titled in Aedes database: Damage Objects)
- ARCH_DB.F2-5 Damage Hydraulic (Nominal) (originally titled in Aedes database: Damage Hydraulic)
- ARCH_DB.F2-6 Damage Electric/gas (Nominal) (originally titled in Aedes database: Damage Electric/gas)

The following tables present the percentage distributions of damages for each cluster. Table 11 summarizes the incidence of non-structural damages, such as coverings, chimneys, eaves, objects, hydraulic, and electric/gas systems. The most severe profile is evident in Cluster 2, where nearly all buildings (over 90%) experienced covering damage, and substantial shares showed issues with chimneys (42%) and objects (48%). This indicates a widespread failure of secondary elements, amplifying usability losses. Cluster 1, though very small, also performed poorly, with 100% of buildings showing covering damage and one-third presenting object damage. In contrast, Clusters 4 and 5 show minimal vulnerability, with only isolated cases of coverings or objects damaged. Cluster 6 presents an intermediate condition, with around two-thirds of buildings sustaining covering damage and smaller but non-negligible shares affected in other categories.

CLUSTER_EQ	ARCH_DB.F2-1 DAMAGE COVERINGS (NOMINAL)	ARCH_DB.F2-2 DAMAGE TILES CHIMNEYS (NOMINAL)	ARCH_DB.F2-3 DAMAGE EAVES (NOMINAL)	ARCH_DB.F2-4 DAMAGE OBJECTS (NOMINAL)	ARCH_DB.F2-5 DAMAGE HYDRAULIC (NOMINAL)	ARCH_DB.F2-6 DAMAGE ELECTRIC/GAS (NOMINAL)
1	100	0	0	33.3	0	0
2	90.8	41.8	13	47.8	7.1	6.5
3	50	0	0	0	0	0
4	20	20	0	0	0	0
5	18.8	0	0	18.8	0	0
6	64.8	17.6	4	24	1.6	0

Table 11. Damage variables' percentages per cluster.

For the rest of the tables, it is important to be reminded from Table 12. *Damage extension percentage for Vertical Structures per cluster.* that the encoding appearing in columns (0,1,2,3) is the level of three types of damage extension (Slight, Medium, Very Heavy), with 0 meaning no damage or negligible damage, 1 meaning extension >2/3, 2 meaning 1/3< extension<2/3 and 3 meaning extension<1/3. Vertical structures (Table 12) show that Cluster 2 and Cluster 6 have the widest distribution of vertical structure damages. Many buildings fall under code 0 (no/negligible damage), yet sizeable shares show code 3 (damage <1/3) and code 2 (damage 1/3-2/3), indicating partial but significant impacts. Cluster 3 is unique, as all buildings are classified under code 0 for medium/heavy damage but still show code 3 slight damage, meaning universal yet localized impairment. Clusters 1 and 4 display a combination of codes 1 and 3, suggesting that even when vertical structures are affected, the extension of both heavy and slight damages is limited. This confirms the structural fragility of certain clusters despite relatively small portions of the element being compromised.

DAMAGE VERTICAL STRUCTURES	CLUSTER_EQ	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	71.2	0.5	6.5	21.7
	3	0	0	0	100
	4	40	0	20	40
	5	56.2	0	6.2	37.5
	6	40.8	0	12	47.2
Medium Damage Extension (%) by Cluster	1	33.3	0	0	66.7
	2	39.1	10.3	26.1	24.5
	3	100	0	0	0
	4	60	0	20	20
	5	93.8	0	0	6.2
	6	64	0	1.6	34.4
Very Heavy Damage Extension (%) by Cluster	1	33.3	0	0	66.7
	2	36.4	2.2	21.2	40.2
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	99.2	0	0	0.8

Table 12. Damage extension percentage for Vertical Structures per cluster.

Damage to floors (Table 13) follows a similar trend to vertical structures. Clusters 2 and 6 again exhibit broader variation, with a mix of codes 0, 2, and 3 across slight, medium, and very heavy categories. This suggests that while some buildings were unaffected, others sustained both moderate and localized severe damage. Cluster 3 is once more distinct, as all buildings show floor damage under code 0 for medium/heavy but code 3 for slight, pointing to universal but limited extension damage. Clusters 4 and 5 present mostly code 0 outcomes.

DAMAGE FLOORS	CLUSTER_EQ	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	69	0.5	4.3	26.1
	3	50	0	0	50

	4	80	0	0	20
	5	81.2	0	0	18.8
	6	55.2	0	3.2	41.6
Medium Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	52.7	3.3	15.2	28.8
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	92.8	0	0	7.2
Very Heavy Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	75.5	1.1	4.3	19
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	100	0	0	0

Table 13. Damage extension percentage for Floors per cluster.

Stair damage (Table 14) is less frequent overall, though patterns align with the vertical structure results. Cluster 2 shows the widest spectrum, with some buildings registering code 1 (extension >2/3) for medium damage and others code 3 (localized impacts). Clusters 1 and 6 show mixed outcomes, including slight and medium damage with code 3 extensions, while Clusters 4 and 5 remain largely undamaged (code 0). Notably, Cluster 3 records universal damage under code 3 slight, pointing again to limited but consistent structural vulnerability.

DAMAGE STAIRS	CLUSTER_EQ	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	71.2	1.1	3.8	23.9
	3	50	0	0	50
	4	100	0	0	0
	5	100	0	0	0
	6	72	0	5.6	22.4
Medium Damage Extension (%) by Cluster	1	33.3	0	33.3	33.3
	2	62.5	7.6	12	17.9

	3	100	0	0	0
	4	80	0	0	20
	5	100	0	0	0
	6	92.8	0	0	7.2
Very Heavy Damage Extension (%) by Cluster	1	100	0	0	0
	2	84.2	2.7	7.1	6
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	99.2	0	0	0.8

Table 14. Damage extension percentage for Stairs per cluster.

Roof damage (Table 15) is widespread across clusters, particularly Clusters 2 and 6, where most buildings exhibit codes 2 or 3 for medium and heavy damage, reflecting non-negligible yet contained impacts. Clusters 1 and 3 again reveal universal roof damage but are consistently coded as 3, meaning heavy but very localised. In contrast, Cluster 5 is the most resilient group, with most buildings coded as 0 (no damage) and only a small minority experiencing slight, localised impairment.

DAMAGE ROOF	CLUSTER_QUAKE	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	67.4	2.2	3.3	27.2
	3	50	0	0	50
	4	80	0	0	20
	5	93.8	0	0	6.2
	6	79.2	0.8	0.8	19.2
Medium Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	92.9	0.5	2.7	3.8
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	100	0	0	0
Very Heavy Damage Extension (%) by Cluster	1	100	0	0	0
	2	89.7	1.6	2.7	6

	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	100	0	0	0

Table 15. Damage extension percentage for Roof per cluster.

Pre-existing damage patterns (Table 16) reveal that most clusters contained buildings with code 0 (no/negligible pre-damage), particularly Clusters 2, 5, and 6. However, in all clusters where pre-existing damage was noted, it consistently appeared as code 3, meaning limited extension (<1/3 of the component). This suggests that although prior vulnerabilities were present, they were typically restricted to small areas.

DAMAGE PRE-EXISTING	CLUSTER_QUAKE	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	94	0	0	6
	3	0	0	0	100
	4	80	0	0	20
	5	87.5	0	0	12.5
	6	84.8	0	1.6	13.6
Medium Damage Extension (%) by Cluster	1	100	0	0	0
	2	98.9	0	0.5	0.5
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	99.2	0	0	0.8
Very Heavy Damage Extension (%) by Cluster	1	100	0	0	0
	2	100	0	0	0
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	100	0	0	0

Table 16. Pre-existing Damage Extension Percentage per cluster.

Partitions (Table 17) display some of the most varied damage distributions. Cluster 6 shows a high proportion of buildings under codes 2 and 3, indicating both medium and heavy damage, usually affecting smaller fractions of the element. Cluster 2 also demonstrates significant vulnerability, with noticeable percentages in codes 2 and 3 across different severities. By contrast, Clusters 4 and 5 exhibit relatively localized damage, while Cluster 3 once again shows universal impairment, but limited in extension.

DAMAGE PARTITION	CLUSTER_QUAKE	0	1	2	3
Slight Damage Extension (%) by Cluster	1	66.7	0	0	33.3
	2	70.7	2.2	8.7	18.5
	3	50	0	0	50
	4	40	0	0	60
	5	62.5	6.2	0	31.2
	6	27.2	0.8	18.4	53.6
Medium Damage Extension (%) by Cluster	1	0	0	33.3	66.7
	2	34.8	11.4	28.3	25.5
	3	50	0	0	50
	4	40	0	0	60
	5	100	0	0	0
	6	74.4	0.8	5.6	19.2
Very Heavy Damage Extension (%) by Cluster	1	100	0	0	0
	2	69.6	1.6	11.4	17.4
	3	100	0	0	0
	4	100	0	0	0
	5	100	0	0	0
	6	99.2	0	0	0.8

Table 17. Damage extension' percentage for Partision per cluster.

Overall, the distribution of damage levels across clusters highlights distinct typological vulnerabilities in Camerino's building stock. While many buildings in several clusters remained undamaged or showed only negligible impairment (code 0), others consistently exhibited code 3 damage patterns, meaning that very heavy, medium, or slight damage was present but limited to less than one-third of the component. This indicates a recurring trend of localised yet widespread damage across multiple structural elements. Clusters 2 and 6 emerge as the most vulnerable, with high shares of medium and heavy damage spanning vertical structures, floors, stairs, and roofs, confirming their susceptibility to seismic impacts. Conversely, Clusters 4 and 5 show greater resilience, with most damage either absent or confined to minor portions of the components. Cluster 3 stands out as a unique case, where damage was universal but always restricted to limited extensions, pointing to structural fragility without total failure. Taken together, these patterns underline that vulnerability in Camerino is not only a function of whether damage occurs but also of its extent and distribution across building components, a factor that must be carefully considered when prioritising retrofit interventions.

5. ASSESSMENT OF ENERGY AND WATER INTERVENTIONS IDENTIFIED IN TASK 2.4

In Chapter 5, we present a structured assessment of the energy and water interventions identified in Task 2.4 by mapping their suitability and impact across the previously defined building clusters. For each cluster, interventions were scored on a 1-to-5-star scale, reflecting criteria such as technical feasibility, historical appropriateness, and spatial constraints. This participatory, cluster-specific ranking methodology aligns with established multi-criteria decision-making frameworks applied in building retrofitting contexts [35] and PROMETHEE-driven rankings at building and district levels [37]. Additionally, similar typology-based decision workflows have been applied to historic building stocks to prioritise interventions under heritage and environmental constraints [38]. By embedding our qualitative ranking within a cluster-resolved framework, the method ensures that proposed solutions are not only technically effective but also appropriate for each cluster's urban and heritage-specific context. Section 5.2 focuses on the prioritisation of nature-based solutions, emphasising their value for both heatwave adaptation and overall urban resilience. The chapter concludes with operative guidelines (Section 5.3) tailored to the specific context of Camerino's historic centre, addressing practical considerations, potential restrictions, and recommendations for the effective implementation of selected interventions.

5.1. HEATWAVE-RELATED INTERVENTIONS

This section evaluates the suitability of interventions for mitigating heatwave risks across the six building clusters. The star-based ranking (from 1 to 5) links each measure to the clusters' thermal vulnerability and spatial characteristics, highlighting broadly effective options such as insulation, shading, and reflective materials, as well as more context-dependent solutions like private gardens or amenity areas. The results provide a targeted basis for reducing heat exposure while respecting the constraints of Camerino's historic fabric.

Notes on Ratings:

- ★★★★★ = Highly suitable and directly impactful for this cluster's typical building/environment.
- ★★★★☆ = Strongly suitable; likely positive but may need adaptation.
- ★★★☆☆ = Moderately suitable or feasible, with some limitations.
- ★★☆☆☆ = Marginal relevance; possible but not a primary solution.
- ★☆☆☆☆ = Not directly applicable or feasible for heat hazard/urban context.

#	SOLUTION	CLUSTER 1	CLUSTER 2	CLUSTER 3	CLUSTER 4	CLUSTER 5	CLUSTER 6
1	Balcony/private garden	★★★★★	★★☆☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆
2	Adopted public spaces (shading/evaporation/etc.)	★★★★★	★★★★☆	★★★★☆	★★★★☆	★★★★☆	★★★★☆
3	Amenity areas (recreation/playground etc.)	★★★★☆	★★☆☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆
4	Parks (abundant tree canopy/shade structures)	★★★★★	★★★☆☆	★★★★☆	★★★★★	★★★★☆	★★★★☆
5	Street trees (shading and cooling effect)	★★★★★	★★★★☆	★★★★★	★★★★★	★★★★★	★★★★☆
6	Reforestation	★★☆☆☆	★☆☆☆☆	★☆☆☆☆	★★★★★	★★☆☆☆	★★★☆☆
7	Cool roofs and ventilated roofs	★★★★★	★★★★☆	★★★★☆	★★★★☆	★★★★☆	★★★★☆

8	Shading devices (awnings/shutters/etc.)	★★★★★	★★★★☆	★★★★★	★★★★☆	★★★★☆	★★★★☆
9	Adequate insulation	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★	★★★★☆
10	Natural ventilation	★★★★☆	★★★☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆
11	Fire-resistant building materials	★★★★☆	★★★★☆	★★★★☆	★★★★☆	★★★★☆	★★★★☆
12	Natural daylighting	★★★★★	★★★☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆
13	Building Monitoring System	★★★★☆	★★☆☆☆	★★☆☆☆	★★★★☆	★★☆☆☆	★★★☆☆
14	Sensors (occupancy/temp/flood/etc.)	★★★★☆	★★☆☆☆	★★☆☆☆	★★★★☆	★★☆☆☆	★★★☆☆
15	Renewable energy (solar/geothermal/etc.)	★★★★★	★★☆☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆
16	Energy storage	★★★★☆	★★☆☆☆	★★☆☆☆	★★★★☆	★★☆☆☆	★★★☆☆
17	Demand and response programmes	★★★★☆	★★☆☆☆	★★☆☆☆	★★★★☆	★★☆☆☆	★★★☆☆
18	Energy communities	★★★★☆	★★☆☆☆	★★☆☆☆	★★★★☆	★★☆☆☆	★★★☆☆
19	Light-coloured and reflective materials	★★★★★	★★★☆☆	★★★★☆	★★★★★	★★★★☆	★★★★☆
20	Passive ventilation through thermal chimneys	★★★★☆	★★★☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆
21	Materials with high thermal mass	★★★★☆	★★★★★	★★★★★	★★★★☆	★★★★★	★★★★☆
22	Active cooling ventilation	★★★★★	★★☆☆☆	★★★★☆	★★☆☆☆	★★☆☆☆	★★★★☆
23	Geocooling and heat pumps	★★★★☆	★☆☆☆☆	★★☆☆☆	★★★☆☆	★★☆☆☆	★★★☆☆
24	Passive dampers	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★★☆☆☆	★☆☆☆☆	★★☆☆☆
25	Jacketing of concrete frame elements	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★★☆☆☆	★☆☆☆☆	★★☆☆☆
26	Electrical/mechanical utilities above flood	★★☆☆☆	★★☆☆☆	★★☆☆☆	★★★☆☆	★★☆☆☆	★★★☆☆
27	Expanded EM-DAT disaster database	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★★☆☆☆	★☆☆☆☆	★★☆☆☆
28	Myclimateservices.eu (capacity building)	★★☆☆☆	★★☆☆☆	★★☆☆☆	★★★☆☆	★★☆☆☆	★★★☆☆
29	OBREC (Wave Energy/harbor protection)	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆
30	QoAir (UHI monitoring/sensors)	★★★★☆	★★★☆☆	★★★☆☆	★★★★☆	★★★☆☆	★★★★☆

31	Unified Fire Protection Units/System	★★☆☆☆	★★☆☆☆	★★☆☆☆	★★★☆☆	★★☆☆☆	★★★☆☆

Table 18. Ranking of energy interventions for heatwaves' hazard.

The ranking table (Table 18) highlights significant variation in the applicability and impact of different energy solutions across the identified clusters. Measures such as adequate insulation, street trees, and cool/ventilated roofs emerge as highly suitable for nearly all clusters, indicating their broad relevance to both older and newer building typologies. In contrast, solutions like balconies/private gardens and building monitoring systems display more variable feasibility, being less applicable in historic cores but highly effective in newer or more adaptable buildings. Solutions demanding substantial space, such as amenity areas and parks, are particularly suitable for peripheral or transitional clusters, where land availability is less restricted. Conversely, dense historic clusters may face greater challenges in implementing spatially extensive or visually impactful interventions due to conservation constraints and a lack of open space. Overall, the ranking demonstrates that a combination of passive, nature-based, and targeted retrofit measures can be tailored to the unique characteristics of each cluster, maximizing both adaptation potential and implementation feasibility.

5.2. EARTHQUAKE-RELATED INTERVENTIONS

This section examines the relevance of interventions in reducing earthquake-related vulnerabilities across the six clusters. The ranking highlights both structural and non-structural measures, with higher suitability assigned to clusters showing the greatest fragility. While clusters with severe usability losses benefit most from envelope strengthening, insulation, and monitoring systems, more resilient groups are prioritized for complementary actions such as shading, urban greening, and efficiency upgrades.

Notes on Ratings:

- ★★★★★ = Highly suitable and directly impactful for this cluster's typical building/environment.
- ★★★★☆ = Strongly suitable; likely positive but may need adaptation.
- ★★★☆☆ = Moderately suitable or feasible, with some limitations.
- ★★☆☆☆ = Marginal relevance; possible but not a primary solution.
- ★☆☆☆☆ = Not directly applicable or feasible for heat hazard/urban context.

#	SOLUTION	CLUSTER 1	CLUSTER 2	CLUSTER 3	CLUSTER 4	CLUSTER 5	CLUSTER 6
1	Balcony/private garden	★★☆☆☆	★☆☆☆☆	★★★☆☆	★★★★☆	★★★☆☆	★★☆☆☆
2	Adopted public spaces	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★☆☆	★★★★★
3	Amenity areas	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★★☆	★★★★★
4	Parks	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★★☆	★★★★★
5	Street trees	★★★★☆	★★★★★	★★★☆☆	★★★★★	★★★★☆	★★★★★
6	Reforestation	★☆☆☆☆	★★★★☆	★☆☆☆☆	★★☆☆☆	★★★☆☆	★★★★☆
7	Cool/ventilated roofs	★★★★☆	★★★☆☆	★★★★★	★★★★☆	★★★★☆	★★★☆☆
8	Shading devices	★★★★☆	★★★★☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
9	Adequate insulation	★★★★★	★★★★☆	★★★★★	★★★★★	★★★★☆	★★★★☆
10	Natural ventilation	★★★★☆	★★★☆☆	★★★★☆	★★★★★	★★★★☆	★★★★☆

11	Fire-resistant materials	★★★★★	★★★★☆	★★★★★	★★★★★	★★★★☆	★★★★☆
12	Natural daylighting	★★★★☆	★★★☆☆	★★★★☆	★★★★★	★★★★☆	★★★★☆
13	Building monitoring	★★★★★	★★★☆☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
14	Sensors	★★★★★	★★★☆☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
15	Renewable energy	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
16	Energy storage	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
17	Demand/response	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
18	Energy communities	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
19	Light/reflective materials	★★★★☆	★★★☆☆	★★★★★	★★★★☆	★★★★☆	★★★☆☆
20	Thermal chimneys	★★★☆☆	★★☆☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
21	High thermal mass materials	★★★★☆	★★★☆☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
22	Active cooling/ventilation	★★★★☆	★★★☆☆	★★★★★	★★★★☆	★★★☆☆	★★★★☆
23	Geocooling/heat pumps	★★★★☆	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★★☆
24	Passive dampers	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★☆☆	★★★★☆
25	Jacketing of frame elements	★★★☆☆	★★★★☆	★★★★☆	★★★☆☆	★★★☆☆	★★★★☆
26	E&M above flood level	★★★☆☆	★★★★☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★★☆
27	EM-DAT disaster DB	★★☆☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆
28	myclimateservices.eu	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★☆☆
29	OBREC	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆
30	QoAir (UHI sensors)	★★★★☆	★★★★★	★★★★☆	★★★★★	★★★★☆	★★★★★
31	Fire protection units	★★☆☆☆	★★★★☆	★★★☆☆	★★★☆☆	★★★☆☆	★★★★☆

Table 19. Ranking of energy interventions for earthquake hazards.

For clusters with the highest structural vulnerability and unusable status, such as Clusters 1 and 2, interventions emphasizing deep envelope retrofitting, advanced insulation, fire-resistant materials, smart building monitoring, and cooling solutions (both passive and active) receive the highest ratings (Table 19). These clusters also benefit from broader urban greening and community-based resilience actions. Clusters 3 and 4, which include taller or newer buildings that remain partially or fully usable, are rated highly for solutions that further reduce heat stress, improve indoor environmental quality, and integrate smart and renewable energy technologies. Meanwhile, the more resilient low-rise and single-storey clusters (5 and 6), though generally less impacted, are prioritized for interventions that sustain their performance, such as urban shading, nature-based cooling, and low-intrusion efficiency upgrades.

5.3. NATURE-BASED SOLUTIONS PRIORITIZATION

There is a growing body of evidence supporting the prioritization of nature-based solutions for heatwave resilience, urban cooling, and community wellbeing [39-42]. NBS not only offer direct microclimate benefits and ecosystem enhancement but also serve a critical role in disaster recovery and multi-hazard adaptation [43, 44]. Nature-based solutions (NBS) occupy a central role in the adaptation strategy for Camerino's diverse building clusters, offering a synergy of climate mitigation, heat stress reduction, ecosystem enhancement, and community resilience. The key NBS identified in the D2.4 solution list—balconies and private gardens, adopted public spaces with shading and vegetation, amenity areas, urban parks, street trees, and, where appropriate, reforestation—provide a suite of interventions that work through natural processes to cool urban environments, support biodiversity, and foster social cohesion.

For heatwave hazards, NBS emerge as top-priority measures across all clusters. The cluster-to-solution ranking clearly highlights that interventions such as balcony/private garden creation, parks with abundant tree canopy, street trees, and the greening of public spaces consistently receive four or five stars for nearly every typology. This reflects both the scientific consensus and local evidence: green infrastructure directly lowers urban air temperatures, reduces heat gain in buildings, and offers crucial thermal comfort to vulnerable populations. The highest-risk and most exposed clusters (such as Cluster 1, comprising dense, modern, multi-family housing) show the strongest alignment with NBS, underscoring their urgent need for cooling, outdoor relief, and microclimate regulation. Meanwhile, more resilient or lower-rise clusters (e.g., Clusters 5 and 6) also benefit substantially from nature-based approaches, reinforcing the value of universal implementation. Notably, reforestation is most suitable for clusters with peri-urban or low-density characteristics, where larger land areas can be restored or managed for cooling, stormwater regulation, and carbon sequestration. In sum, for heatwave resilience, NBS should be prioritized alongside (and often above) technical or mechanical interventions, due to their proven, multi-dimensional effectiveness.

In the context of earthquake hazards, while nature-based solutions are not substitutes for structural retrofitting or direct seismic risk reduction, they still hold significant value in fostering holistic resilience. Clusters characterized by high vulnerability—especially older, mid-rise buildings in Clusters 2 and 6—are highly rated for interventions involving street trees, parks, and adopted public spaces. These solutions contribute to post-disaster recovery by providing safe assembly areas, psychological relief, and opportunities for community engagement. Private gardens and green amenity areas, while less directly protective against seismic damage, help enhance overall well-being, offer informal refuge, and support long-term recovery. Importantly, the benefits of NBS in this context are amplified when considering the risk of heatwaves and secondary hazards in the aftermath of an earthquake; shaded, green public areas become vital in periods of disrupted infrastructure and elevated environmental stress.

NBS INTERVENTION	HAZARD	CLUSTER 1	CLUSTER 2	CLUSTER 3	CLUSTER 4	CLUSTER 5	CLUSTER 6	OVERALL NOTE
Balcony / private garden	Heatwave	★★★★★	★★☆☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	Highly effective in dense modern clusters; limited in historic cores.

		★★☆☆☆	★☆☆☆☆	★★★☆☆	★★★★☆	★★★☆☆	★★☆☆☆	Supportive for wellbeing and informal refuge post-quake.
Adopted public spaces (shading/vegetation)	Heatwave	★★★★★	★★★★☆	★★★★☆	★★★★☆	★★★★☆	★★★★☆	Strong, consistent performance across clusters.
	Earthquake	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★☆☆	★★★★★	Critical for recovery and safe gathering spaces.
Amenity areas (playgrounds, recreation)	Heatwave	★★★★☆	★★☆☆☆	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	Most feasible in peripheral/less dense clusters.
	Earthquake	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★★☆	★★★★★	Highly valued for community engagement post-disaster.
Parks (tree canopy, shade)	Heatwave	★★★★★	★★★☆☆	★★★★☆	★★★★★	★★★★☆	★★★★☆	Universally suitable, especially effective for cooling.
	Earthquake	★★★☆☆	★★★★★	★★★☆☆	★★★★☆	★★★★☆	★★★★★	Key for safe assembly areas and psychosocial recovery.
Street trees	Heatwave	★★★★★	★★★★☆	★★★★★	★★★★★	★★★★★	★★★★☆	One of the strongest performers across all clusters.
	Earthquake	★★★★☆	★★★★★	★★★☆☆	★★★★★	★★★★☆	★★★★★	Multipurpose: cooling + recovery infrastructure.
Reforestation	Heatwave	★★☆☆☆	★☆☆☆☆	★☆☆☆☆	★★★★★	★★☆☆☆	★★★☆☆	Best for peri-urban/low-density areas.
	Earthquake	★☆☆☆☆	★★★★☆	★☆☆☆☆	★★☆☆☆	★★★☆☆	★★★★☆	Limited in urban cores; useful in

								rural/peripheral settings.

Table 20. Cumulative table of NbS interventions.

Comparatively, the prioritisation of NBS is highest for heatwave adaptation, where their direct benefits on temperature, air quality, and public health are most pronounced (Table 20). For earthquake resilience, their role is supportive and complementary, adding value by improving quality of life, aiding psychological recovery, and addressing compounding risks such as heat and drought. Thus, a policy that foregrounds nature-based solutions for heatwave resilience—while ensuring their integration within multi-hazard strategies for all clusters—will maximise the returns in both immediate adaptation and long-term urban sustainability. These interventions, where space and local context allow, should be considered essential infrastructure in Camerino's future urban planning and disaster risk reduction efforts.

5.4. OPERATIVE GUIDELINES TO BE APPLIED ON CAMERINO HISTORIC CENTRE

In the context of the historic centre, the installation of environmental monitoring systems must comply with both cultural heritage regulations and the structural and functional limitations resulting from the earthquake. These conditions introduce specific constraints that influence sensor placement, operation, and maintenance. The main restrictions to be considered are as follows:

- Heritage protection for exterior installations: Installing weather stations, air quality monitors, or temperature/humidity sensors on building exteriors still requires *Soprintendenza* approval. However, these sensors are generally smaller and less invasive than structural monitoring equipment. Modern miniaturised sensors can be more easily integrated into existing architectural elements like downspouts, under eaves, or within window frames, making approval more likely.
- Interior monitoring advantages: Indoor environmental quality (IEQ) sensors for temperature, humidity, CO_2, and comfort parameters face fewer restrictions as they don't affect building exteriors. These can be particularly valuable in the 15% of buildings that remain usable (Category A) and the 8% with limited use (Category B), including university facilities, municipal offices, and residential units.
- Infrastructure limitations: Many buildings lack functioning utilities due to earthquake damage. Environmental sensors requiring continuous power may need battery operation or solar options, though small solar panels on roofs would again require heritage approval.
- Access for maintenance: Environmental sensors still require periodic maintenance, calibration, and data collection. Most of the buildings of the historic centre have access limits due to the earthquake damage.
- Privacy considerations: Indoor comfort monitoring in residential buildings requires explicit consent from occupants and must comply with GDPR regulations, particularly for sensors that could indirectly monitor occupancy patterns.

In Camerino area, the applicability of the solutions identified may encounter restrictions of various kinds, for example, in the case of limitations imposed on buildings and landscapes protected by *Soprintendenza,* regulated by "Codice dei Beni Culturali e del Paesaggio" (Cultural Heritage and Landscape Code) - Legislative Decree 42/2004; as well as impediments due to structural aspects, mainly regulated by "Norme Tecniche per le Costruzioni" (Technical Standards for Construction) – Ministerial Decree 17/01/2018. In both cases, the construction of new balconies or the greening of existing ones; the creation of new openings in the façade or roof to increase natural ventilation and natural lighting; the integration of renewable energy systems and energy storage devices; the installation of electrical and mechanical systems above flood level; the use of high thermal mass materials; the inclusion of passive dampers and the jacketing of concrete frame elements may have limitations.

Structural analyses are necessary to assess whether the affected structures are adequate to withstand the new loads introduced by the aforementioned solutions.

At the same time, in areas subject to landscape restrictions, interventions involving modifications to existing structures, renovations that alter the external appearance, the construction of infrastructure, and the installation of energy systems require a landscape permit. Therefore, even in the case of gardens, adopted public spaces, amenity areas, parks, street trees and reforestation there could be limitations.

If the building is protected by *Soprintendenza*, however, its authorisation is always required for any intervention, including minor ones and not listed before, like shading devices, building monitoring systems, sensors, light-coloured and reflective materials, active cooling ventilation and insulation. In this regard, external cladding should be avoided in these buildings, as it affects the aesthetics of the façades. Internal cladding or insulating cavity wall insulation is therefore preferable. These techniques, however, must also be evaluated based on the structure. For example, if insulating masonry walls using an internal insulation layer, it's advisable to use low-permeability insulation combined with a vapor barrier to prevent condensation. For stone walls, however, it's preferable to use highly breathable insulation and plaster. Regarding the insertion of insulation into cavity walls, however, it's important to keep in mind that historic walls are often not sealed in the area in contact with the floor slab or don't have a uniform thickness. For this reason, it's always advisable to verify the possibility of uniform insulation by performing infrared thermography.

Other restrictions affecting the applicability of the identified solutions concern those due to building regulations of the Municipality of Camerino and other urban planning instruments in force in the area. “Regolamento Edilizio” (building regulations) – Regional Law No. 8 of May 3, 2018, is the local regulatory instrument that governs the construction, modification, and maintenance of buildings and open spaces within the Municipality of Camerino, defining technical, aesthetic, health, and safety standards to ensure urban quality and the livability of the area. “Norme Tecniche di Attuazione” – NTA (Technical Implementation Standards), on the other hand, are a set of detailed rules and regulations that complement general urban planning plans, such as the “Piano Regolatore Generale” – PRG (General Regulatory Plan). They specify the quantitative and qualitative guidelines for carrying out construction and urban planning interventions, defining parameters such as maximum building heights, permitted intended uses, building densities, and distances between buildings. In short, the NTAs provide practical instructions for implementing the broad provisions of urban planning across the territory. Compared to the urban planning regulations, the solutions that may encounter limitations primarily concern those that affect outdoor environments, such as balconies, adopted public spaces, amenity areas, parks, street trees, reforestation, natural ventilation, and natural daylighting.

For energy retrofitting projects, compliance with the Ministerial Decree of June 26, 2015, known as the "Decreto Requisiti Minimi” (Minimum Requirements Decree), is mandatory in Italy. It establishes the rules for calculating the energy performance of buildings and defines the minimum requirements for the energy efficiency of the building envelope and systems (air conditioning, hot water, and ventilation), as well as for the integration of renewable energy sources. This decree applies to both public and private projects and to both new and existing buildings.

From a sustainability point of view, however, the main restrictions in the Camerino area that take into account buildings as well as urban solutions are linked to the “Criteri Ambientali Minimi” – CAM (Minimum Environmental Criteria for public projects only). For any public intervention, it is mandatory at the Italian national level, requiring compliance with CAM, which are environmental requirements aimed at identifying the most environmentally sound design solution throughout the life cycle. For the same reason, even in the case of private projects, it is still an excellent decision to respect the requirements.

Over time, various CAMs have been published to cover different topics. Those applicable to infrastructure projects are governed by the following ministerial decrees: Ministerial Decree of June 23, 2022 (for buildings), Ministerial Decree of March 10, 2020 (for public green spaces), and Ministerial Decree of August 5, 2024 (for road infrastructure). Projects involving the following solutions are required to comply with the minimum environmental criteria described below, which must be integrated into the design and demonstrated through a specific report to be submitted among the project documents.

- Balconies and gardens, adopted public spaces, amenity areas, parks, street trees and reforestation:
  - Selection of the plant species (D.M. 10 marzo 2020, n. 63): the selected plant species must be native to promote the conservation of nature and its balance; they must guarantee the absence of uncontrolled spread of these species and of phytopathological and human health problems; they must take into account the climate changes underway in the Camerino area and the main pollution factors present; they must consist of pools of species belonging to plant associations consistent with the potential vegetation series of the site and with the specific ecological conditions (avoiding monospecificity); they must have low water consumption, high resistance to environmental stress, the "heat island" phenomenon, and phytopathologies, and capable of activating autonomous organizational capacities towards more evolved forms of plant communities; the tree species must be specifically selected for the type of intended use (for example, street trees with a defined height of scaffolding, a contained root system preferably with deep development, rows with a specific crown morphology, and uniformity of the crown). Furthermore, specifically, tree species must have high structural stability, low management costs, and reduced conflict with overhead and underground infrastructure and pavements; shrub species are preferably selected in free-form rather than formal hedges, except in locations where there are landscape or historical constraints; and finally, lawns are created with herbaceous species suited to the spatial distribution (slope areas, shaded areas, highly maintained ornamental areas, shrubby areas, flowerbeds, trees, etc.) of the planting site, and their selection is made taking into account the ability to intercrop.
  - Conservation and protection of wildlife – with the exception of balconies (D.M. 10 Marzo 2020, n. 63): they must be ensured by complying with the following requirements: creation of water points; promotion of the area's connection to the city's system of gardens and green spaces through the creation of ecological corridors where green spaces are interrupted by road infrastructure; creation of areas with permanent, spontaneous vegetation without intervention, where the characteristics of the project and the area allow; creation of structures to encourage nesting/reproduction (e.g., artificial nests); selection of plant species based on the creation of feeding, mating, and refuge areas for wildlife; use of tree and shrub species characteristic of the area; use of nectariferous species, etc.; encouragement of vegetation stratification (low shrubs, medium shrubs, large shrubs, and trees) to promote differentiated habitats; balanced use of deciduous and evergreen species to create shelters and concealment areas; where possible, plant shrubs in the area to create thickets and areas difficult to access.
  - Stormwater management – with the exception of balconies (D.M. 10 marzo 2020, n. 63): it must be implemented through preservation and restoration of permeable surfaces; containment of surface runoff; groundwater recharge; utilization of soil filtering capacity. Where landscaping and plant material selection are not sufficient to ensure optimal results, technical solutions must be identified to slow water flow and temporarily store it before

releasing it in a controlled manner (small retention/infiltration basins, such as rain gardens, flood ditches, and open-air basins permanently or partially flooded by rainfall). Furthermore, when designing the irrigation system, site conditions (climate, soil, rainwater collection system, spatial layout, terrain morphology, topography, use, etc.) must be taken into account, as well as the type of shrubs and herbs to be irrigated and all the elements that constitute the existing system. When determining the placement of species, hydrozones must be identified in which to place plants with similar water requirements. In small, complex areas, highly exposed to wind, or on sloped surfaces, subsurface irrigation systems must be used. Furthermore, technologies and techniques must be employed to control and prevent any accidental losses due to malfunctions and breakages of the irrigation systems through the use of the following devices: modular and complete controllers connected to sensors that automatically adjust start times based on weather changes; low-mist sprinklers; pressure regulation systems; flow monitoring valves; flow shut-off valves in the event of a fault; soil moisture sensors; climate stations with rain and wind sensors.

- Naturalistic engineering – only in relevant interventions (D.M. 10 marzo 2020, n. 63): in relevant interventions such as the hydrogeological arrangement of embankments or the redevelopment of slopes or watercourses, naturalistic engineering techniques must be foreseen.
- Composting area – with the exception of balconies (D.M. 10 marzo 2020, n. 63): where the size of the landscaped area allows, a composting area must be provided, enclosed by an adequate fence that prevents access by unauthorized personnel. This area must be designed to promote optimal climatic conditions, which, with appropriate measures and practices, allow for an optimal natural decomposition process, resulting in humus-rich soil for use as fertilizer on the site itself.
- Permeability of the land surface – with the exception of balconies, street trees and reforestation (D.M. 23 giugno 2022, n. 256): new construction projects must provide for a permeable land surface of at least 60% (for example, green areas and external paved surfaces for pedestrian or bicycle use, such as walkways, sidewalks, squares, courtyards, and cycle paths). Permeable surfaces are defined as surfaces with a runoff coefficient of less than 0.50. All undeveloped permeable surfaces that prevent rainfall from reaching the groundwater table because they are enclosed on all sides by impermeable structures cannot be considered in the calculation.
- Reduction of the “heat island” effect and air pollution – with the exception of balconies, street trees and reforestation (D.M. 23 giugno 2022, n. 256): a green area equal to at least 60% of the permeable surface must be designated. Furthermore, an assessment of the bioclimatic efficiency of the vegetation must be carried out, expressed as a percentage of the radiation transmitted in the different seasonal settings, particularly for deciduous broadleaf trees. When choosing species, given the need to mitigate solar radiation, preference must be given to those with a low percentage of transmission in the summer and a high percentage in the winter. Regarding paved surfaces, the pavements of driveways and areas intended for parking or vehicle parking must have a Solar Reflectance Index (SRI) of at least 29, in order to reduce heat absorption. External surfaces intended for parking or vehicle parking must be shaded by ensuring that at least 10% of the gross parking area is made up of green cover; the perimeter of the area must be delimited by a green belt no less than 1 meter high; and there must be spaces for motorcycles, mopeds, and bicycle racks, proportionate to the number of potential

users. Finally, if part of the project, building roofs (excluding surfaces used for installing equipment, technical spaces, photovoltaic panels, solar collectors, and other devices) must include green areas, ventilated roofs, or roofing materials that guarantee an SRI of at least 29 for slopes greater than 15%, and at least 76 for slopes less than or equal to 15%.

- Reducing the impact on the surface and underground hydrographic system with the exception of balconies, street trees and reforestation (D.M. 23 giugno 2022, n. 256): measures must be implemented to ensure proper flow of surface water from impermeable surfaces, also to minimize the effects of exceptional weather events. Where runoff water is potentially polluted, purification systems, including natural ones, must be adopted.
- Collection, purification, and reuse of rainwater – with the exception of street trees and reforestation (D.M. 23 giugno 2022, n. 256): a separate network for rainwater collection must be installed. Rainwater collection can be achieved using linear drainage systems (manufactured according to UNI EN 1433) or point drainage systems (manufactured according to UNI EN 124). Water from non-polluted drainage surfaces (sidewalks, pedestrian and cycle paths and roads, gardens, etc.) must be conveyed directly into the rainwater network and then into collection tanks for reuse for irrigation purposes or to fill toilet cisterns. Water from polluted drainage surfaces (driveways, parking lots) must be conveyed through purification and oil separation systems, including natural systems, before being released into the rainwater network. The project must be drawn up on the basis of the UNI/TS 11445 standard.
- Areas equipped for separate waste collection – with the exception of balconies, street trees and reforestation (D.M. 23 giugno 2022, n. 256): specific areas for local separate waste collection must be provided, in accordance with Camerino's waste management regulations.
- Urban furniture - with the exception of balconies and reforestation (D.M. 7 febbraio 2023): they must ensure accessibility and inclusion for all. Furthermore, land use must be limited by enhancing the natural beauty of the area to be developed, as far as technically possible, and maximizing the presence of greenery.

- Shading devices: they must comply with the following criterion:
  - Shading devices (D.M. 23 giugno 2022, n. 256): in urban renovation, new construction, demolition, and reconstruction projects, direct solar radiation entering the interior must be controlled by ensuring that the external transparent parts of buildings, both vertical and inclined, are equipped with fixed or movable shading systems, either outward or from east to west, via south. This requirement can also be met through specific features of the glass component alone (for example, with selective or solar control glass). Solar shading systems must have a total solar transmittance value, coupled with the type of glass used for the protected glazed surface, of less than or equal to 0.35, as defined by the UNI EN 14501 standard.
- Adequate insulation: it contributes to satisfying the criterion on:
  - Energy performance of buildings (D.M. 23 giugno 2022, n. 256): for major first-level renovations requires that the periodic thermal transmittance Yie for each individual opaque structure of the external envelope, calculated according to UNI EN ISO 13786, be less than 0.09 W/m^2K for vertical opaque walls (with the exception of those in the Northwest/North/North-East quadrant) and less than 0.16 W/m^2K for horizontal and sloped opaque walls.

Furthermore, the insulation must comply with the following criterion:

- Thermal and acoustic insulation (D.M. 23 giugno 2022, n. 256): for the purposes of this criterion, insulation materials, excluding any cladding, metalwork, and other accessories present in finished products, meet the following requirements:
    a) thermal insulation materials used to insulate the building envelope, excluding those used to insulate systems, must bear the CE marking, either through the application of a harmonised product standard for insulation materials or through an ETA for which the manufacturer can draw up a DoP (Declaration of Performance) and affix the CE marking. The CE marking requires the declaration of essential characteristics relating to Basic Requirement 6, "Energy Savings and Heat Retention". In these cases, the manufacturer indicates in the DoP the thermal conductivity with declared lambda values λD (or thermal resistance RD). For pre-coupled products or kits, it is possible to refer to the DoP of the individual thermal insulation materials present or to the DoP of the system as a whole. In the case of CE marking via an ETA, during the transitional period in which an ETA is in the process of being issued or the publication of the relevant EAD references for an ETA already issued has not yet occurred in the OJEU, the material or component may be used provided that the manufacturer produces a formal communication from the TAB (Technical Assessment Body) certifying the status of the ongoing procedure for issuing the ETA and the determined performance with regard to the aforementioned thermal conductivity (or thermal resistance);
    b) No substances included in the candidate list of substances of very high concern (SVHC) pursuant to the REACH Regulation (Regulation (EC) No. 1907/2006) are added in concentrations greater than 0.1% (w/w). Any specific use authorisations provided for by the same Regulation for substances included in Annex XIV and specific restrictions provided for in Annex XVII of the Regulation remain unaffected;
    c) They are not produced with blowing agents that cause ozone depletion (ODP), such as HCFCs;
    d) They are not produced or formulated using lead catalysts when sprayed or during the formation of the plastic foam;
    e) If produced from an expandable polystyrene resin, the blowing agents must be less than 6% of the weight of the finished product;
    f) If made from mineral wool, they comply with Note Q or Note R of Regulation (EC) No. 1272/2008 (CLP) as amended.

- Natural ventilation: it must comply with the following criterion:
    - Ventilation and air quality (D.M. 23 giugno 2022, n. 256): in all rooms where occupancy by people is expected, even for short periods of time; natural ventilation must be guaranteed.
- Natural daylighting: it must comply with the following criterion:
    - Natural daylighting (D.M. 23 giugno 2022, n. 256): natural illumination must be at least 300 lux, verified at at least 50% of the measuring points within the room, and 100 lux, verified at least 95% of the measuring points (minimum level). These values must be guaranteed for at least half of the daylight hours.

      For primary and secondary schools, a natural illumination level of at least 500 lux, verified at 50% of the measuring points, and 300 lux verified at 95% of the measuring points, must be guaranteed for at least half of the daylight hours (average level). For preschools and daycare centres, however, a natural illumination level of at least 750

lux, verified at 50% of the measuring points, and 500 lux verified at 95% of the measuring points, must be guaranteed for at least half of the daylight hours (optimal level).
The UNI EN 17037 standard applies to the calculation and verification of the indicated parameters. In particular, the average daylight factor is calculated using UNI 10840 for school buildings and using UNI EN 15193-1 for all other buildings.
In building renovation projects as well as restoration and conservative redevelopment projects where it is not possible to guarantee such levels of illumination, either because architectural solutions are not possible (opening of new windows, light wells, skylights, window frames with thin profiles, etc.), or for objective reasons (absence of walls or roofs in direct contact with the outside) or due to the effect of regulations for the protection of architectural heritage (legislative decree 22 January 2004, n. 42 "Code of cultural and landscape heritage, pursuant to article 10 of law 6 July 2002, n. 137") or for specific indications from the Superintendencies, an average daylight factor greater than 2% must be guaranteed for any intended use, excluding those for which specific sector regulations are in force (such as operating rooms, radiology rooms, etc.) and excluding nursery schools, kindergartens and primary and secondary schools for which the average daylight factor is greater than 2%, daylight to be guaranteed, is greater than 3%.

- Sensors and Building Monitoring System: it must comply with the following award criterion (not mandatory):
  - Building Automation, Control, and Monitoring System (D.M. 23 giugno 2022, n. 256): a bonus score is awarded to a project that, for the use of technological, air conditioning, and lighting systems, includes an automation, control, and technical management system for building technologies (BACS – Building Automation and Control System) corresponding to efficiency class A, as defined in Table 1 of the UNI EN standard 15232-1 "Energy performance of buildings - Part 1: Impact of automation, control, and technical management of buildings - Modules M10-4, 5, 6, 7, 8, 9, 10" and subsequent amendments or equivalent standard. This automation system must allow for adequately monitoring the appropriate energy, water, and, where applicable, other resource performance indicators and ensure that the building's energy performance is the highest possible through optimal automatic management of the systems.
- Renewable energy, energy storage and energy communities: they contribute to the following criterion:
  - Energy supply (D.M. 23 giugno 2022, n. 256): in areas undergoing new construction or urban renovation, the buildings' overall energy needs must be met, wherever possible, by systems powered by renewable sources that produce energy on-site or nearby, such as cogeneration or trigeneration plants; photovoltaic or wind farms; solar thermal collectors for domestic water heating; shallow geothermal systems; heat pump systems; and biogas systems, particularly encouraging participation in renewable energy communities. The criterion, however, only requires a qualitative and not quantitative verification (e.g., it does not require reaching a certain percentage of energy produced from renewable sources).
- Light-coloured and reflective materials: they must comply with the following criterion:
  - Reduction of the “heat island” effect and air pollution (D.M. 23 giugno 2022, n. 256): as previously analysed, the pavements of driveways and areas intended for parking or vehicle parking must have a Solar Reflectance Index (SRI) of at least 29 to reduce heat absorption. Building roofs (excluding surfaces used for installing equipment, technical spaces, photovoltaic panels, solar collectors, and other devices) must include green areas, ventilated roofs, or roofing materials that guarantee an SRI of at least 29 for slopes greater than 15% and at least 76 for slopes less than or equal to 15%.

- Materials with high thermal mass: they contribute to the following criterion:
  - Energy performance of buildings (D.M. 23 giugno 2022, n. 256): for major first-level renovations requires that the surface mass referred to in paragraph 29 of Annex A of Legislative Decree No. 192 of 19 August 2005, referring to each individual vertical opaque structure of the external envelope, is at least 250 kg/m^2.
- Active cooling ventilation: it must comply with the following criterion:
  - Ventilation and air quality (D.M. 23 giugno 2022, n. 256): it is necessary to ensure adequate indoor air quality in all habitable spaces through the installation of mechanical ventilation systems, in accordance with current regulations. For all new construction, demolition and reconstruction, expansion and additions, and major first-level renovations, the external air flow rates required by UNI 10339 must be guaranteed, or at least Class II of UNI EN 16798-1 must be guaranteed. Very low-polluting buildings for new construction, demolition and reconstruction, expansion and additions, and low-polluting buildings for major first-level renovations must be guaranteed. In both cases, the thermal comfort requirements (set out in paragraph 15) and the reduction of thermal energy requirements for ventilation must be met. For major second-level renovations and energy retrofits, if it is technically impossible to achieve the flow rates required by UNI 10339 or Class II of UNI EN 16798-1, Class III is permitted. The ventilation strategies adopted must limit heat loss, noise, energy consumption, and the entry of pollutants and cold and hot air from outside during the winter and summer months. To limit the thermal energy requirement for ventilation, mechanical ventilation systems must also include heat recovery, i.e., an integrated system for recovering the energy contained in the exhaust air and transferring it to the incoming air (pre-treatment for heating and cooling the filtered air to be introduced into the rooms).
- Passive dampers and jacketing of concrete frame elements: the materials they are made of must comply with the following criteria:
  - Steel (D.M. 23 giugno 2022, n. 256): for structural applications, steel produced with a minimum content of recovered or recycled material, or by-products, must be used. This is defined as the sum of the three fractions, as specified: unalloyed electric furnace steel, minimum content of 75%; alloyed electric furnace steel, minimum content of 60%; integrated cycle steel, minimum content of 12%.
  - On-site and pre-mixed concrete (D.M. 23 giugno 2022, n. 256): it must contain at least 5% recycled, recovered, or by-product content of the product weight, calculated as the sum of the three fractions. This percentage is calculated as the ratio between the dry weight of recycled, recovered, and by-product materials and the weight of the concrete net of water (effective water and absorption water). To calculate the mass of recycled, recovered, or by-product material, the amount that actually remains in the final product must be considered. The percentage indicated is the sum of the contributions made by the individual fractions used.
  - Precast concrete products, autoclaved aerated concrete and vibro-compressed concrete (D.M. 23 giugno 2022, n. 256): precast concrete products must be produced with a content of recovered or recycled materials, or by-products, of at least 5% of the product weight, calculated as the sum of the three fractions. Autoclaved aerated concrete masonry blocks, on the other hand, must be produced with a content of recycled or recovered materials, or by-products, of at least 7.5% of the product weight, calculated as the sum of the three fractions.

The percentages indicated are the sum of the contributions made by the individual fractions used.

- In general, the products used must have a minimum recycled content (measured as % of the weight of the product) in accordance with the following (Table 21):

MATERIAL	MINIMUM RECYCLED CONTENT AS % OF PRODUCT WEIGHT
Site-mixed and pre-mixed concrete	5%
Prefabricated concrete products	5%
Autoclaved aerated concrete masonry blocks	7.5%
Structural unalloyed electric arc furnace steel	75%
Structural alloyed electric arc furnace steel	60%
Structural steel from a complete cycle	12%
Non-structural unalloyed electric arc furnace steel	65%
Non-structural alloyed electric arc furnace steel	60%
Non-structural steel from a complete cycle	12%
Bricks used for masonry and floors (Whether they contain only recycled or recovered material)	15% (10%)
Bricks for roofing, floors and exposed brickwork (Whether they contain only recycled or recovered material)	7,5% 5%
Wooden products	70%
Cellulose	80%
Glass wool	60%
Rock wool	15%
Cellular glass	50%
Polyester fibres environment – environment –	50%
Sintered polystyrene foam	15%
Extruded polystyrene foam	10%
Rigid polyurethane foam	2%
Flexible polyurethane foam	20%
Polyurethane agglomerate	70%
Rubber agglomerate	60%
Textile fibres	60%
Partition walls, perimeter counter walls and false ceilings	10%

(Gypsum-based)	(5%)
Stone and mixed walls	100%
Flooring made of plastic materials	20%
Rubber flooring	10%
PVC blackout windows	20%
PVC and polypropylene pipes	20%
Plastic urban furniture or products made of plastic-wood blends in green areas	95%
Plastic urban furniture in playgrounds	60%
Products made of plastic-glass mixtures in green areas and playgrounds	30%
Multilayer sports surfaces containing rubber agglomerate	30%
Rubber agglomerate products and surfaces	50%
Bituminous or inert material used for play or recreational areas	60%
Ceramic products (porcelain stoneware)	30%

Table 21. Minimum recycled content measured as % of the weight of the product.

In summary, implementing energy building and urban solutions in the Camerino area requires careful consideration of a complex web of regulations, technical standards, and environmental criteria. Restrictions tied to cultural heritage, landscape protections, and both national and local building codes shape how and where interventions can occur. Each solution – from the integration of energy-efficient materials to the selection of plant species – must align with these multifaceted requirements, balancing the preservation of historic and natural assets with the pursuit of energy performance, resilience, and sustainability. Ultimately, successful projects in Camerino depend on an integrated approach, where regulatory compliance goes hand in hand with thoughtful design and environmental stewardship. By understanding and navigating these constraints, stakeholders can foster urban and architectural transformation that respects the unique character of the area while advancing toward a more sustainable and liveable future.

Below a summary table (Table 22) is provided:

OPERATIVE GUIDELINES	SOURCE	SOLUTIONS AFFECTED
Buildings protected by *Soprintendenza*, always require its authorization for any interior and exterior intervention on the building	“Codice dei Beni Culturali e del Paesaggio” (Cultural Heritage and Landscape Code) - Legislative Decree 42/2004	Balconies
		Natural ventilation (e.g. new openings in the façade/roof)
		Natural daylighting (e.g. new openings in the façade/roof)
		Renewable energy
		Rnergy storage
		Electrical and mechanical systems and utilities above flood level
		Materials with high thermal mass
		Passive dampers
		Jacketing of concrete frame elements

		Shading devices
		Building monitoring systems
		Sensors
		Light-coloured and reflective materials
		Active cooling ventilation
		Insulation
Landscapes protected by *Soprintendenza*, always requires its authorization for interventions involving modifications to existing structures, renovations that alter the external appearance, the construction of infrastructure, and the installation of energy systems	"Codice dei Beni Culturali e del Paesaggio" (Cultural Heritage and Landscape Code) - Legislative Decree 42/2004	Balconies
		Natural ventilation (e.g. new openings in the façade/roof)
		Natural daylighting (e.g. new openings in the façade/roof)
		Renewable energy
		Energy storage
		Electrical and mechanical systems and utilities above flood level
		Materials with high thermal mass
		Passive dampers
		Jacketing of concrete frame elements
		Gardens
		Adopted public spaces
		Amenity areas
		Parks
		Street trees
		Reforestation
Structural analyses are necessary to assess whether the affected structures are adequate to withstand the new loads introduced by the solutions adopted	"Norme Tecniche per le Costruzioni" (Technical Standards for Construction) - Ministerial Decree 17/01/2018	Balconies
		Natural ventilation (e.g. new openings in the façade/roof)
		Natural daylighting (e.g. new openings in the façade/roof)
		Renewable energy
		Energy storage
		Electrical and mechanical systems and utilities above flood level
		Materials with high thermal mass
		Passive dampers
		Jacketing of concrete frame elements
Technical, aesthetic, health, and safety standards must be complied with	"Regolamento Edilizio" (building regulations) -	Balconies / private gardens
		Amenity areas
		Cool roofs and ventilated roofs

	Regional Law No. 8 of May 3, 2018	Shading devices
		Adequate insulation
		Natural ventilation
		Fire-resistant building materials
		Natural daylighting
		Renewable energy
		Energy storage
		Light-coloured and reflective materials
		Passive ventilation through thermal chimneys
		Materials with high thermal mass
		Active cooling ventilation
		Geocooling and heat pumps
		Passive dampers
		Jacketing of concrete frame elements
		Electrical and mechanical systems and utilities above flood level
Urban planning, that provides quantitative and qualitative guidelines through parameters such as maximum building heights, permitted intended uses, building densities and distances between buildings, must be complied with	“Norme Tecniche di Attuazione” - NTA (Technical Implementation Standards)	Balconies
		Adopted public spaces
		Amenity areas
		Parks
		Street trees
		Reforestation
		Natural ventilation
		Natural daylighting
Requirements for energy efficiency interventions must be respected	Ministerial Decree of June 26, 2015, known as the "Decreto Requisiti Minimi” (Minimum Requirements Decree)	Cool roofs and ventilated roofs
		Shading devices
		Adequate insulation
		Natural ventilation
		Fire-resistant building materials
		Natural daylighting
		Light-coloured and reflective materials
		Passive ventilation through thermal chimneys
		Materials with high thermal mass
		Active cooling ventilation
		Geocooling and heat pumps
		Balconies / gardens

Plant spieces selection for public projects must comply with "Criteri Ambientali Minimi"	D.M. 10 marzo 2020, n. 63	Adopted public spaces
		Amenity areas
		Parks
		Street trees
		Reforestation
Conservation and protection of wildlife for public projects is required and must comply with "Criteri Ambientali Minimi"	D.M. 10 marzo 2020, n. 63	Gardens
		Adopted public spaces
		Amenity areas
		Parks
		Street trees
		Reforestation
Stormwater management for public projects is required and must comply with "Criteri Ambientali Minimi"	D.M. 10 marzo 2020, n. 63	Gardens
		Adopted public spaces
		Amenity areas
		Parks
		Street trees
		Reforestation
Naturalistic engineering for public projects (in relevant interventions such as the hydrogeological arrangement of embankments or the redevelopment of slopes or watercourses) could be required and must comply with "Criteri Ambientali Minimi"	D.M. 10 marzo 2020, n. 63	Gardens
		Adopted public spaces
		Amenity areas
		Parks
		Reforestation
Composting area for public projects could be required and must comply with "Criteri Ambientali Minimi"	D.M. 10 marzo 2020, n. 63	Gardens
		Adopted public spaces
		Amenity areas
		Parks
		Street trees
		Reforestation
Permeable land surface of at least 60% for public projects is required and must comply with "Criteri Ambientali Minimi"	D.M. 23 giugno 2022, n. 256	Gardens
		Adopted public spaces
		Amenity areas
		Parks
		Gardens

Reduction of the “heat island” effect and air pollution for public projects is required and must comply with “Criteri Ambientali Minimi”	D.M. 23 giugno 2022, n. 256	Adopted public spaces
		Amenity areas
		Parks
		Light-coloured and reflective materials
Reduction of the impact on the surface and underground hydrographic system for public projects is required and must comply with “Criteri Ambientali Minimi”	D.M. 23 giugno 2022, n. 256	Gardens
		Adopted public spaces
		Amenity areas
		Parks
Collection, purification, and reuse of rainwater - with the exception of street trees and reforestation	D.M. 23 giugno 2022, n. 256	Balconies / Gardens
		Adopted public spaces
		Amenity areas
		Parks
Areas equipped for separate waste collection for public projects are required and must comply with “Criteri Ambientali Minimi”	D.M. 23 giugno 2022, n. 256	Gardens
		Adopted public spaces
		Amenity areas
		Parks
If present, urban furniture for public projects must comply with “Criteri Ambientali Minimi”	D.M. 7 febbraio 2023	Gardens
		Adopted public spaces
		Amenity areas
		Parks
		Street trees
Shading devices for public projects must comply with “Criteri Ambientali Minimi”	D.M. 23 giugno 2022, n. 256	Shading devices
Energy performance of buildings for public projects must comply with “Criteri Ambientali Minimi”	D.M. 23 giugno 2022, n. 256	Adequate insulation
		Materials with high thermal mass
Thermal and acoustic insulation must comply with “Criteri Ambientali Minimi”	D.M. 23 giugno 2022, n. 256	Adequate insulation
Natural ventilation is required in all rooms where occupancy by people is expected, even for short periods of time	D.M. 23 giugno 2022, n. 256	Natural ventilation

for pyblic project in compliance with "Criteri Ambientali Minimi"		
Natural daylighting for public projects must comply with "Criteri Ambientali Minimi"	D.M. 23 giugno 2022, n. 256	Natural daylighting
Building Automation and Control System corresponding to efficiency class A, as defined in Table 1 of the UNI EN standard 15232-1, are highly recommended for public projects according to "Criteri Ambientali Minimi"	D.M. 23 giugno 2022, n. 256	Building Monitoring System
Buildings' overall energy needs must be met, wherever possible, by systems powered by renewable sources that produce energy on-site or nearby, according to "Criteri Ambientali Minimi"	D.M. 23 giugno 2022, n. 256	Renewable energy
		Energy storage
		Demand and response programs
		Energy communities
		Geocooling and heat pumps
Mechanical ventilation systems for public projects are required and for in all habitable spaces and must comply with "Criteri Ambientali Minimi"	D.M. 23 giugno 2022, n. 256	Active cooling ventilation
Construction products used in public projects must comply with "Criteri Ambientali Minimi" with regard to recycled content	D.M. 23 giugno 2022, n. 256	All

Table 22. Summary table of operative guidelines.

6. CONCLUSION

This deliverable presents the results of Task 8.4, which focused on identificatying, assessing, and contextualising resilience-enabling energy retrofit interventions for Camerino's historic centre. The work combined systematic extraction of building typologies with hazard-specific clustering and the evaluation of tailored adaptation and mitigation solutions. By addressing both climate-related (heatwave) and geophysical (earthquake) hazards, the study offers a comprehensive understanding of vulnerability patterns and provides a solid evidence base for prioritising interventions.

Methodologically, the approach used in this task adopted a rigorous, data-driven process. Preprocessing of building-level variables, selecting of hazard-relevant features, and employing Gower distance allowed us to capture the mixed nature of the dataset, which included numerical, ordinal, and nominal variables. Clustering with Agglomerative Hierarchical and K-Medoids methods enabled the identification of six distinct building groups for both hazards, while validation indices (silhouette score, Dunn index) ensured internal consistency. For earthquakes, an additional analytical step was included: cluster-specific distributions of damage levels were calculated, linking typological characteristics directly to patterns of structural and non-structural damage. This improved understanding of vulnerability confirmed the particular fragility of certain clusters (e.g., post-2002 mid-rise and pre-1919 masonry structures) while highlighting the relative resilience of others (e.g., older single-storey units).

For heatwaves, the clustering revealed that construction period and exposure to local microclimates (temperature gradients) were decisive factors in assessing risks. Older building clusters with limited thermal performance were more likely to overheat, whereas newer clusters, despite some resilience, often faced challenges related to dense urban morphology. For earthquakes, usability classifications and detailed damage coding further demonstrated how both historic and recent constructions can be susceptible to localised or systemic failures. Overall, these findings emphasise the need for multi-hazard approaches that consider multi-parameters to reflect the combined impacts of age, morphology, and hazard exposure.

Building on these typological insights, the deliverable evaluated a broad set of interventions, originally identified in Task 2.4, against the defined clusters. The ranking exercise employed a participatory, multi-criteria framework, using a 1-to-5-star scale to reflect technical feasibility, heritage appropriateness, and spatial constraints. Results highlighted the universal value of certain measures—such as insulation upgrades, cool/ventilated roofs, fire-resistant materials, and urban greening—which consistently scored highly across all clusters. At the same time, the analysis showed that some interventions, such as balcony/private garden retrofits, monitoring systems, or the creation of large amenity areas, are more cluster-specific, being highly effective in adaptable, lower-density locations but limited in dense historic centres.

Nature-based solutions have become a key part of the adaptation portfolio. Interventions like street trees, parks, and reforestation offer significant co-benefits by reducing heat stress, improving environmental quality, and providing social and psychological benefits. Although they do not directly address seismic risk, their importance in post-disaster recovery, community cohesion, and managing compounding hazards (such as heatwaves after an earthquake) is vital. The emphasis of NBS in this document affirms their role as essential, multifunctional infrastructure that can complement structural retrofitting and technological upgrades.

The integration of hazard-specific typologies with intervention ranking offers a practical decision-support framework for Camerino. By connecting data-driven cluster profiles to targeted solutions, the approach guarantees that interventions are not only technically sound but also sensitive to local context, respecting heritage limitations and spatial realities. This method directly advances the objectives of MULTICLIMACT by linking scientific analysis with operational guidance, helping policymakers, planners, and local stakeholders to prioritise measures that enhance resilience across multiple scales.

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