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An Energy-Resilient Retrofit Methodology to Climate Change for Historic Districts. Application in the Mediterranean Area

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Abstract: Focusing on the uncertainties of climate change and its effects on the built environment, on the energy responsibilities of residential building stock and on the dichotomy between the transformation and preservation of cultural heritage with a long-term perspective, this paper proposes a detailed methodology aimed at managing energy retrofit transformations and preservation actions in historic districts following "resilience thinking." The proposed methodology pursues the traditional process of retrofitting for cultural heritage, and identifies—on building and component scales—a structural process aimed at: (i) recognizing and testing the adaptive qualities of traditional built constructions to climate change based upon the *genius loci* experience; (ii) diagnosing critical energy emergencies which occurred due to historical transformations or exposure to criticalities of climate change; (iii) identifying and managing improvement requirements according to priority levels of transformation (MUERI). The test on a representative case study in the south of Italy (Mediterranean area) highlighted some significant results: (i) the importance of compactness and of light-colored materials in fighting local microclimate alterations; (ii) the pivotal responsibility of roofs in current and future trends in energy consumption, promoting and testing both innovative and traditional solutions; (iii) the reduction into a limited number of buildings cases to assess, solving the complex and various combinations of features, with which suitable solutions and guidelines are associated.

Keywords: resilience; energy retrofit strategy; historic urban built environment; inherent adaptive behaviors; climate change in Mediterranean area; south of Italy

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1. Introduction

1.1. Climate Change and the Urban Built Environment

Today, cities and their built environments characterize the key focus of scientific debate and global management of the effects of climate change. Despite the inherent complexity in assessing cause-effects in the climate change process, the residential sector plays a considerable role because of its relevance as the largest end-use sector worldwide [1], accounting for 24% of total global final energy use [2] and generating 19% of all global 2010 greenhouse gas (GHG) emissions [3], as well as its effects on the health and safety of its inhabitants [4,5].

According to the results of the Intergovernmental Panel on Climate Change (IPCC), the European Commission recognized the need to combine mitigation and adaptation strategies for building stock aiming at managing the growing consumption—due to increasing global temperatures—and emergencies—i.e., for human health and energy supplies—during extreme heatwaves [6]. For this reason, the European community moved to address building deficiencies, e.g., inefficiency of the envelope and energy systems, and to promote the use of renewable energy sources as the main instruments for the long-term mitigation of climate-altering emissions, with the goal of achieving "near-zero energy buildings" (nZEBs) [7]. On the other hand, adaptability strategies aim at limiting or preventing damage due to extreme natural events, above all by improving urban environments—i.e., green and blue areas, as well as controlling vehicular traffic—and buildings, through the introduction of cool solutions and rethinking urban assets according to optimal adaptability features [8]. Furthermore, the monitoring process on the urban scale is recognized as the main instrument to predict, control, and manage extreme events in cities. The World Meteorological Organization (WMO) supported the use of standard and nonstandard stations for this purpose, applying specific guidelines [9].

Most of the adaptive solutions for buildings were derived from an assessment of microclimate alteration studies in cities. The Urban Heat Island (UHI) phenomenon is not related to global climate change, but it can magnify the effects of the global increasing temperatures at the local scale [10,11]. The phenomenon of UHI depends on the combination of technological characters of surfaces (albedo, heat capacity), morphological assessment of buildings (orientation, Height/Width ratio) and anthropogenic heat loads (traffic, industry activities or energy losses by buildings) [12,13].

The combined influence of UHI issues, as well as the relevance of environmental monitoring and the increasing need to decrease energy consumption and GHG emissions suggest the introduction of net zero energy districts as a natural consequence of improvements to multi-buildings systems on a neighborhood scale [14]. Here, the integration of more efficient energy grids (system solutions) also based upon renewable energy and the thermal improvement of the building envelope (technical solutions) support, on a wider scale, the transition toward carbon-neutral cities [15,16]. Several cities have become promoters of wide-scale efficiency and sustainability, supporting multisectorial actions (transportation, public buildings, etc.) with the ultimate objective of influencing new city plans (i.e., Covenant of Major [17]).

The emergency in European cities is especially pronounced in the Mediterranean area, where the combination of a hot summer climate, future increasing trends, and the probability of heatwaves will overwhelm energy systems and have consequences for human health and indoor/outdoor comfort [18,19].

The scientific community has tested and promoted several building solutions aimed at enhancing the envelopes of buildings, i.e., correcting energy and optical performance, by means of:

- Reflective materials and cool roofs based on the maximization of solar radiation reflection and dissipation. Thus, cool materials represent efficient solutions for mitigating both local overheating air and temperatures of building surfaces. In Europe, cool roof potentialities have been supported by Synnefa and Santamouris [20–22] and the European Union, promoting the Cool Roofs Project and establishing the European Cool Roof Council (ECRC). The effectiveness of cool roofs in Mediterranean residential buildings was analyzed by [23–29];
- Reflective products combined with phase change materials (PCMs); specifically, in addition to the positive effect of cool materials, researchers have combined latent heat storage materials with solar reflective materials to reduce and delay the peak heat load, leading to important energy savings and improving thermal comfort conditions [30]. Relevant research in testing and applications in the Mediterranean area have been described in [30–33];
- Green roofs are currently considered a key technology to interplay with outdoor air conditions in order to mitigate the UHI phenomenon [10,34] and improve the thermal and energy performance of the built environment, both during the summery and wintry seasons [26]. As with previous solutions, green roofs were fully tested and discussed for residential buildings in the Mediterranean area in [35–40].

1.2. Historic Districts in Mediterranean Cities and Resilient Strategies for Climate Change

In Europe, 35% of buildings are 50 years old, 14% were built before 1919, and 12% were constructed during the period 1919–1945 [41]. Most buildings are aggregated and refer to the "old core" or "historic center" of cities, currently constituting the urban landscape value of cities [42]. Buildings in historic districts have specific socio-economic relevance for the reuse of residential building stock [43] in cities, as well as socio-cultural significance of historic and formal value [42,44] and environmental weight as local and traditional examples of interactions between the necessity to accommodate "home" needs, i.e., health, safety and self-sufficiency, and external territory conditions [45,46]. Due to these features, residential buildings assessed in historic districts constitute an exception in terms of management, planning, and transforming necessity, as well as in mitigation strategies [47].

Mediterranean traditional buildings are usually considered "sustainable" and energy-efficient due to their arrangement in compact districts [48,49] and to the use of specific architectural "types" [50–52] or technical "solutions" [53,54] on the building scale. However, the current energy emergency, the comfort requirements for users, and in-progress environmental changes can threaten this concept [55,56]. In fact, the latest study by the Building Performance Institute of Europe (BPIE) affirmed that practical restrictions in energy improvements on historic buildings depend on overarching authorities, whereas heritage buildings—even if not directly listed as such—are not excluded by mitigation strategies. Thus, the BPIE suggests moderate renovations [41]. However, the energy retrofit activities in historic buildings are considered challenging because of the necessity to solve le balance between the "invasive" nature of some actions and the preservation requirements for buildings values [57,58].

Several European projects have proposed solutions, technologies or specific methodologies for historic buildings; however, most of them have been focused on single case studies [59–62] or have highlighted the relevance of bioclimatic characteristics in specific traditional cases (e.g., Trulli) [63,64] as inherent capacities to adapt to the environmental conditions.

As far as the adaptation process is concerned, cultural heritage was discussed in the IPCC dissertation in the context of the effects of extreme weather events on material preservation (e.g., damage due to thermal stress), changes in the traditional flux of tourists during the summer period and the maintenance of collections in museums [65]. Some scientific European studies and projects (AMECP [66], LASERACT [67], No-ah's Ark [68], Friendly Heating [69], OnSiteforMasonry [70], SMooHS [71], Climate for Culture [72]) have focused on the effects of climate change on listed heritage, highlighting the necessity to assess buildings during different periods and in different locations in Europe by using comparable instruments for weather conditions to provide a classification system at the required scale. These issues were supported by the use of local climate data derived from weather tools such as Meteonorm [73], and using building typologies to provide their categorizations according to the energy requirements with a long-term perspective. However, residential buildings are excluded from case studies.

Even though historic districts are part of cities, the concept of the near-Zero Carbon District appears distant for them, above all due to the fact that the integration of renewable sources at the district scale is in conflict with "regulation barriers" [74].

1.3. The Work Aim

Starting from the scientific overviews which exist in the literature, the energy improvement of residential buildings in historic districts should be related to the uncertainties of future climates and inherent adaptive features, supporting the formal representativeness of these contexts, both on single building and district scales. In a resilient perspective, these buildings are themselves part of the sources to be preserved, guaranteeing their long-term use; moreover, energy improvements should address the necessity to transform such buildings, safeguarding their value. In this sense, inherent adaptive features and consequent deficiencies need to be identified in order to assess the behavior of the whole traditional built environment faced with external climate variability and energy shortfalls.

Finally, in order to address the multiple combinations characterizing these historical transformation processes, the identification of "types", as virtual models of recurring and representative forms, technologies and performances of built heritage, is a key strategy.

Herein, a robust methodology for the retrofitting of buildings in historic districts is proposed, incorporating the mitigation and adaptations actions which are required from the district to the building scale, and promoting integrated and structured actions. The combinations seek to ensure the homogeneity of the results of solutions, and optimization of the regeneration strategies on the district level, as well as in logistics management on the same scale. The methodology does not support the creation of energy district models, but aims to identify energy priorities for interventions according to buildings types, taking into account: (i) the peculiarities of each case and their changes over the time; (ii) inherent qualities of adaptation to climate change derived by the *genius loci* experience; and (iii) potential use of nontraditional (technical) solutions and technologies, with formal value preservation on the building scale. These issues are in line with two of the Sustainable Development Goals (SDGs) [75], i.e., 11: to "Make cities and human settlements inclusive, safe, resilient and sustainable"; and 13: to "Take urgent action to combat climate change and its impacts".

A discussion of the proposed methodology in presented in Section 2; this methodology is tested on a representative case study in Section 4. In between, there is a subsection for each phase of the methodology (Sections 3.1–3.6). Finally, supporting results and future research scenarios are presented in Section 4 (Discussion and Conclusions).

2. Materials and Methods

Actual and future conditions on the local and microlocal scales in urban areas amplify the complexity of managing the recovery process in historical districts aimed at preserving the peculiarities of these built environments, above all, in some Mediterranean areas. Here, the high incidence of such buildings and the likelihood of experiencing heatwave conditions in the summer period coalesce to create a unique context for energy analysis. From an energy-resilience point of view, the proposed methodology is based on the necessity to start thinking about a system of activities intended to cope with actual challenges of the climate change, as a precrisis phase. In light of previous experiences in energy retrofitting to historic buildings and the widespread activities aimed at matching adaptation and mitigation actions on residential stock, a methodology tailored for buildings in historic districts is discussed. Specifically, it follows the refurbishment process for the built heritage and the required features of *resilience thinking* to highlight the complexity of the strategy.

As a general necessity, different levels of detail are applied, linking the local features to energy behaviors on the building scale, and the necessities of buildings to the priorities at district level. However, the *file rouge* is the necessity to outline a dynamic process in terms of knowledge, diagnosis and transformation phases as a circular method to recognize adaptability and transformability features.

The need to guarantee the persistence of values is managed to apply a closed process of analysis that connects the *capacity to learn*—as the first phase of "knowledge" of values—and the *dependency of local resources* from the district to the buildings scale in assessing transformation solutions—as new and final systems (Figure 1). Additionally, the evolution of external conditions is addressed by introducing a monitoring process as a control parameter for the climate and local microclimate; this provides instrumental support for the methodology in recognizing inherent qualities—e.g., bioclimatic characteristics—and local vulnerabilities. The "diagnosis" phase is structured according to the need to test inherent adaptive behaviors—e.g., the inherent energy *responsiveness* level of the system—in addition to the traditional shortcomings in terms of energy performance. Finally, the "intervention" phase includes recognition of the *resourcefulness* of the system, i.e., the ability to accept new materials aiming at the improvement of the critical properties. Here, the potential for transformation is supported by codes of suitable interventions following the need to undertake the transformations in an overarching way and giving technical sustenance in selecting materials and solutions aiming at the guidelines to "how to do it" [76,77].

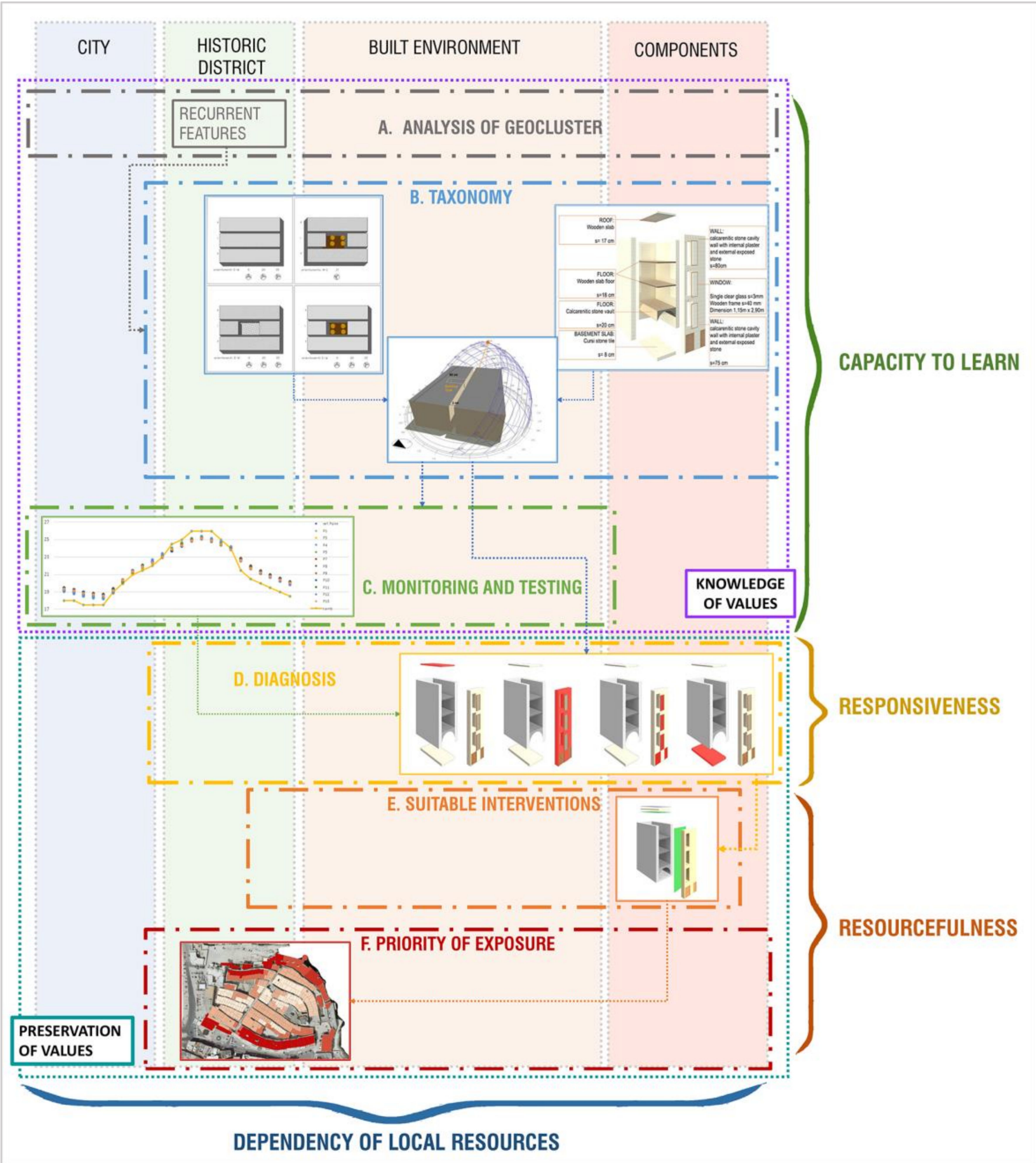


Figure 1. Resilient perspective applied to the phases of the proposed methodology.

Due to the relevance of these districts as systems of buildings, open areas and environmental conditions, the proposed methodology was developed following a multiscale approach. It is predicated upon the need to first identify the relationships between the environmental conditions (microclimate, pollution, regional climate), the regulation framework (national, regional and municipal) and the system of buildings, and finally, the representative building types. An assessment of interventions and a characterization of homogeneous systems needs to focus firstly on the component scale, and then on the district one.

The phases are as follows:

A. *Analytic Phase* (Figure 2), involving a systematic investigation of environmental (Ae), architectural and construction (Ac) features and regulation norms for energy improvement (AnE) and preservation (AnP) on different scales. Notably, data are classified into specific fields, as follows:

Ae *Environmental* field, for the investigation of:

Ae1.a *Typical and actual local climate* features including statistical and historical monitored data used for the classification of typical climate on national, regional and local scales; focusing on the latter, the support of research activities in other fields, when applicable, can strongly support the management and collection of more detailed data;

Ae1.b *Projection of the local climate*, referring to the stochastic global changes introduced in IPCC scenarios;

Ae2 *Historical development of the district*, focusing on the main characteristics of the use of land over time for development;

Ae3 *Urban assessment and state of use*, focusing on the use of buildings, services, energy distribution grids and traffic regulations;

Ac Architectural and construction features, as analyses of:

Ac1 *Morpho-typological characteristics of buildings* on a district scale, referring to height, typologies and relationships with the asset of the districts; these data may be collected using archival and bibliographic records, and through on-site investigations;

Ac2 *Codification of building features* in a *Table of categories of systems and subsystems categories* which assess the predominant technologies and materials of the built envelope and energy systems in order to define possible transformations; in this case, direct on-site tests (stratigraphy, material properties) may be required;

Ac3 *State of maintenance and the actual state of use* of the residential stock on the district and building scales;

Ac4 *Energy systems* available on the building scale, focusing on cooling and heating, when data are available. Energy systems are translated in specific alphanumeric codes, providing the *Ac2* collected features in the *Table of systems and subsystems categories*.

An *Energy improvement* (**AnE**) and *Preservation regulations* (**AnP**) from the national to local scale, toward compliance with the national normative framework; overlapping built features and preservations thresholds, a *Table of values* is useful to summarize the provided data.

The systematic collection of data will enrich the GIS 2D model, derived by regional or national scans, which constitutes the main database of information.

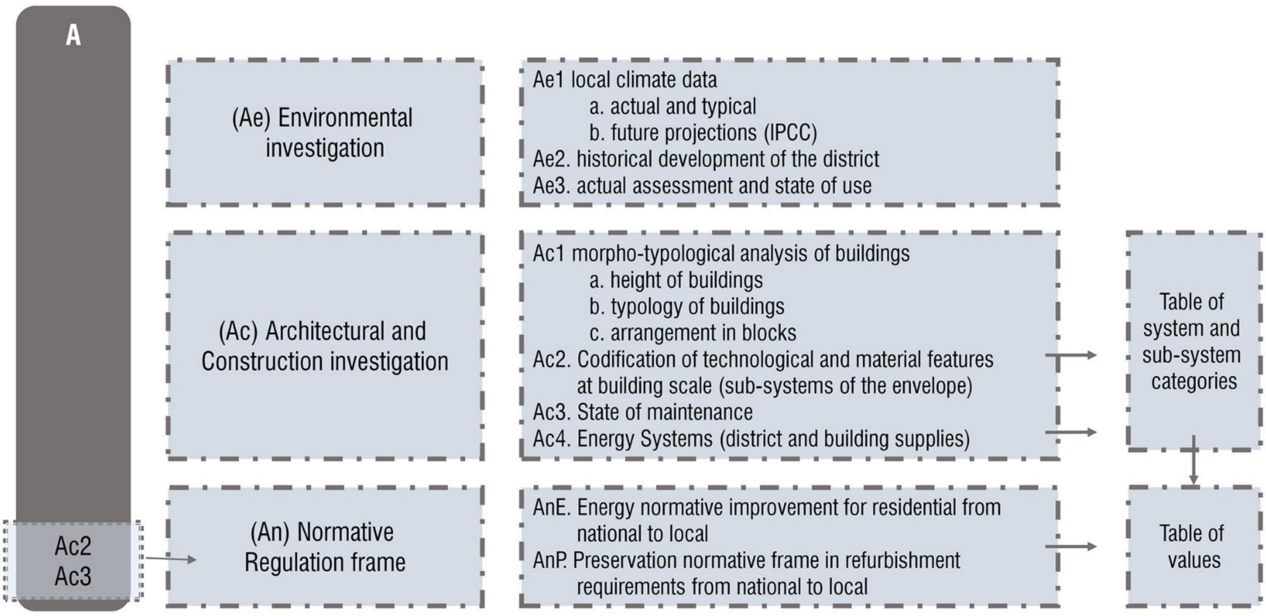


Figure 2. Methodological schematic of the Analytic phase (A).

B. The *Taxonomy phase* (Figure 3) represents the codification of all the data collected in the previous phase aiming at identifying a limited number of illustrative cases to support the aim of extending the results to similar cases and to analyze their representativeness. In fact, the "types" should be representative of different levels of information and interactions of the system and its elements with the environment, aiming at:

B1. *Characterization in the Local Climate Zone*, as the first macro-parametrization of the whole district using the LCZ characterization process [13]; in particular, the district is analyzed focusing on the geometric and surface cover features, and thermal, radiative and metabolic properties collected in *Ae2, Ae4, Ac1*, to provide a building surface ratio (%), impervious and pervious surface ratio (%), average Sky View Factor (-), average building height [m], aspect ratio (-), roughness length (classes), surface admittance [$J/(m^2\ s^{1/2}\ K)$], surface albedo (-) and anthropogenic heat gains [Wm^{-2}];

B2. *Characterization of "Canyon Type"* as the result of a detailed analysis of data collected in *Ae3, Ae2* and *Ac3;* it aims at delineating a system of representative street canyons in terms of main orientation (cardinal) and geometrical features, i.e., aspect ratio (H/W), Sky View Factor (SVF) and local alteration of the street canyon distribution in the district, as well as information on the street canyon surface materials (pavement of streets, walls and roofs of buildings).

B3. *Characterization of "Building Type"* resulting from the taxonomical analysis of predominant use, height, geometrical and material features and construction techniques identified in detailed subphases of *Ac*. This *Type* presents the minimum representative element of whole interactions, and is useful for identifying transformation strategies.

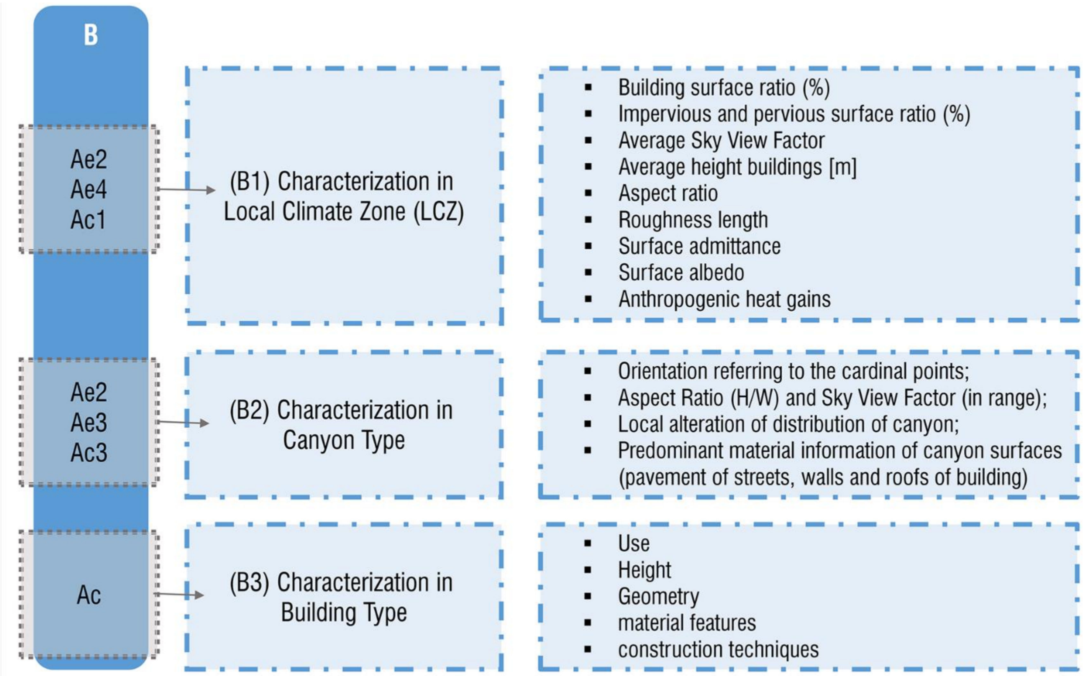


Figure 3. Methodological schematic of the Taxonomy phase (B).

C. *Monitoring and Testing phase of local behavior* (Figure 4) constitutes the main instrument with which to monitor external dynamic processes in the long-term and, relating to the present, to provide a connection between taxonomy and diagnosis on different scales. For these reasons, it represents the main phase of the methodology aimed at the recognition of inherent qualities (adapting ones) and vulnerabilities. For this phase, two steps are considered:

C1. *Monitoring of local microclimate* is the main instrument for the identification and assessment of relationships between building arrangements in historical districts and the local climate. In fact, according to the difficulty of identifying real and local behavior, measures should be taken to provide a system of comparable measurements between standard and similar instruments in different physical positions. Moreover, it could be useful to compare the representativeness of measurements with the LCZ classification on the district scale. To these ends, WMO guidelines should be followed to achieve a robust campaign, following practical reference indications; specifically, the measure points should be located at a comparable height and use a specific system to limit errors and overheating of the sensors; focusing on the choice of site, three measure points should be determined, taking into account:

- The choice of representative measurement points (E1) inside the historic center; following the identification of the "*Canyon Type*" in phase *B2*, this monitoring point should be representative of the widespread characteristics, avoiding local exceptions (geometry, materials);
- An external measurement point (E2) in an undisturbed area; such a zero-reference point must be representative of the exposure of local weather conditions;
- A comparative point (E3), located externally to the historic district, that is representative of the rest of the city and referring to an intermediate point between the historic district and external undisturbed conditions.

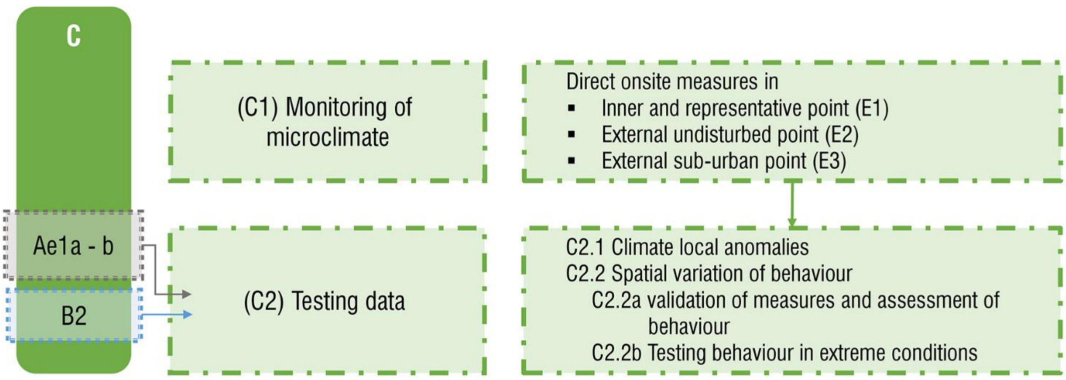


Figure 4. Methodological schematic for the Monitoring and Testing phase of local behavior (C).

C2. *Testing Data* aims at the assessment of exceptions in local climate conditions and system behavior due to of local differences on a district scale. For these purposes, monitored data may be analyzed:

C2.1 Temporally, aiming to identify *local anomalies*, relative to historical data;

C2.2 Testing *Spatial variation of behaviour*, using monitored data to check the reference point of measure (E1) and its horizontal variations by means of ENVI-met©. The district is modelled with the objectives of:

C2.2a Firstly, testing the reference measure point to *validate horizontal measurements*, using and calibrating physical features of materials (*Ac2*) at the street canyon scale, and then extending the test horizontally to the wider district model;

C2.2b *Testing behavior in extreme conditions* (if measured in *C2.2b*) on the same model; in this case, the recognition of extreme events follows the definition of the Warm-Spell index [78], and provides the opportunity to assess adaptive behavior in the reference point and the differences on the district scale, changing from typical to extreme conditions.

D. The *Diagnosis phase* (Figure 5) concerns the study of energy consumption according to building type. Recognition of typical microclimate and local exceptions in the district and the physical and thermal features of the building envelope makes it possible to assess energy deficiencies and building pathologies, on one hand, and to recognize distinctive features of the original fabric, such as interactions with microclimates and the inherent qualities of the building, on the other. Specifically, diagnoses are the result of an iterative process of energy consumption variations, aiming at the characterization of behavior in term of:

- **D1.** *Reactions to climate change projections*, referring to the different statistical weather conditions analyzed in phase Ae1.b, in order to determine the long-term potential of energy improvements;
- **D2.** *Reaction to the local microclimates* based on the reference point data and the generated microclimates along street canyons, as observed in *C2.2*. In this subphase, energy qualities and adapting features, as well as energy deficiencies, are assessed both at the street canyon and building type scales, focusing respectively on microclimate variations and the properties of the envelope subsystem.

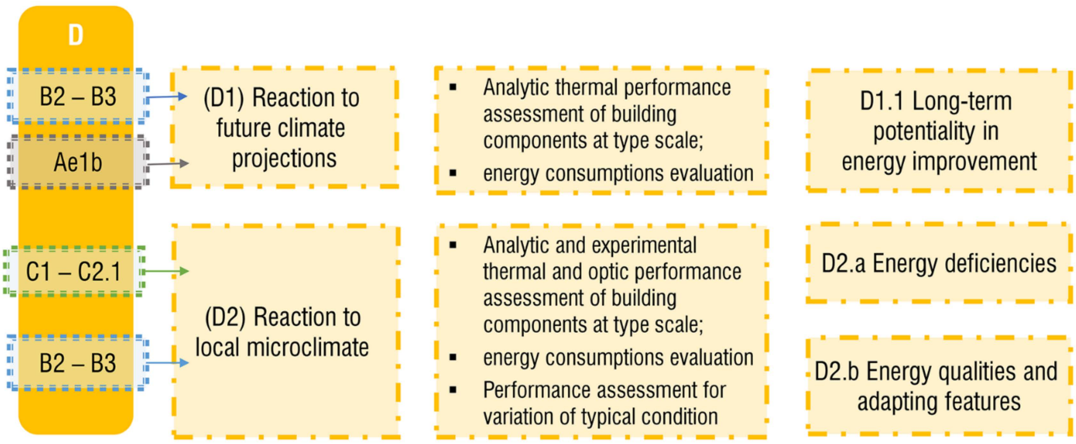


Figure 5. Methodological schematic of the Diagnosis phase (D).

E. *Taxonomy of suitable interventions* (Figure 6); here, all the deficiencies delineated in the previous phase are assessed in terms of possible transformation of the system and preservation regulations (*AnP*). Specifically:

- **E1.** According to *resilience thinking*, the "transformability" of a building describes the capacity to correct its present vulnerabilities. The definition of *Transformation Degree*, namely the building attitude to be modified without altering its historical and architectural features, is introduced as the combination of the state of maintenance (*Ac3*) and the formal values (*AnP*) on a building scale;
- **E2.** As the second step, transformation solutions are combined with preservation codes, as a *System of suitable interventions*, referring to the mitigation and adaptation of technical solutions; in particular, the developed solutions for each critical building component are conceived as design guidelines and best practices to be translated into the selection of technological solutions, based on both traditional and innovative products and systems for energy efficiency. The solutions are chosen to address energy deficiencies according to weaknesses, with present-day and long-term perspectives, in order to safeguard the appropriate qualities.

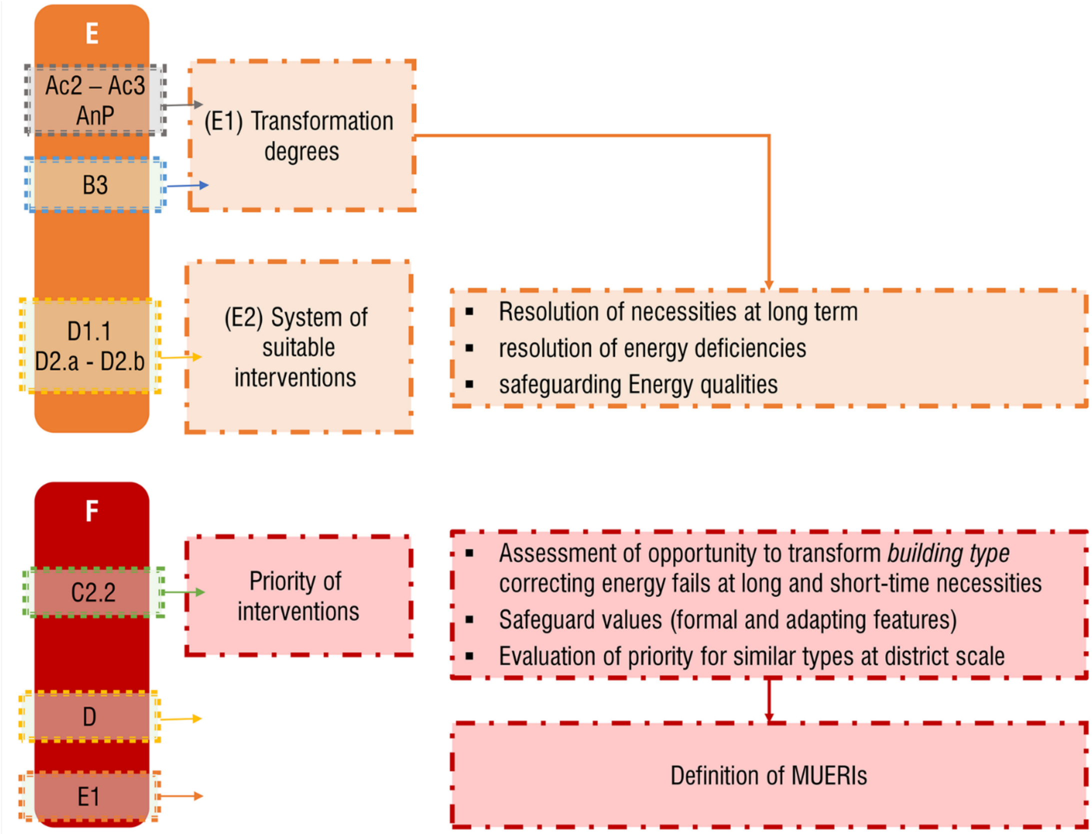


Figure 6. Methodological schematic of the Taxonomy of suitable interventions (E) and Assessment of priorities of intervention (F) phases.

F. *Assessment of priorities for intervention* (Figure 6) on the district scale, delineating an integrated system of recurrent "resilient" units. In this sense, different levels of adaptability on the street canyon scale, as defined in *C2.2*, and the transformability of vulnerable elements on the building scale serve to identify different combinations of "*Minimum Unit of Energy-Resilient Intervention*" (MUERI); these units should help in creating scenarios for the overall regeneration of homogenous urban/building areas, involving common priorities and controlled actions supported by technical datasheets. Notably, datasheets include all the information about MUERI type in terms of location, exposure level, transformability degree of the envelope subsystems, etc. Additionally, it can be useful to schedule and guide transformations.

In the following section, the methodology is applied to a pilot case in the south of Italy.

3. Results of the Case Study

As discussed in the previous sections, the proposed methodology supports the energy retrofitting of buildings in historic districts. In order to validate the proposed approach, a case study in the Apulia region (South of Italy) was chosen as representative of coastal ancient centers in this area, partly due to the detailed data about the whole district which had been previously collected [79]. In detail, the case study is the historic district of Molfetta, located 25 Km north of Bari (Figure 7). Its representativeness lies in its compact and dense urban arrangement and the prevalent use of local calcarenitic limestone.

Figure 7. Location of Molfetta (**a**) and the position of its historic center (**b**) (base source: Google Earth, modified by the authors).

As noted in the methodology discussion, all the collected data are inserted in the basic 2D GIS model of Molfetta derived from the regional cartography [80].

In the interest of brevity, some results from previous activities are simply described, introducing references of previous works.

3.1. Analytic Phase (A)

Here, an analysis of the environmental (Ae), architectural and constructional (Ac) features is presented, and the regulation norms for energy improvement (AnE) and preservation (AnP), from the regional to the building scale, are discussed.

Molfetta has a hot summer (**Ae1.a**) Mediterranean climate (Csa), consistent with the climate of Apulia. Winds from the west at 5–7 knots are considered representative throughout the year, although wind is less frequent during the summer. Typical weather data from Meteonorm from 2000–2009 in Molfetta [73] were compared with local data. The latter comprised measurements taken in 2017 at an urban standard station of ARPA Puglia (Regional Environmental Protection Agency of Apulia) (ARPA_2017), located in a residential/commercial subdistrict of Molfetta. As reported in Table 1, the statistical weather data (Meteonorm_Act) differed little from local data, and thus, were considered acceptable for the following analyses.

Table 1. Comparison between mean monthly temperature dataset of the urban standard station (ARPA_2017) and statistical weather data from Meteonorm (Meteonorm_Act) [°C].

	Jan	Febr	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Meteonorm_Act	9.1	9.1	12.5	16.9	20.6	24.6	28.2	27.3	22.1	18.8	14.6	10.6
ARPA_2017	8.8	8.8	12.1	16.3	20.2	24.2	27.7	26.9	21.9	17.6	13.9	10.7

As the second step of the Ae1, the statistical weather data (Meteonorm_Act) were transformed using the IPCC algorithms, referring to 2030 and 2050 periods and the A2, A1B, and B1 scenarios (**Ae1.b**). As the main results of the analysis, it was found that increasing temperatures during cold periods will support the reduction of energy usage for heating, whereas during spring and summer, cooling requirements will need to be studied separately.

Regarding historical development (**Ae2**), the historic district of Molfetta has a medieval center inside a boundary wall. From the Angioin period (14th–15th century) to the 17th century, the historic district was recognized. It follows the NW–SE axis in the city center. Development along the N–S axis of the city center was the result of construction during the 1930s. Then, a phase of abandonment of residential buildings occurred and the municipality made efforts toward preservation; additionally, some extreme and disruptive events during the 1960s–1970s modified the layout of the district. Notably, the transformed layout created "close gardens" featured by low density of vegetation and carousels, intended to serve as public spaces; these gardens were built inside the walls of collapsed buildings allowing to preserve the original plan asset (Figure 8). These spaces are characterized by paved surfaces with a low percentage of pervious surfaces. A second urban variation was the creation of a paved square that replaced further collapsed buildings, erasing part of the district asset and creating large fronts (Figure 8). Today, the district is predominantly residential, with a few special purpose buildings (churches, city halls, tourist accommodation, etc.) (**Ae3**).

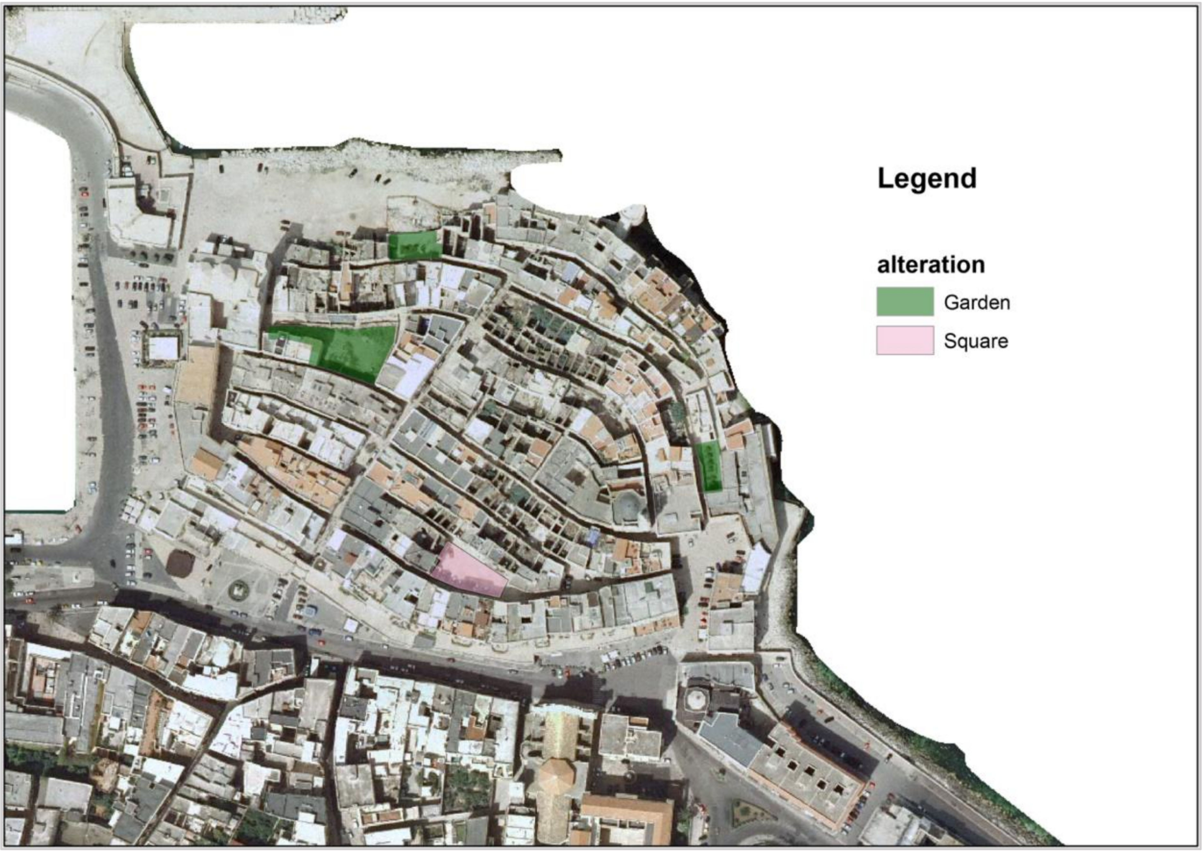


Figure 8. Overview of the historic district of Molfetta and local alterations of the ancient asset of the district after 1960s–1970s.

Finally, as a common element, the old core of Molfetta is characterized by traditional calcareous paving, using irregular, square stones with a thickness of 15–20 cm, providing an impervious surface.

Regarding the architectural and construction features, the *Tower house* was recognized as the prevalent typology (**Ac1**); this is characterized by vertical development with a simple plan, i.e., with only one room per floor, and vertical connection via an inner staircase. The heights of the Tower houses vary from 11.5 to 15.5 mt [79].

Occupied buildings are well maintained, while some long-abandoned structures are in a state of decay (**Ac3**). Regarding the building types and their codification (**Ac2**), representative features at the subsystem level of the envelope may be summarized as follows:

- Masonry, i.e., compound walls, are typically thick (50–90 cm) and made of calcarenitic squared blocks; inner façades are always plastered, while external ones are prevalently unplastered (Wa2) with few exceptions (plastered—Wa2);

- Ceilings vary in material and construction depending on the position; usually, a barrel vault divides the ground floor from the first one, which may or may not be plastered (Cg1 and Cg2, respectively); the inner ceilings are thin and feature wooden beams; finally, roofs are usually like inner ceilings (wooden) (Cin) with different external finishes;
- On the ground floor, the basement slab is made of concrete and is placed above a layer of stone blocks and gravel (Bf);
- Windows represent a low percentage of the opaque envelope (max 10%) according to the need for low exposition to solar radiation in a hot climate; generally, windows have a wooden frame and double-glazing (Wi1).

Some elements of the envelope had been modified, for example:

- Some roofs have external paving using calcarenitic stone tiles (Cex.b), called "chiancarelle" or "cotto" (Cex.a) tiles, or a waterproof membrane (Cex.c); the aforementioned tiles were used as a substitute for the original calcarenitic tiles. In terms of performance, these roofs display similar transmittance values (by the static sublayer) and differ in terms of their optical characteristics due to the external layer; albedo values vary from 0.1 for bituminous surfaces (Cex.c), 0.4 for "cotto" tiles (Cex.b) to 0.6 for stone pavement (Cex.a). The loss of the original characteristics cannot be attributed to administrative negligence, but rather, to widespread poor conservation;
- Windows present a common level of transformation; even if the wooden frame is preserved, original single glazes have been widely substituted with double ones.

Overlapping categories exist among the subsystems and national and regional laws for preservation (DD 42/2004 and PPTR—Regional Landscape Plan called "Piano Paesaggistico Territoriale e Regionale") (**AnP**); see Table 2.

Table 2. Table of Values (AnE) for buildings in the historic district of Molfetta.

Built Element	Code	Preservation Action	Preservation Code
Building scale			
Wall	Wa1	Substitution of plaster not avoided Covering of stone detail avoided Use of clear colored plaster	V.Wa1
	Wa2	Maintenance of exposed stone Covering avoided	V.Wa2
Window	Wi1	Maintenance of wooden frame Observance of dimensions Substitution of glasses not avoided	V.Wi1
Ground floor ceiling	Cg1	Substitution of plaster not avoided if lacking decorations	V.Cg1
	Cg2	Maintenance of exposed stone Covering avoided	V.Cg2

Table 2. *Cont.*

Built Element	Code	Preservation Action	Preservation Code
Roof (inner)	Cin	Maintenance of wooden beams Covering avoided Overloading avoided	V.Cin
Roof (external)	Cex.a	No action on external surfaces Preservation of wooden subsystem	
	Cex.b	Maintenance of stone tiles Replacement avoided	V.Cex.b
	Cex.c	No action on external surfaces Preservation of wooden subsystem	
Basement slab	Bf1	Maintenance of stone tiles Replacement avoided	V.Bf1
District scale			
"Basole"	B1	Maintenance of stone tiles Replacement avoided	V.B1

Finally, regarding energy properties, buildings are characterized by poor thermal properties compared with normative thresholds (**AnE**). Additionally, optical properties (albedo and emissivity) were analyzed for each external subsystem; see Table 3.

Table 3. Optical properties for walls and roofs in tower houses located in the historic district of Molfetta.

Code	Albedo	Emissivity
Wa1	0.60	0.95
Wa2	0.5	0.9
Cex.a	0.4	
Cex.b	0.6	0.9
Cex.c	0.07	

Referring to energy grids (**Ac4**), the penetration of cooling systems already affected buildings as a clear necessity at this latitude and it depends on the availability of electricity. Regarding heating, all the buildings are linked to a methane grid thus, all them are supposed to be equipped with heating systems that use this source. Nonetheless, for both heating and cooling, differences existed in terms of technology (inverter or on-off control for cooling and traditional or condensing boiler for heating); however, in the absence of other details, the period of installation was used as a reference (Table 4).

Table 4. Categories for heating and cooling systems in tower houses located in the historic district of Molfetta.

S_H	Heating System	S_C	Cooling System
S_H.1	condensing boiler	S_C.1	air conditioning with inverter technology
S_H.2	new gas-fired boiler	S_C.2	air conditioning with on-off control

3.2. Taxonomy Phase (B)

The *Characterization in Local Climate Zone* (**B1**) on the district scale comprised a study of geometric, thermal and optical features, according to the LCZ classification (Table 5):

- High geometric compactness, considering the aspect ratio, i.e., the relationship between height (H) and width (W), H/W, of the street canyon–air volume, and the sky view factor (SVF), i.e., the ratio of the amount of sky visible from ground level. H/W was prevalently high (>3.5) while SVF values varied among very narrow street canyons (<0.1), narrow ones (0.1–0.2) and open spaces (0.3).
- The low permeability of the district due to the high building ratio (62.1%) and low pervious ratio (2.5%).
- The prevalent materials, recognizing calcareous stone as one of the main features of the district (for horizontal surfaces and walls).
- Finally, the energy loads were characterized by a zero value for anthropogenic heat due to the absence of vehicular traffic.

Table 5. Characterization of the historic district of Molfetta according to its geometrical and morphological features.

	Building Surface Ratio (%)	Impervious Surface Ratio (%)	Pervious Surface Ratio (%)	Average Sky View Factor		Average Height of Buildings [m]	Aspect Ratio (H/W)	Roughness Length
Molfetta	62.1%	35.4%	2.5%	Very Narrow street canyon	<0.1	11.5	>3.5	skimming
				Narrow street canyon	0.1–0.2			
				Open spaces	>0.3			

Consequently, characterization on the street canyon scale (**B2**) followed the LCZ parametrization and recognized a street canyon in the south-west part of the old town as the representative one (*Canyon type*). A SVF value lower than 0.1 and H/W > 4, combined with an orientation of 20 or 35° along the E-W axis, unplastered walls, bituminous roofs, and calcarenitic stone tiles for the external pavements characterized the street *Canyon type*.

Finally, as a result of the taxonomy process, a characterization of the envelope (**B3**) for Tower houses showed a recurrent combination of construction materials and physical properties (Table 6). The energy deficiencies which result from such a combination are reported in Table 6 (AnE), based upon previously collected data [79].

Table 6. Geometric, thermal and optical features of each component in the building type of Molfetta.

Building-Type	Comp. Code	Component	Thickness [m]	Current Thermal Conductance [W/m^2 K]	Pase Shift τ/ Attenuation of Thermal Wave σ	Normative Threshold [W/m^2 K]
Middle Tower house	Wa2	Wall	0.75	2	12h/0.7	0.38
	Cex.c	Roof	0.17	2.83		0.36
	Bf1	Basement slab	0.08	1.83		0.40
	Wi1	Window	-	5.40		2.40

3.3. Monitoring and Testing Phase of Local Behavior (C)

As discussed in the methodology, the on-site measurements (**C1**) need to be representative of the analyzed district, taking into account the location but avoiding local and unrepresentative elements, and taking care to observe the correct positions between points of reference. The inner measurement point was located in the defined representative street canyon (E1) while the outer one (E2) corresponded to the Harbor Master office, located along the dock. The measuring phase followed a structured protocol of measurements at nonstandard stations. In particular, these stations were created using a wooden envelope (20 × 20 × 20 cm) as the shading element for the measuring device; to limit overheating, surfaces were painted white, and openings (two 1 cm wide slits on each face) were created around the envelope to ensure internal ventilation. Inside, a RH/temperature datalogger, model EL-USB-2 of Lascar electronics (resolution 0.5 °C, Accuracy 0.55 °C), was suspended to reduce measurement errors due to superficial changes. The measurement protocol was applied during the summer of 2017, recording temperatures and RH every hour from March to October. The E3 measurement point was located near the ARPA station, i.e., about 0.823 and 0.937 km from the E1 and E2 stations, respectively. Measurements from this station served to validate the instruments.

According to the goals of testing subphase (**C2.1**), local climate anomalies were found by comparing historical data series recorded in Molfetta during 2009–2016 and the experimental period (2017), using ARPA standard station measurements. Anomalies were identified according to the Warm Spell Duration Index (WSDI), as defined by ET-SCI [78]. The WSDI describes extreme events merging the intensity of higher temperatures (warm-spells) and their duration, assessed as the number of days in intervals of at least six consecutive days in a specific period according to the formula:

$$TX_{ij} > TX_{ib90} \quad (1)$$

where TX_{ib90} is the calendar day 90th percentile centred on a 5-day window for the base period b, and TX_{ij} is the daily maximum temperature on day i in period j [78]. Three warm spells were recognized during the analyzed period: a three-day period at the end of June with an intensity of +5 °C, a two-day stretch in July with intensities of +1 °C, and a three-day period of +3 °C in August.

Then, the monitored data using nonstandard stations were assessed according to the goals of the **C2.2** subphase. Firstly, E1 and E2 measurements were compared to identify trends and highlight some specific issues (Table 7), as follows:

- A consistent reduction of temperature during the day, i.e., $\Delta T_{maxE1\text{-}E2} \approx -1.5$ °C, generated by the high compactness level of the built environment;
- In contrast, there was a nocturnal UHI effect, i.e., $\Delta T_{minE1\text{-}E2} \approx +0.5$ °C, as a direct consequence of this compactness; in this case, the closeness of districts and the absence of wind decreased the heat exchange. Moreover, the nocturnal effect depended on the reflectiveness of surfaces that could not exchange the longwave radiation;
- Finally, a shrinking effect of temperature variations during the day, expressed as variations in the standard deviation between monthly temperatures ($\Delta\sigma_{E1\text{-}E2} \approx -1$).

Table 7. Maximum (T_{max}), minimum (T_{min}), mean (T_{mean}) temperatures and Standard Deviation (σ) of hourly measurements at representative points of comparison (E1—inner point of measure, E2—Outer onsite point of measure, P1 and P2—open areas, P3 halfway canyon)—(17 August).

Measure Point	T_{Max} [°C]	T_{Min} [°C]	T_{mean} [°C]	σ
E1	33.00	24.70	28.15	2.75
E2	34.5	23.50	27.75	3.85
P1/P2	33.40	25.55	28.65	2.55
P3	33.30	25.10	28.40	2.95

In order to evaluate variations of behavior in the built environment, the whole district was modelled using ENVI-met®. The model had a 2 mt grid resolution with a final extension of 150 × 170 × 25 grids; optical and thermal properties were introduced based upon information collected in analysis phase (Table 3); finally, computational fluid dynamics (CFD) analyses were performed using daily outer conditions (E2 measurements). Notably, for all the monitored period, one day for each month was chosen considering its representativeness at the monthly scale (mean, maximum, minimum temperatures, anemometric features). Details of the simulation tests and the results for the analyzed day are reported in Appendix A. Focusing on the results, the inner microclimate alteration refers to the external point of measure (E2) and it was homogeneous throughout district; in fact, daytime temperatures were similar in every narrow street canyon, underlining the insignificant effects due to compactness or variations in the orientation of the blocks and finishing materials. This effect directly depended on prevalent shading in the district, creating a low level of interaction between wall features and district temperatures. At the same time, the use of a good reflective pavement ($\alpha = 0.6$) contributed to a reduction of temperatures during the day, while different materials on roofs did not generate interactions with the air in the street canyon. However, some remarks could be made, above all regarding the nighttime measurements (Table 7):

- By increasing SVF in open spaces (as the superior extreme value in garden P1 and square P2), different temperature values were found; the open spaces were characterized by a temperature difference of nearly +1 °C at night time because of the higher solar heat storage during the day and the lower dissipation during the night due to low wind intensities; during the day, temperatures in open spaces reached a difference of nearly 0.5 °C; therefore, open spaces were characterized by an increasing mean daily temperature (+0.5 °C) and a higher reduction in the standard deviation of daily temperatures (compared to street canyon E1);
- A halfway condition is highlighted in street canyons where SVF and H/W values (e.g., P3) varied between narrow and open space cases; even if good shading properties ensured similar temperatures during the day and a comparable standard deviation of daily measurements (compared with narrow reference street), during the night, temperatures increased (+0.5 °C);
- Finally, in addition to simulations for inner points of the district, boundary blocks had similar conditions to the Harbor Master office measurements.

Therefore, four levels of microclimate reactions were introduced to correlate the inherent summer behavior of each street canyon:

- R.1 refers to narrow street canyons where both nocturnal and daytime temperatures were modified, compared to external ones (E2);
- R.2 concerns middle street canyons, where only nocturnal conditions differed;
- R.3 describes open areas where temperature conditions were affected both in maximum and minimum conditions;
- R.4 identifies external conditions for boundaries.

3.4. Diagnosis Phase (D)

The diagnosis phase focused on the representative tower house and its interaction with the generated microclimates on the district scale. The building type, as a middle unit in a long block, was modelled in DesignBuilder® using the constructive characteristics and thermal and optical properties collected in previous phases B (see Tables 3 and 6). Due to its position relative to other units, the model featured the use of three adiabatic walls, leaving the façade along the street dispersant. A long block featuring the same thermal and optical properties was modelled and located 2 m from the model of the building type. Finally, the system was rotated following the prevalent exposition of +20° on the E–W axis in order to have a fully representative model of the street canyon type. For HVAC technologies, a gas boiler heating system and an electric fan coil for cooling, as representative technologies, were introduced, using 20 °C and 25 °C, respectively, as the set-point temperatures.

According to the subphase **D1**, the model was simulated in order to assess the energy relevance of each subsystem in the envelope in relation to future climate scenarios. This analysis allowed us to simulate the model with improved roof and dispersant wall, introducing one basic insulation layer to the outer surface, in order to meet the current Italian normative thresholds, and to compare the energy effects to the Meteonorm climate file (Metenorm_Act) and its projections for 2030 and 2050, as derived from Meteonorm using the IPCC algorithms and in reference to the A2, A1B and B1 scenarios. Windows and ceiling at the ground floor were excluded [81–83]. In the results, and according to future trends in the Mediterranean area (Figure 9), if energy consumption for heating decreases due to the increasing trend of temperatures, the cooling reduction will have a major effect on the properties of the roof. The percentage of cooling variations has positive values as a result of the combination of increased cooling needs and future increasing temperatures. Additionally, the implementation of a thermal roof will be supported, with major effects on cooling, highlighting the necessity to focus on the horizontal subsystem in the envelope. In contrast, the wall will become representative for the wintry case.

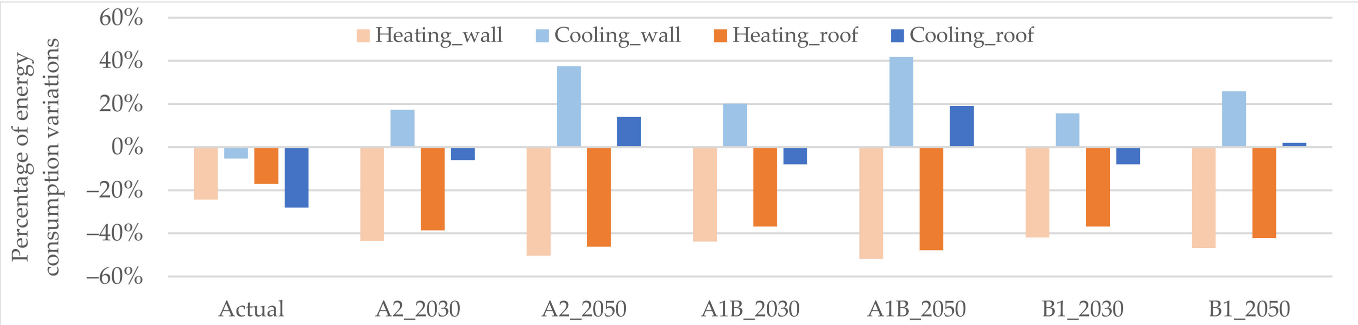


Figure 9. Variation in percentages of energy consumption after thermal improvement of roof and wall under current (Actual) and future climate scenarios: A2, A1B and B1 for 2030 and 2050.

Regarding the **D2** subphase, the building type was analyzed, taking into account: (i) the local microclimate measurements (RH, T—subphase C2.2), adding the solar radiation intensity and wind information (by ARPA standard station) about monthly representative days in 2017, and (ii) geometric variations of the street canyon and its surrounding features. Combinations of these variables generated three main conditions for the building type, which were modelled and simulated in DesignBuilder® as follows:

- Su.A: tower house in street canyon type (as modelled), considering the temperatures measured in the street canyon (E2);
- Su.B1: tower house type located in the square (without the on-face block), considering temperatures measured in the street canyon (E2); this represents an intermediate case aimed at comparing the effect of openness and constantly increasing temperatures in separate ways;
- Su.B2 tower house type in the square (without on-face block), considering the temperatures measured in the street canyon, with increments of 0.5 °C (E2 + 0.5 °C).

As discussed in the previous section, the results are presented only for 17 August, as this date was considered representative of the analyzed period.

The results of the energy effects on the building types in three combinations are reported in Figure 10. Specifically, the feature of compactness are analyzed in terms of efficacy in energy reduction, where:

- The main shading effect on the building type supported a reduction in cooling demand during the daytime (−20% Su.A-Su.B1—Blue line in Figure 10);
- Microclimate alterations, combined with the loss of shading in open areas, have a minor additional influence on cooling reduction, i.e., approaching −25% (−20% Su.A-Su.B2—Purple line in Figure 10);
- In contrast, during the night, the cooling reduction was prevalently related to alterations in the microclimate (+0.5 °C), with a lower effect than in the daytime (−17% at 06:00 and 12% at 00:00—Bars graph in Figure 10).

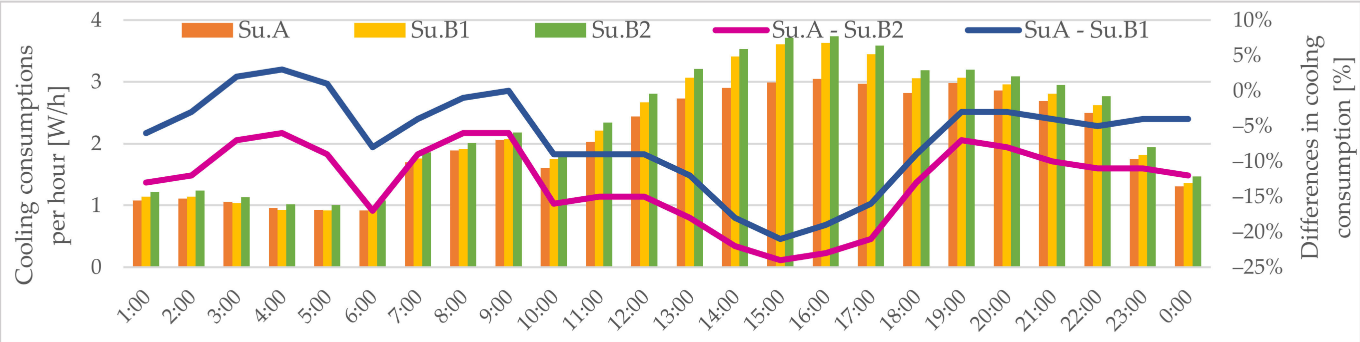


Figure 10. Assessment of hourly energy consumption by building type considering three combinations, i.e., Su.A, Su.B1 and Su.B2 (bars graph), and differences between Su.B1 and Su.B2 with Su.A (line graph) (17 August).

These results highlight the effects of the microclimate alterations for combinations R1 and R3, suggesting two different levels of adaptability with specific percentages of energy variations. All building types in R2 were unified with the R1 ones, due to the similar influence in terms of energy efficacy during the daytime.

Due to the close connection between the vertical subsystems of the envelope and the generated microclimate on the street canyon scale, a double level of diagnosis was applied to the analysis of thermal properties. Vertical opaque and transparent subsystems of the building type were improved following the multistep process: for the wall, this corresponded to reductions of its thermal transmittance of 20%, 40%, 60%, 80% and 100% (as the difference between current and normative thresholds) by means of an external insulation layer; for the transparent subsystem, double glass (+60%), Low-E double glass (+80%) and Low-E double glass with argon (+100%) technologies were coupled with the wooden frame to reach the normative thresholds of the windows. As far as the results in Figure 11 are concerned, their improvement had similar limited impacts (−10%) in terms of reducing cooling consumption, for both the normative thresholds and the exposed building type (Su.B2). However, thermal improvement of the wall has positive effects also on wintry conditions while for windows it remains limited due to their modest contribution to the total dispersant surface area (10%, see Section 3.1, Analytic phase).

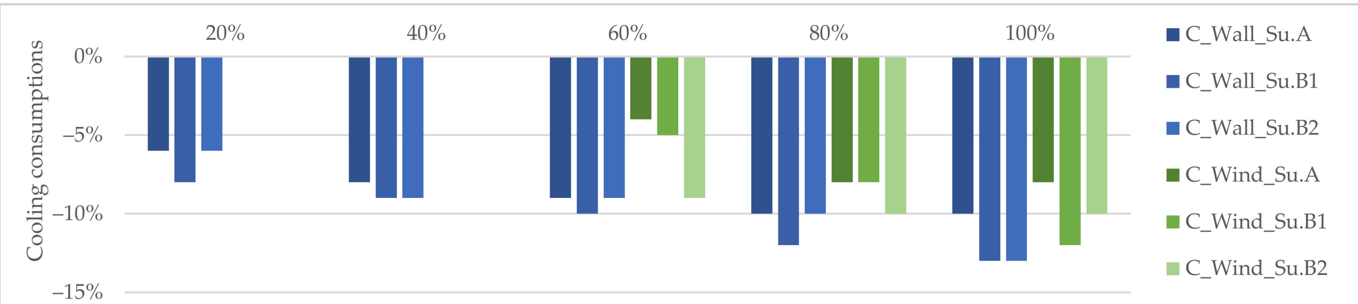


Figure 11. Energy cooling assessment of subsystems for the building type improving (5-steps process) thermal feature of the wall (C_Wall) and windows (C_wind) in three combinations (Su.A, Su.B1, Su.B2).

In contrast, as demonstrated in Section 3.3, roofs do not influence or are influenced by microclimate variations at the street canyon scale. Due to that, the representative wooden roof (C.ex.c) is analyzed to test its technological details (i.e., thermal and optical properties), but not its outer environmental conditions. So, the applied iterative process focused on the thermal and optical improvement of the wooden roof in two ways: in order to improve the normative thresholds for thermal transmittance, the roof was modified by introducing an insulation layer under the external bituminous layer following the same multistep process as that applied to the wall; concerning the optical improvement, five steps were identified, starting from the worst value of albedo for the dark bituminous layer (α = 0.1) to the best (α = 1). Concerning the results in Figure 12, the optical feature represented the most relevant property in terms of jeopardizing the summer performance of the roof (reduction of cooling reached −26% with the maximum value of albedo—Blue bars—and for the best thermal condition −15%—green bars). Relating the results to the real roof types in the historic districts (0.1 for bituminous, 0.4 for "cotto" paved and 0.6 for calcareous paved roofs), the analysis supported the use of three classes of exposure according to which paved roofs were more efficient than the waterproof ones (−6% and −14% for "cotto" and "basole" tiles, respectively—blue bars).

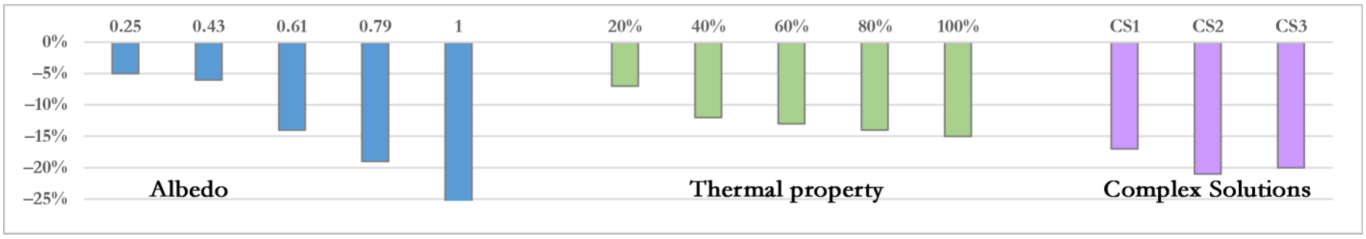


Figure 12. Cooling energy assessment for optical (blue bars) and thermal (green bars) sensitivity analyses (five-step process) and test of complex solutions (purple bars) for roof.

Finally, according to the relevance of innovative solutions which are available on the market and already tested in the Mediterranean area, the efficacy of three solutions (CS) is tested. In particular, the solutions mixed thermal, optical and inertial improvements, reaching the Italian thresholds for the roofs of new constructions (U = 0.36 W/m^2 K):

- CS1 is an extensive green roof (LAI = 1, soil depth Sd = 0.25 m) combined with an insulation sublayer; a low-impact real solution.
- CS2 is a smart solution for roofs involving the use of PCMs, i.e., light-density materials that improve the thermal inertia of the subsystem, characterized by a thickness of 70 mm and a latent melt temperature of 25 °C, and an outer reflective finishing layer (α = 0.84, ε = 0.89).
- CS3 is a widespread solution for roofs in hot climates, characterized by a well-designed insulating layer and an outer reflective finishing layer (α = 0.84, ε = 0.89).

CS3 and CS2 represent solutions with higher efficacy in summery conditions (purple bars in Figure 12) for this building type, while a lower efficacy is demonstrated for CS1 solution.

The original value of using calcareous stone tiles ("chiancarelle") was lost over time due to infiltration repairs to this subsystem; in such interventions, dark bituminous surfaces were favored.

3.5. Taxonomy of Suitable Interventions (E)

According to the preservation aim discussed in AnP and the goal of phase **E**, classes of transformation degrees (**E1**) are identified in order to define possible levels of improvement, on both the district and building scales. Concerning the former, any level of transformation is limited by the impossibility of modifying certain assets and of removing stone paving (AnE). On the building scale, degrees of transformation are defined by envelope values (AnP) and their state of conservation (Ac.3), above all for roofs and walls. For HVAC systems, cooling and heating types are classified in terms of alterations of the final technologies and levels of connection with urban energy grids. Therefore, three degrees of transformability are identified for roofs:

[T.R.H] HIGH: severely damaged or collapsed roofs; for them, interventions involve reconstruction;

[T.R.M] MEDIUM: roofs covered by waterproofing layer (Cex.c) or not original pavement (Cex.a); the design and application of a compatible finishing material are required;

[T.R.L-M] LOW-MEDIUM: roofs covered by the original or other valuable roof tiles; interventions have to preserve the formal and material identity of the external finish (e.g., removing, treating and reusing the stone tiles (Cex.b)).

Similarly, three levels of transformability are introduced for walls:

[T.W.H] HIGH: severely damaged or collapsed walls; interventions aim at reconstruction;
[T.W.M-H] MEDIUM-HIGH: plastered walls; transformation involves the replacement of the original finishing with compatible and superior ones;
[T.W.L] LOW: unplastered walls; interventions are limited to the inner surfaces or in the nucleus, in order to preserve the outer surface.

Regarding the particular case of the northern part of the district, the tower houses in the ancient core mainly comprise Medium-High and Low levels of transformability, according to the *Table of systems and subsystems categories* defined in Ac2.

Finally, cooling and heating systems are divided into three levels:

[T.S.H] HIGH: constructions are already equipped with systems and connected to distribution grids;
[T.S.M.] MEDIUM: buildings had energy systems but they are not connected to the distribution grids;
[T.S.L.] LOW: buildings with obsolete systems which are disconnected from the grids.

In the case study, methane and electric grids cover the whole historic district, and all the buildings are connected. Thus, the tower houses in the analysis can be associated with the high level of transformation. This feature cannot be assumed for all cases [84].

Thus, suitable interventions are discussed (E2), mainly for major dispersant subsystems of the envelope. In detail, compatibility with the previous level of transformability and widespread technological solutions available for the built market are combined to identify appropriate interventions. As far as wooden roofs and combinations of finishing layers are concerned, two levels of intervention are supported, according to the physical factors noted in the D2 subphase:

[I.C.Opt] Introduction of finishing solutions with good optical properties, which may be classified into two types:

- [I.C.Opt.1] Finishing additives or substitutions for roofs which are not easily accessible; in such cases, the use of field-applied coatings or fluid applied membranes can support ordinary maintenance, covering or substituting the bituminous surfaces;
- [I.C.Opt.2] Substitution of nonoriginal paving on accessible roofs with reflective technologies, such as clear reflective concrete or "cotto" tiles;

[I.C.Th] Enhancement of thermal properties by inserting insulation panels under finishing sublayers; the use of insulation panels can achieve the lowest increase of thickness (e.g., aerogel, VIPs, multilayer reflective boards), thereby reducing variation. The main differences concern the external finishing treatments:

- [I.C.Th.1] In the case of nonoriginal paving and industrial external products (C.ex.a and C.ex.c), substitution is allowed;
- [I.C.Th.2] For original or comparable pavements (C.ex.b), removal and substitution are to be avoided in favor of reuse after thermal improvement of roofs, according to the degree of transformability.

[I.C.Ti] Increase the thermal inertia of the roof by inserting new layers into the structural parts; the main solutions involve the replacement of the inclined screed above the slab, introducing insulation and lightweight concrete (e.g., with expanded clay, pumice, or expanded glass) or adding coatings or doped pavement with phase changing materials on the external surface to enhance attenuation and time shift of summer temperature peaks through controlled latent heat storage and release.

In this second case, the possibility of introducing these materials depends on the penetration capacity of PCMs in the market, and thus, is a question of cost.

Green roofs are excluded from the present solutions for T.R.M and T.R.L-M classes; in fact, as demonstrated in the previous section, the efficacy of extensive solutions is lower than traditional ones in this building type; moreover, green solutions feature a higher impact, altering the formal value of roofs. Extensive interventions are excluded due to their incompatibility with thin wooden roofs.

Referring to wall deficiencies, thermal vulnerability in winter conditions can be reduced by one of three methods, according to the preservation values (APn):

[I.Wa.1] Installation of insulation panels on the external façade to achieve the lowest thickness (e.g., aerogel, VIPs, multilayer reflective boards), including a thermo-insulating plaster coating (e.g., hydraulic lime with EPS additives) in cases with outer plastered surfaces. When compatible with the thermal goals, natural and recyclable insulation panels are also allowed.

[I.Wa.2] Filling the inner cavity with insulation mixtures (e.g., hydraulic lime with nanoparticles) for unplastered facades; thermal improvement along the inner surfaces of walls is to be avoided in order to preserve the thermal inertia and prevent interstitial condensation.

[I.Wa.3] When extremely damaged, the construction of a new wall, observing the thermal threshold values defined by the law; using clear plaster to achieve formal homogeneity with the historic district.

In reference to energy systems on the building scale, solutions are categorized according to their degree of penetration:

[I.S.1] Upgrade cooling and heating systems when the building is already connected to urban supplies.

[I.S.2] Connection of the systems to urban supplies and use efficient technologies.

[I.S.3] Introduction of efficient systems that do not require grid supplies (e.g., biomass boilers).

Table 8 summarizes the interventions codes with building codes and values.

Table 8. Summary of building codes, transformation degrees and intervention codes for the analyzed building types in Molfetta.

Component	Component Code	Transformation Degree	Intervention Code
Wall	Wa1	T.W.M-H	I.Wa.1
	Wa2	T.W.L	I.Wa.2
Roof	Cex.a + C.in	T.R.M	I.C.Opt.2 + I.C.Th.1
	Cex.b + C.in	T.R.M-L	I.C.Th.1
	Cex.c + C.in	T.R.M	I.C.Opt.1 + I.C.Th.1
HVAC system	S_H–S_C	T.S.H	I.S.1

3.6. Assessment of Intervention Priority (F)

Minimum Units of Energy-Resilient Interventions (MUERIs) are introduced as recurrent building types characterized by similar levels of energy deficiencies and adaptation capacities, according to the adopted meaning of energy resilience. In this phase (**F**), all the results concerning the energy quality, both at the street canyon and building scales, and deficiency at the building scale (subphases C.2.2 and D2) are summarized, codified and systemized in order to identify recurrent combinations for middle tower houses:

1. On the street canyon scale, three levels are recognized in terms of modifying the local microclimate to achieve a positive effect on reducing cooling demands:

   [A.C.H] HIGH for inner street canyons for all assets; here, the minimum average daily temperatures and maximum values of reduction of standard deviations generated the maximum reduction of energy consumption for daytime cooling (R1 and R2, section C2.2);

[A.C.M] MEDIUM along open areas where average values of daily temperatures increased due to the nocturnal UHI effect (+0.5 °C) but reflected good behavior in terms of reducing daytime ones (R3);

[A.C.L] LOW along the boundary where any adaptability capacity can be considered.

2. On the building scale, adaptability describes the potential capacity to reduce local overheating outside the air volume of street canyon, and therefore, focuses on the optical properties of the roof materials (see results in Section C2.2, Figure 12):

[A.R.H] HIGH for paved roofs made of stone (“chiancarelle”) with good optical features (C.ex.a);

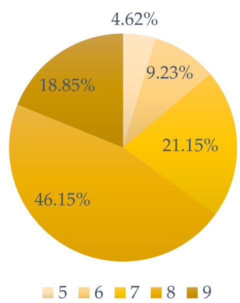
[A.R.M] MEDIUM for paved roofs with medium albedo values (C.ex.b);

[A.R.L] LOW for roofs with low optical performance, such as those with a bituminous finish (C.ex.c).

Thus, transformability and adaptability are codified using multiscore parameters. For each code, a score between 1–3 is assigned using 1 for the lowest level of transformability and 3 for the highest; in other words, the 1–3 scale refers to the level of adaptability. Scores are assigned to single tower houses mapped in a GIS model; then, they are combined according to the specific properties of single (tower) buildings introduced in the database, defining 13 MUERIs for the different tower house types. Table 9 reports the scores and the total number of middle tower houses for each MUERI code in the district. Figure 13 shows the GIS plots of their geographical distribution on the district scale.

Table 9. Summary of Minimum Units of Energy-Resilient Intervention (MUERI) codes and resilient score for the analyzed building type in the historic district of Molfetta.

MUERI Code	Adapt_Canyon	Adapt_Roof	Transf_Roof	Transf_wall	Score	Representa-Tiveness for Building Type [%]	Incidence of Emergency
1	A.C.H.	A.R.H.	T.R.M-L.	T.W.L.	8	7.31%	
2	A.C.H.	A.R.H.	T.R.M-L.	T.W.M-H.	9	10.38%	
3	A.C.H.	A.R.M.	T.R.M.	T.W.L.	8	6.54%	
4	A.C.H.	A.R.M.	T.R.M.	T.W.M-H.	9	8.46%	
5	A.C.H.	A.R.L.	T.R.M.	T.W.L.	7	10.77%	
6	A.C.H.	A.R.L.	T.R.M.	T.W.M-H.	8	30.38%	
7	A.C.M.	A.R.H.	T.R.M-L.	T.W.L.	7	0.77%	
8	A.C.M.	A.R.H.	T.R.M-L.	T.W.M-H.	8	1.92%	
9	A.C.M.	A.R.L.	T.R.M.	T.W.L.	6	2.69%	
10	A.C.M.	A.R.L.	T.R.M.	T.W.M-H.	7	9.62%	
11	A.C.L.	A.R.H.	T.R.M-L.	T.W.L.	6	1.92%	
12	A.C.L.	A.R.L.	T.R.M.	T.W.L.	5	4.62%	
13	A.C.L.	A.R.L.	T.R.M.	T.W.M-H.	6	4.62%	



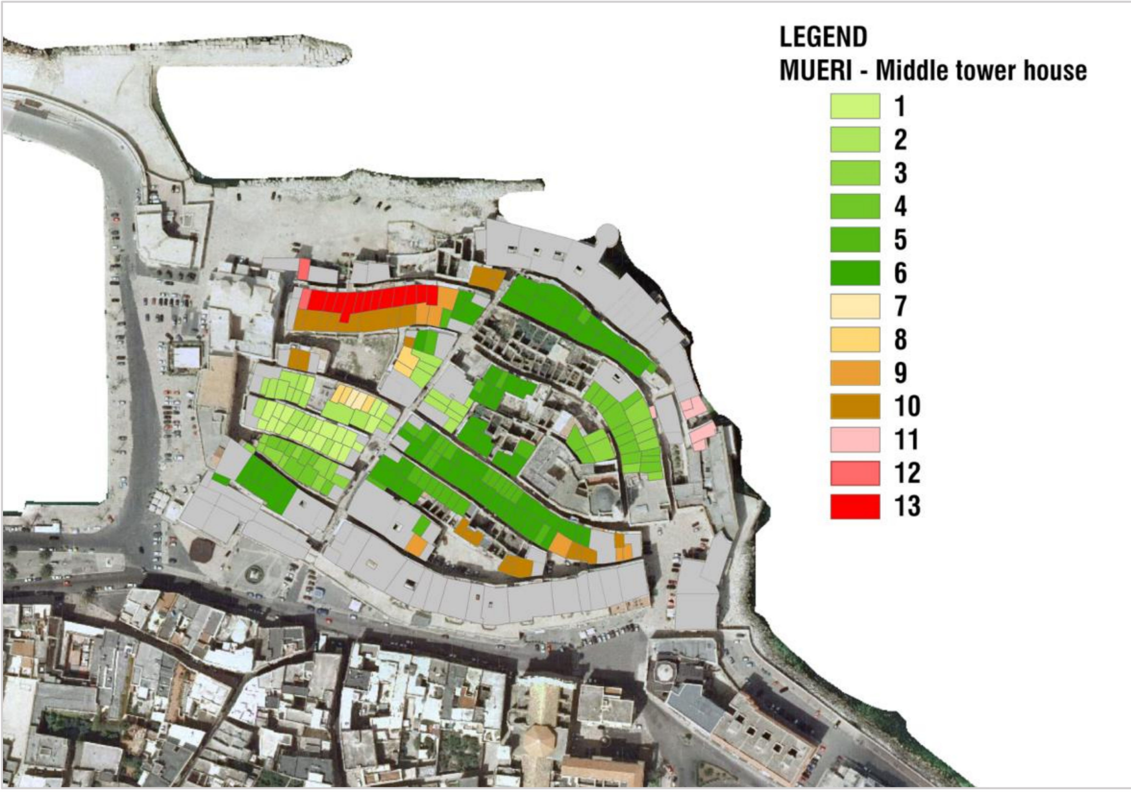


Figure 13. Plot of geographical distribution at district scale of MUERI codes for the analyzed building type in the historic district of Molfetta.

The codification of building types in terms of their resilience characteristics and the use of MUERIs for the characterization of common combinations supported the management of this built heritage. As discussed in the methodology, phase F is intended to support local administrations in managing these buildings, pursuing detailed datasheets for the management of MUERIs and related systems of transformation. Figure 14 shows a datasheet of the MUERI n.6, describing the combination of actions within the subsystem of the analyzed envelope. For each of them, a specific code, the transformation degree and action description are included, as the first level of the MUERI description. Then, for all actions, specific solutions are introduced according to the reference code. As an exemplary case, Figure 15 shows a datasheet created for the roof C.ex.c (with an outer waterproof bituminous layer) in MUERI N.6 which is intended to provide support for technicians seeking to improve the optical properties of the subsystem using field-applied and fluid-applied coatings.

GEOGRAPHIC LOCATION: Molfetta (BA), Italy, 0 - 143 mt a.s.l. 41° 12' 00" N, 16° 36' 00" E		CLIMATIC CLASSIFICATION: 1202 D.D. , ZONE C (DPR 142/1993)		CURRENT ENERGY REGULATION: D. 26 June 2015	
M.U.E.R.I. CODE: 6					
COMBINATION OF ACTION	Sub-system of Envelope	Env. Code	Transformation Degree	Action Descriptions	Action Code
	Wall	Wa2	T.W.L.	Decrease thermal transmittance with an inner insulation layer	I.Wa.2
	Roof	C.In C.ex.c	T.R.M.	Decrease thermal transmittance increase optical features; increase thermal inertia	I.C.Th.1 I.C.Opt.1 I.C.Ti
	Heating and Cooling Systems	S.H2 S.C2	T.R.M.	Upgrade cooling and heating systems	I.S.1

Figure 14. Datasheet for the MUERI 6 (first level of information).

GEOGRAPHIC LOCATION: Molfetta (BA), Italy, 0 - 143 mt a.s.l. 41° 12' 00" N, 16° 36' 00" E			CLIMATIC CLASSIFICATION: 1202 D.D. , ZONE C (DPR 142/1993)		CURRENT ENERGY REGULATION: D. 26 June 2015
M.U.E.R.I. CODE: 6					
Sub-system code: Cex.c	State of desrepair: good	Energy resilient level: medium	Compatible Systems of Intervention	Action Descriptions	
	Transformation Degree: T.R.M.	Dominant features: low transmittance, inertia, albedo	[I.C.Opt.1] Outer coating application	Field-Applied Coating	Applied coating in case of substitution or protection of waterproof layer, covering and protecting the whole surface having care to overlap external strip. material featured by stable and high emissivity (ε) and albedo (α) values are preferred.
				Fluid applied Membrane	Applied coating in case of substitution or protection of waterproof layer, covering and protecting the whole surface having care to overlap external strip. material featured by stable and high emissivity (ε) and albedo (α) values are preferred.

Figure 15. Datasheet for C.ex.c roof, a subsystem of the MUERI 6 (second level of information).

4. Discussion and Conclusions

The high energy consumption and GHG emissions of buildings represent the main challenge for policies from global to national scales. The uncertainties surrounding future climate change scenarios have led the European community to assess precrisis states and promote adaptive solutions in planning activities. The Mediterranean area is a critical region due to the combination of a hot-summer climate and future increasing trends.

As anomalous elements of cities, i.e., in terms of their design and the complexity of their historical origin and development, historic districts suffer from and participate in global changes and local interactions as innate elements of their environments. However, despite the widespread need to improve them, such buildings require customized methodologies to manage their energy solutions because of their socio-cultural, socio-economic and environmental significance; in fact, their preservation and transformation should be planned in a dynamic way, aiming at persistence as a cultural responsibility of and public administrations, focusing on both formal and energy characteristics. In fact, the widespread significance of compact Mediterranean cities, i.e., in terms of their adaptive potential, should be recognized and included in resilience strategies.

The proposed methodology aims at addressing some current criticisms by: (i) working on the local scale in order to analyze, diagnose and, above all, provide tailor-made solutions, according to the overarching necessity to preserve local identity; (ii) determining a Feature—Type—Behavior process of analysis in order to recognize opportunities, deficiencies and potential efficiency, undergoing the single-cases peculiarities of buildings, as well as controlling and managing supported solutions with a long-term perspective and through a priority-based approach; (iii) supporting performance-based systems of solutions in order to select compatible ones and products that are usually related to the technological and commercial evolution or penetration in a certain area; (iv) the introduction and the assessment of energy-resilient characteristics, as a combination of "Adaptability" and "Transformation" degrees, and as an instrument with which to recognize and properly resolve different levels of exposure to energy imbalances at a building scale.

The application of the methodology in a representative case study in the Apulian region made it possible to identify some remarkable features and vulnerabilities; at the same time, it was possible to extend the methods to similar cases according to usefulness of "types". Constant temperature variation was observed in the entire district during the summer days, e.g., decreasing daytime temperatures (−1.5 °C) and increasing nighttime (+0.5 °C) ones, with exceptions in open areas. This result has little influence on assessments of alterations of walls (stone or clear plaster) and roof materials (bituminous, "cotto" and stone tiles), or of the morpho-distribution of blocks. At a reduced scale of analysis, a middle tower house located in a very narrow street (2 m wide) presented highly adaptive performance because of (i) the prominent level of shading due to nearby buildings, (ii) good optical performance of the local calcareous stone used in the masonry and street pavement and (iii) finally, the high thermal inertia of the walls. On the other hand, roofs constitute a weak element; despite their weaker influence on a district scale in terms of altering local microclimates at human height, their low adaptability level depends on (i) low efficiency in terms of both thermal and optical features generating a high level of dispersion, and (ii) the lower level of thermal inertia, generating fluctuating temperatures in residential spaces.

Finally, further elements can be highlighted in future studies. Firstly, the proposed methodology could be supported by applying regional instruments for climate study. On the other hand, the methodology should be open to other factors affecting solution choices, such as economic feasibility as well as the impact of the use of specific materials (i.e., LCA).

Finally, the use of GIS databases to support the management of buildings could be improved by linking them with the BIM or CityGML models and energy cadastral data lists as a new approach to assess energy consumption, thereby taking into account inhabitant behavior.

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Abbreviations

Table of abbreviations used in this paper.

IPCC	Intergovernmental Panel on Climate Change
UHI	Urban Heat Island
PCM	Phase Change Material
SVF	Sky View Factor
WMO	World Meteorological Organization
LCZ	Local Climate Zone
MUERI	Minimum Unit of Energy Resilient Intervention
ARPA	Regional Agency for the Protection of the Environment (Agenzia Regionale per la Protezione Ambientale)
RH	Relative Humidity
WSDI	Warm Spell Duration Index

Appendix A

This appendix section shows the detailed tests and results of a CFD analysis on a district scale, as briefly reported in Section 3.3.

Figure A1 shows the results of simulation and measured data on 17 August. Specifically, it reports the results on the reference point (E1) both in measured temperatures (E1—orange line), simulated ones (light blue line) and their compared Mean Bias Error (MBE) values for each simulated hour (green line). Due to the low error values (<5%), the model was shown to be well-calibrated, and thus, all results can be accepted.

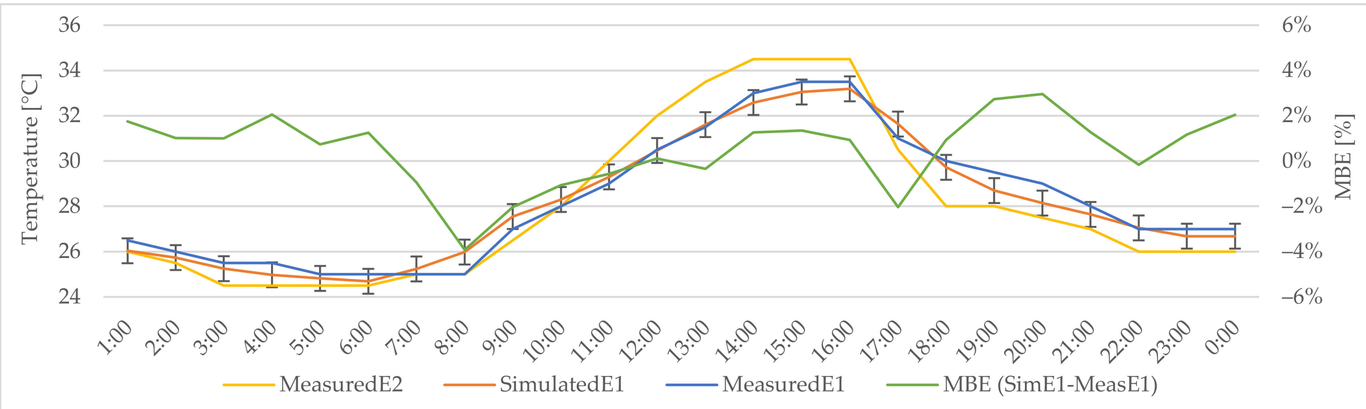

Figure A1. Hourly comparison of temperatures measured on-site (MeasuredE1—blue line), simulated in Envi-met model (SimulatedE1—orange line), environmental on-site measurements (MeasuredE2—yellow line), and Mean Bias Error (MBE) between measured and simulated temperatures (17 August 2017).

Figures A2 and A3 report extended results of ENVI-met simulation on 17 August for the district scale of Molfetta.

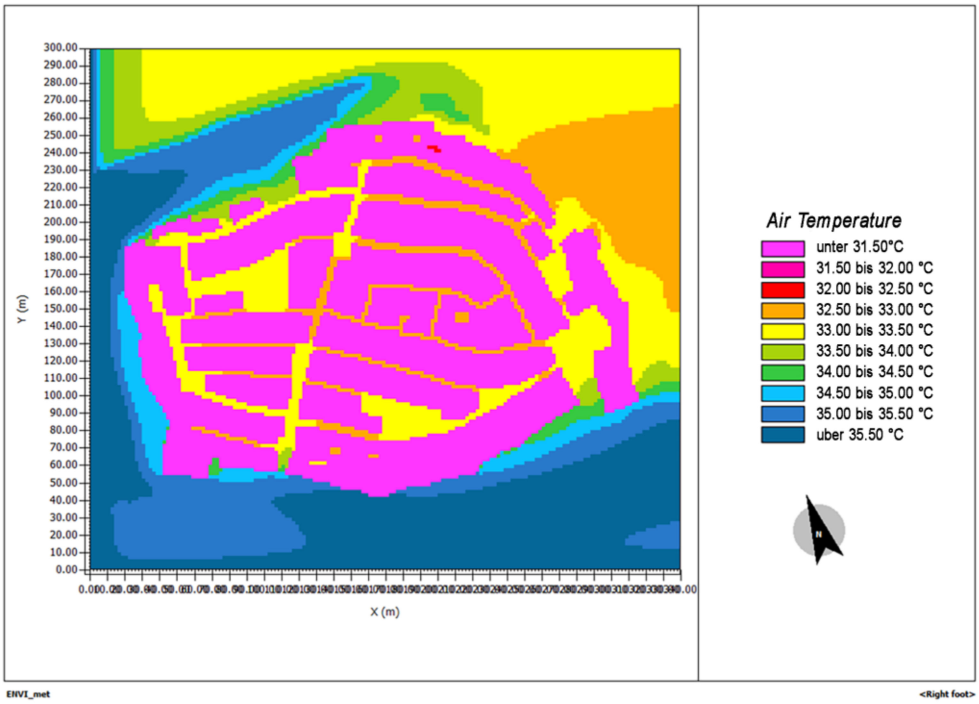

Figure A2. Variation of higher daily temperature inside the analyzed district (17 August—15:00).

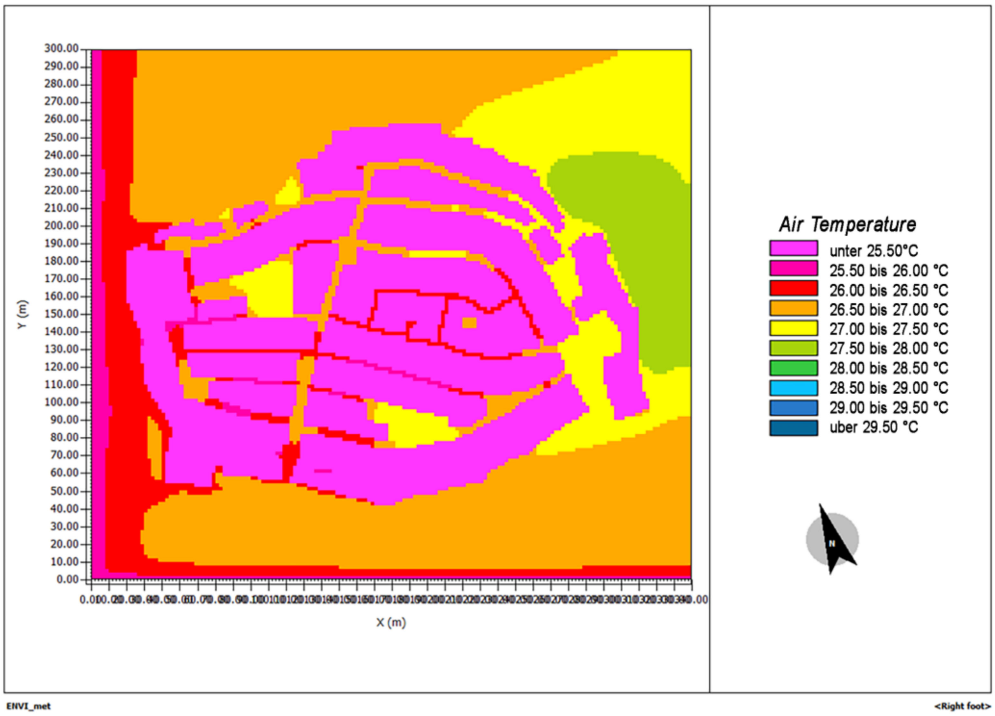

Figure A3. Variation of lower daily temperature inside the analyzed district (17 August—15:00).

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