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Exploring the Performance of Historic Residential Buildings in South Tyrol: Considerations on Present and Future Climate

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Abstract

The European Union aims to achieve a 32.5% reduction in energy consumption by 2030 and to be climate-neutral by 2050 (an economy with net-zero greenhouse gas emissions). In order to achieve this efficiency target, Member States have set national goals to refurbish 3% of total residential and commercial buildings annually. Historic buildings account for more than one-quarter of Europe’s existing building stock and are going to be crucial in the achievement of future energy targets. Thus, conservation compatible solutions are urgently needed to guarantee modern standards of comfort while reducing the energy consumption and loss of heritage. Although a drastic reduction in the carbon emissions would slow climate change, some alteration in the climate is already certain, and therefore the impact of future climate should be considered when retrofitting a historic building. In South Tyrol, the annual temperature are expected to increase 1.2-2.7 °C by the end of the century, and extreme climatic events will be more frequent, such as heatwave and intense precipitation. The impact of these changes should be studied in terms of energy performance, occupants’ comfort, and heritage conservation. With climate change, inappropriate interventions might weaken the potential of original passive climate-adaptive systems, such as thermal mass and night cooling, leading to higher risks of overheating. This would ultimately lead to higher levels of discomfort or energy use for cooling. Additionally, retrofit solutions could change the moisture dynamics of historic envelopes, which might lead to moisture damages when combined with more extreme precipitation events.

In this study, an in-depth review is conducted to collect recent literature that provided evidence of climate change’s impact on retrofitted buildings, revealing potential future risks. Then, the climate of South Tyrol is studied and divided into three homogeneous climate zones, and residential buildings are analyzed and categorized according to these climate zones and their most representative characteristics. It is found that there is a strong relationship between local climate and the characteristics of historic South Tyrolean residential buildings. The importance of other socio-economical parameters that go beyond purely climatic factors is also highlighted. The analysis and categorization of the built heritage stock allow proposing reference buildings that represent each category. Through the assessment of ten case studies of local renovation practice, current retrofit solutions are defined. Reference buildings with and without current retrofit solutions are simulated in present climate scenarios so that the performance of current retrofit solutions is assessed. Current retrofit solutions could achieve significant energy savings in winter in all three climate zones, and their negative impacts on overheating are limited in most of the reference buildings. In the case of moisture-related risks, the effect of the retrofit is closely related to the local climate. To quantify the impact of climate change of buildings performance, reference buildings (with and without current retrofit solutions) are simulated and compared in future climate scenarios. Retrofit solutions can still achieve important energy savings in the future in all three climate zones. However, with future climate change, overheating hours in retrofitted buildings increase significantly. Moreover, moisture-related risks also rise in some climate zones. The analysis of the performance shows that direct solar gains, the surface to volume ratio of the building and ventilation strategy are significant factors in thermal comfort; the main moisture source leading to moisture risks in wall is outwards vapor diffusion. According to the performance assessment, compatible retrofit solutions are proposed that could bring low energy use and improved thermal comfort to each reference building both in the present and future scenarios.

Keywords: Historic buildings; climate change; energy retrofit; South Tyrol; energy performance; overheating; moisture risk

Abstract (italiano)

L'Unione europea ha stabilito la riduzione del 32,5% nel consumo di energia come scopo da raggiungere entro il 2030 verso una "climate-neutral economy" entro il 2050 (un'economia con emissioni nette pari a zero). Al fine di raggiungere questo obiettivo di efficienza, gli Stati membri hanno fissato obiettivi nazionali per rinnovare il 3% del totale degli edifici residenziali e commerciali ogni anno. Gli edifici storici rappresentano oltre un quarto del patrimonio edilizio esistente in Europa. Il loro efficientamento sarà cruciale nel raggiungimento dei futuri obiettivi energetici e pertanto sono urgentemente necessarie soluzioni compatibili con la conservazione per garantire standard contemporanei di comfort e per diminuire il consumo di energia contribuendo alla conservazione del patrimonio architettonico. Sebbene una drastica riduzione delle emissioni di carbonio rallenterebbe i cambiamenti climatici, un'alterazione del clima è già certa e pertanto l'impatto del clima futuro dovrebbe essere preso in considerazione quando si interviene su un edificio storico. In Alto Adige, è previsto che la temperatura annuale aumenti di 1,2-2,7 °C entro la fine del secolo e che gli eventi climatici estremi, come le ondate di caldo e le precipitazioni intense, saranno più frequenti. L'impatto di questi cambiamenti deve essere studiato in termini di comportamento energetico, comfort degli occupanti e conservazione del patrimonio. Con i cambiamenti climatici, interventi inappropriati potrebbero indebolire l'effetto delle soluzione passive originariamente utilizzate nell'architettura storica adattata ai climi esistenti, come la massa termica e il raffreddamento notturno. Ciò produrrebbe maggiori rischi di surriscaldamento inducendo livelli più elevati di disagio o aumento del consumo di energia per il raffrescamento. Inoltre, inappropriate soluzioni di risanamento potrebbero cambiare la dinamica dell'umidità nelle murature storiche, con conseguenti danni legati all'umidità se associate a eventi di precipitazione più estremi.

In questa tesi, lo studio approfondito della letteratura recente fornisce delle prove dell'impatto che il cambiamento climatico porterà sugli edifici risanati, rivelando potenziali rischi futuri. Il clima dell'Alto Adige viene studiato e diviso in tre zone climatiche omogenee. Gli edifici storici residenziali vengono analizzati e classificati in base a queste zone climatiche e alle loro caratteristiche più rappresentative. Si è constatato che esiste una forte relazione tra il clima locale e le caratteristiche degli edifici residenziali storici dell'Alto Adige. L'importanza di altri parametri socio-economici che vanno oltre i fattori puramente climatici è anche evidenziata. L'analisi e la categorizzazione dello stock del patrimonio costruito permettono di proporre una serie di edifici di riferimento. Attraverso la valutazione di dieci casi di studio, le pratiche locali di risanamento vengono studiate.

Le prestazioni degli edifici di riferimento, con e senza le soluzioni di risanamento attualmente adottate, sono state analizzate attraverso simulazioni in scenari climatici attuali per valutare le soluzioni di risanamento odierne. Il risanamento di edifici storici porta a significativi risparmi energetici in inverno in tutte e tre le zone climatiche e i loro impatti negativi sul surriscaldamento sono limitati nella maggior parte degli edifici di riferimento. Nel caso dei rischi legati all'umidità, l'effetto del risanamento è strettamente correlato al clima locale. Per quantificare l'impatto dei cambiamenti climatici sulle prestazioni degli edifici, sono state effettuate simulazioni (con e senza le soluzioni di risanamento attualmente adottate) per diversi scenari climatici futuri. Dall'analisi risulta che il risanamento permette ancora una volta di ottenere importanti risparmi energetici nei climi futuri in tutte e tre le zone climatiche. Tuttavia, con i futuri cambiamenti climatici, le ore di surriscaldamento negli edifici aumenteranno significativamente. Inoltre, in alcune zone climatiche aumenteranno anche i rischi legati all'umidità. L'analisi delle prestazioni mostra che i guadagni solari diretti, il rapporto superficie/volume dell'edificio e la strategia di ventilazione sono fattori significativi nel comfort termico. La principale fonte di umidità che comporta rischi di degrado nel muro è la diffusione del vapore verso l'esterno. Attraverso la valutazione delle prestazioni, vengono proposte soluzioni di risanamento compatibili con gli edifici storici e che potrebbero portare a un minore consumo di energia e a un maggiore comfort termico sia negli scenari presenti che futuri..

Parole chiave: edifici storici; cambiamento climatico; risanamento energetico; Alto Adige; prestazione energetica; surriscaldamento; patologie da umidità

Nomenclature

Acronym			
C	Material coefficient for mold decline	DQM	quantile detrended quantile mapping
F1	Near future scenario (2041-2050)	F2	Far future scenario (2091-2100)
GCMs	General Circulation Models	GHG	Greenhouse gases
HDD	Heating Degree Days	IPCC	Intergovernmental Panel on Climate Change
k1	Intensity coefficient for mold growth	k2	Moderation coefficient for mold growth
M1	Climate scenario with Climate model 1 (RCP 8.5-ICHEC-EC-EARTH_DMI-HIRHAM5)	M2	Climate scenario with Climate model 2 (RCP 8.5-ICHEC-EC-EARTH_SMHI-RCA4)
M3	Climate scenario with Climate model 3 (RCP 8.5-IPSL-IPSL-CM5A-MR_SMHI-RCA4)	M4	Climate scenario with Climate model 4 (RCP 8.5-MPI-M-MPI-ESM-LR_CLMcom-CCLM4)
MC	Moisture content	MGI	Mold growth index
NZEB	Nearly zero-energy building	P	Present scenario (2008-2017)
Pr	Precipitation	QDM	quantile delta mapping
QM	Quantile mapping	RCMs	Regional climate models
RCPs	Representative Concentration Pathways	RH	Relative humidity
RH_{min}	Minimum RH for mold growth	RH_{crit}	Critical RH threshold for mold growth
VO	Vapor open insulation system	VT	Vapor tight insulation system
WDR	Wind-driven rain		
Notation			
A_w	Water absorption coefficient [$kg/m^2s^{0.5}$]	C_p	Specific Heat Capacity [J/kgK]
j_v	Density of water vapor diffusion flow rate [$kg/(m^2s)$]	p_v	Water vapor partial pressure [Pa]
S	the relative occupancy of the pore space by moisture content	S_{crit}	The ratio of the moisture content when all accessible pores are filled with water
Sd	Diffusion-equivalent air layer thickness [m]	t	Time [h]
Greek symbols			
μ_{dry}	Water vapor resistance in dry material [-]	μ	Water vapor resistance [-]
θ_{por}	Porosity [m^3/m^3]	λ	Conductivity [W/mK]
θ_{rm}	Running mean outdoor temperature [°C]	θ_{max}	Upper temperature limit[°C]
δa	Water vapor permeability of air [-]	θ_{min}	Lower temperature limit[°C]
ρ	Density [kg/m^3]		

1. Introduction

1.1 Research context

The severity and impact of climate change have been rigorously assessed in scientific literature. According to IPCC's (Intergovernmental Panel on Climate Change) Fifth Assessment report [1], the increase of global surface temperature by the end of the 21st century is expected to exceed 2.6 - 4.8 °C compared to 1986-2005 in the most pessimistic scenario. Together with this temperature increase, extreme climate events are expected to occur more frequently. For instance, the length, frequency, and intensity of heat waves might increase in large parts of Europe, Asia and Australia. It is also likely that "extreme precipitation events will become more intense and frequent in many regions" [1]. The EEA (European Environment Agency) also confirmed this tendency [2]. However, the changes among different regions will not be uniform. Heavy precipitation are likely to become more frequent in most parts of Europe, especially in Scandinavia and eastern Europe in winter. Studies carried out in the Alpine context have confirmed the serious challenge of climate change for the region. The 2018 South

Tyrolean Climate Report [3] indicates that the temperature increase during summer periods will be up to 5°C under the most pessimistic scenario by 2100. There would be more tropical nights (Nights during which the temperature remains above 20 °C) in summer. Moreover, heatwaves and extreme rain events would be more frequent. Besides the temperature increase, extreme precipitations will become more frequent in this Alpine region.

Climate change is an increasing challenge for the conservation of the built heritage. It could lead to accelerated degradation or loss of cultural heritage [4], due to continuous degradation or destructive climatic events. Weather- and climate-related natural hazards, such as river/coastal floods, landslides, wildfires etc. could cause catastrophic failure of the historic buildings. Buildings exposed to natural hazards attract much attention because of the immediacy of the losses. On the other hand, cumulative degradation-risks are increasing due to climate change. For instance, the temperature increase in winters could lead to a higher prevalence of insect pests and fungal attack, warping of timber elements, staining, and discoloration of masonry [5]. In this regard, cumulative degradation-risk assessment and adaptation are necessary to ensure buildings' resilience to new climate conditions.

Since the change of the century, several European projects studied the impact of climate change on historic buildings. For instance, the European project NOAH'S ARK [6] defined the meteorological parameters that are critical to the built heritage and developed a vulnerability atlas and a guideline to prepare structure and materials for future risks. On this basis, the CLIMATE FOR CULTURE project [7] enhanced the risk prediction method with high-resolution climate models and whole building simulation for specific regions. NANOMATCH [8] aimed at producing nanostructured materials for historic materials under the climate change context, and PARNASSUS [9] focused on the impact of future flood and wind-driven rain on historic buildings due to climate change and the validation of adaptation measures. Nowadays, researchers from the ADAPT NORTHERN HERITAGE project [10] are working on the identification of possible adaptation activities for heritage sites in the Northern Periphery and Arctic. These projects confirmed the relevance of investigating the impact of climate change on historic buildings. The studies looked into the consequences of higher temperatures, shifting precipitation patterns, higher flooding risks, and rising sea levels, which will influence heritage conservation, energy performance, and retrofit decisions. However, all these studies considered historic buildings in their original state, that is, before any energy improvement intervention.

To limit climate change and guarantee energy security, increasing attention is paid to the energy retrofit of historic buildings. The construction sector contributes with 39% of energy and process-related anthropogenic GHG (greenhouse gas) emissions in 2018 [11]. Historic buildings constitute a considerable share of building stocks in Europe since more than 14% of existing buildings were built before 1919, 12% were built between 1919 and 1945 [12], and more than 40% were made before 1960 [13]. Most of these historic buildings have not undergone any energy retrofit. As a result, the average energy consumption in historic buildings is considerably higher than in modern buildings [13]. It is estimated that the renovation of European dwelling stock built before 1945 could save up to 180 Mt of CO_2 per year afterward [12] and improve the thermal comfort of occupants.

Despite the urgency, the renovation rate of historic buildings is still very low. One of the barriers in the built heritage sector to climate change mitigation is the compatibility of retrofit solutions with the historic fabric [14]. Retrofit interventions can change building's performance substantially, from indoor climate to envelope's moisture dynamics [15, 16]. Combined with a changing climate, inappropriate choice of retrofit solutions might further endanger building conservation and weaken the building's performance. There is a need to investigate the performance of the retrofitted historic building in the context of climate change. South Tyrol, an alpine region in the North of Italy, has a considerable historic building stock. The performance of these buildings might be threatened by extreme events intensified by climate change. For instance, the relationship between moisture dynamics in historic buildings, rain pattern changes, and retrofit solutions should be evaluated on a regional basis, as well as the specific role of thermal mass and natural ventilation in alpine historic buildings and their combined effect with a changing climate. In conclusion, retrofit solutions should be defined based on the knowledge mentioned above and a clear awareness of future risks to maximize energy efficiency, occupant thermal comfort, and ensure a proper building conservation.

1.2 Research question and structure

The research question could be summarized as "What role will climate play in the performance of retrofitted historic residential buildings of South Tyrol?" Since the research is conducted under the context of South Tyrol, the reference buildings being investigated should be representative of the region. Therefore, the first task (Task A) of the research is to select the representative buildings and climatic conditions of South Tyrol. After that, the impacts of current retrofit solutions should be assessed in present climate scenarios to understand their effect on energy use, indoor climate, and envelope moisture dynamics (Task B). With this knowledge, the additional impact of climate change could be assessed in the next task (Task C). Current retrofit solutions are simulated under future climate scenarios, and the results are compared with the results obtained in Task B. Meanwhile, the original buildings without any retrofit are simulated for comparison. Based on the performance of current retrofit solutions in present and future climate scenarios, improvements are suggested and verified (Task D).

For each research task, several hypotheses are proposed based on the literature review, which will be presented in the next chapter. Through each task, these hypotheses will be validated or discarded at the end.

1.2.1 Task A: Building categorization and reference buildings

Hypothesis: The local climate closely influences the characteristics of Historic South Tyrolean residential buildings.

Task A aims to select robust and reliable building references based on climate analysis and stock inventory analysis. In this first subtask, the goal is to collect enough data from building inventories to understand the characteristics of historic residential buildings in South Tyrol (SubtaskA.1). Due to the mountainous terrain of South Tyrol, the climate and the extent of climate change in South Tyrol differs significantly. Therefore, it is necessary to divide the whole climate in South Tyrol into homogeneous sub-climate zones (SubtaskA.2). For each climate zone, the correlation between the characteristics of historic buildings and the climate is studied, and the structure of the categorization is defined (SubtaskA.3). For each homogenous category, reference buildings are proposed to present the group (SubtaskA.4). Eventually, five reference buildings are developed for further studies in the following section of this thesis.

1.2.2 Task B: Current best retrofit impacts

Hypotheses: i) Current retrofit solutions will achieve considerable energy savings in winter, ii) their effect on the risk of overheating in summer is limited, iii) if adequately designed, WDR would not suppose a risk for the wall's durability.

Task B aims to assess the performance of the current best retrofit solutions in present climatic conditions. The retrofit solutions should reflect real practice in South Tyrol, so ten retrofit cases are studied (SubtaskB.1). The retrofit package of the historic buildings is studied, including the energy target of the retrofit solutions, the insulation material and thickness, the choice of windows, etc. After a summary of current "best retrofit solutions," their performance is assessed in terms of indoor comfort, energy use (SubtaskB.2), and moisture risks (SubtaskB.3) before and after retrofit solutions. Energy demand and indoor climate are calculated using dynamic simulation software Energy Plus, and the hygrothermal performance of the constructions is calculated by the numerical simulation with Delphin 6.0. Weather files for the simulations contain eight successive years of monitored climate data from 2010-2017.

1.2.3 Task C: Impacts of future climate

Hypothesis: current "best retrofit solutions" i) will achieve limited energy savings in winter, ii) will increase overheating risks in summer, and ii) will increase the risk of moisture-related damages under future weather conditions.

The aim of Task C is to assess the combined impacts of climate change and retrofit solutions. In previous tasks, the effect of current retrofit solutions in present climate scenarios has been determined. To assess the impact of climate change in Task C, future weather data is needed. The weather file includes ten continuously years at the "near" future (2041-2050) and "far" future (2091-2100) (SubtaskC.1). The impact is assessed by looking at the changes in indoor comfort, energy use (SubtaskC.2), and moisture risks in the envelope (SubtaskC.3) before and after retrofit solutions. Eventually, buildings performance under different scenarios is compared.

1.2.4 Task D: Adaptive solutions

Hypothesis: proposed retrofit solutions will achieve balanced performance in terms of energy saving in winter, thermal comfort in summer, and safe moisture conditions under present and future weather conditions.

Task D aims to propose compatible retrofit solutions that could also bring low energy use and improved thermal comfort to each reference building both in the present and future scenarios. The simulation results from Task B & C are analyzed (SubtaskD.1). Based on these results, new retrofit solutions are proposed (SubtaskD.2). To validate proposed retrofit solutions, energy use, indoor comfort, and moisture state of the buildings are compared between "best retrofit solutions" and offered retrofit solutions (SubtaskD.3) in present and future climate scenarios.

2. State-of-the-art

This chapter presents a detailed literature review, which starts with the concept and legal basis of energy retrofit in historic buildings and continues with the potential challenges brought by climate change and retrofit interventions. The impacts of climate change and retrofit on the performance of historic buildings are summarized into three aspects: energy consumption, indoor climate, and building conservation.

2.1 Concepts and related regulations

Historic buildings are defined in this paper in line with the scope of European standard EN 16883:2017 *Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings* [17]. That is, a historic building does not necessarily have to be formally "listed" or protected. Historic building, therefore, refers to any building that is worth preserving. This study focuses on listed historic buildings [18] since they have the priority to be conserved and retrofitted, and specifically on residential buildings, as they represent the largest portion of the listed stock in South Tyrol and most parts of Europe [19, 20]. At the same time, retrofit refers to the modification of the existing structure, aiming at improving the building's conditions to an acceptable level while minimizing energy consumption.

Mitigation and adaptation are two main policy responses to climate change. Climate change mitigation refers to the efforts to limit global warming through cutting the GHG emission. EU-wide, the climate-energy policy framework has been developed to mitigate climate change since the early 1990s [21]. In 2009, the "Climate and energy package" set three main targets: 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewables, and 20% improvement in energy efficiency [22]. Moreover, the EU renewed its commitment to the goal of keeping global warming below 2°C over pre-industrial levels. Heads of State and Government also formally adopted the objective to reduce emissions by 80-95% by 2050 in comparison to 1990 levels.

In the building sector, several directives are issued to improve the energy performance of both new and existing buildings (Table 1). In EPBD 2002/91/EU [23], a minimum energy performance is defined, but Member States are in charge of the detailed implementation. And after that, EPBD Recast 2010/31/EU [24], the standards to calculate energy performance and the compulsory energy certification are formulated. To fulfil the energy requirements, the directive also introduced the nearly zero-energy building (NZEB) concept. Member States should ensure that by the end of 2020, all new buildings are NZEBs. Directive 2012/27 [25] establishes a common framework in order to ensure the achievement of the 20% headline target on energy efficiency. To fulfil the target, Member states shall establish a long-term strategy for mobilising investment renovation, and public bodies' buildings should play an exemplary role. It is asked to renovate 3% of the total floor area of heated and/or cooled public buildings annually to meet the minimum energy performance requirements. Recast 2018/844 [26] requires the Member States to plan long-term renovation strategies and update every three years as part of the National Energy Efficiency Action Plan. All directives state that buildings officially protected because of their special architectural or historical merit, and buildings for worship and religious activities are exempt from energy performance requirements [25].

Table 1 Directives on the energy performance of buildings

Legislation	Subject matter	Scope	Content
EPBD 2002/91/EU	The Directive promotes the improvement of the energy performance of buildings	New and existing buildings within European Union	• General framework for calculation of energy performance • Application of minimum energy requirements

			• Energy certification of buildings • Regular inspect and assessment of instruments
EPBD Recast 2010/31/EU	Same as 2002/91	New and existing buildings within European Union	• Main content from EPBD 2002/91/EU • Expanded scope of minimum energy requirements • Independent control systems for certificates and inspection • National plans for increasing the number of NZEB
EPBD 2012/27/EU	The Directive establishes a common framework for the promotion of energy efficiency, and removes barriers in the energy market	New and existing buildings within European Union	• Energy efficiency targets for 2020 and obligation schemes • A long-term strategy for mobilizing investment in building renovation • Promotions on energy audit, management, meter, billing, supply systems • other measures to promote energy efficiency
DM 26/06/2015		New and existing Building in Italy	An instrument of attesting building energy performance: • minimum energy requirements • energy certification standards • methods for technical report
EPBD recast 2018/844		New and existing buildings within European Union	Amendment to Directive 2010/31/EU and 2012/27/EU: • Insertion of the emission target and long-term renovation strategies for mobilising investment

All directives state that buildings officially protected because of their special architectural or historical merit, and buildings for worship and religious activities are exempt from energy performance requirements[25].

The DM 26/06/2015 is the latest Italian decree on building energy, and it is derived from European directives. It frames the minimum energy requirements for new and existing buildings. It also provides guidelines for building energy performance certification and for the methodology to calculate the energy performance. Building retrofit actions are classified into two levels. First level renovation refers to interventions (including building service renovation) that affect over 50% of the total heated/cooled area. For first-level renovation, energy requirements apply to the entire building, so benchmarks for primary non-renewable energy, heat transfer coefficient, and elements transmittance are established in the decree. Second level renovation refers to interventions that will affect 25% to 50% of the total heated/cooled area. For second-level renovation, energy requirements apply to the renovated part of the building only. In this case, the heat transfer coefficient and elements transmittance are also set by the decree.

According to EU Climate action, Climate change adaptation means “anticipating the adverse effects of climate change and taking appropriate action to prevent or minimise the damage they can cause, or taking advantage of opportunities that may arise. It has been shown that well planned, early adaptation action saves money and lives later” [27]. Compared with the climate mitigation policies, climate adaptation policies fall behind significantly. The Commission of the European Communities set out a first framework to reduce the EU’s vulnerability to the impact of climate change in the White Paper published in 2009 [28]. It addresses the objectives and actions to increase the resilience of several sectors, including physical infrastructure. A key deliverable is the web-based European Climate Adaptation Platform (Climate-ADAPT) [29]. After that, EU adaptation strategy is launched in 2013 [30]. It fills both knowledge and action gaps and complement these efforts through the strategy on EU level. By creating a basis for better informed decision-making on adaptation and making key economic and policy sectors more resilient to the effects of climate change, this strategy encourages and supports Member States action on climate adaptation.

In building sector, the EU adaptation strategy includes a Staff Working Document [31] which provides guidance to adapt the infrastructure. It addresses the common challenges brought by climate change and the instruments on EU level that might need to be revised. One of the most important type of instrument used to regulate infrastructure sectors are standards. Since 2014, the European Standardization Organizations are fostering the integration of climate change adaptation in standardization of the construction/building sector [32].

2.2 Energy performance of historic buildings

2.2.1 The implications of changing energy needs

A change in the climate will cause a change in the heating and cooling requirements to achieve a comfortable indoor environment. Therefore, energy consumption will vary with the changes. There is still a substantial lack of understanding when it comes to the historic building stock. Most studies investigate how historic building could play its role in climate-change mitigation instead of the impacts of climate change on its energy performance. Retrofit action is justified in a climate mitigation perspective [33], the enablers and barriers for the historic building to mitigate climate change are discussed [14, 34], as well as the energy and GHG emission saving potential (section 2.2.2).

Due to the increasing global temperature, heating load is decreasing, and the cooling load is rising in historic buildings [35], as has been found in general building stock [36, 37]. However, the impact on the total energy use varies with climate zones in general building stock. In the USA [38], a systematic investigation was carried out to analyze the climate change impact on various types of buildings throughout the country. Buildings in hot climates like Houston, Miami, and San Diego, will experience a net increase in primary energy needs while regions in cold or frigid weather will have a decrease. Additionally, Li et al. [39] summarized the impact of climate change on energy use in different climate zones around the world. In severely cold climates, energy use tends to decrease because the heating load reduction would outweigh the modest increase in summer cooling. In the hot summer and cold winter climate zones where both winter heating and summer cooling requirements are essential, the magnitude of reduction in heating and the magnitude of increase in cooling could be comparable. The changes in energy use highlight the need for adaptation and mitigation strategies. Since the existing climate zones may change in the future [40, 41], as well as heating and cooling degree days [42, 43], any new or updated regulation should consider these changes [40]. Moreover, inadequate sizing of systems could lead to energy inefficiency or discomfort. Large variations of energy performance due to climate change are found within and between building types, as well as climate zones around the world [44-47]. In a campus model of Michigan, the additional cooling energy use by the end of the 21st century reaches 46% of the total power plant annual production, which is alarming for the utility [40]. However, in California, climate change only prompts modest increases in grid resource capacity (electric grid configuration on 2050) [48].

2.2.2 Energy retrofit and building performance

The impact of energy retrofit on the energy performance of historic buildings has been examined previously, including a wide range of retrofit interventions regarding the envelope improvement and HVAC system update [49, 50]. Overall, the positive impact of retrofit on the energy performance encourages the promotion of retrofit in historic buildings. For instance, in a historic residential building built in the early 1900s of Havre (USA), an energy retrofit could achieve 81% energy saving with a payback period of 4-8 years [51]. Savings in energy consumption and carbon emissions are a dominant criterion when assessing the effectiveness of an energy retrofit [52]. Previous studies on energy consumption after retrofit confirm the importance (and limitations) of building energy simulation (BES) in assessing the impact of retrofit [52]. Another review work outlined energy retrofit impacts in different building types, and the great energy potential between 20% and 68% in residential buildings is shown [53]. Beyond the energy performance, other topics related to the impact of retrofits in historic buildings, such as the use of new analytical tools [54], or occupancy behavior [55], are currently being investigated.

Established energy targets and the development of new energy systems urges the energy efficiency improvement of the entire built heritage [56]. Thus, the performance of the historic building stock as a whole, rather than at the individual building scale, is also explored. Some practical barriers, like lack of local plans, lack of coordination and integration among local planning instruments, or lack of knowledge of the actual energy situation and intrinsic value of heritage [57, 58], are limiting its implementation at a wider scale. Indicators like EPC (Energy Performance Certificates), vacant ratio, and building age [59] have been used to overcome these barriers. With a similar bottom-up method, Csoknyai et al. developed and compared seven residential building typologies from four countries in Eastern Europe and found that the energy-saving potential achieved with the deep renovation of buildings built before 1945 ranges between 60.4% and 79.8% [60]. Most of Urban Building Energy Modelling (UBEM) rely on typical building typologies or archetypes to represent the most frequent categories in the stock. In [61], an attempt is made to implement heritage value into the building archetypes to improve their reliability. Alternatively, a top-down approach is used to perform the GHG balance of the medieval historic center of Siena (Tuscany, Italy) in [62]. The results show that the installation of photovoltaic panels on the roof (outside the medieval district) could enable the carbon neutrality of the historic center in about 30 years.

2.3 Internal climate of historic buildings: comfort and energy

A building’s envelope is the interface between indoor and outdoor environments. Besides thermal conductivity, the two main interactive processes controlled by this interface and that influence the indoor climate are thermal inertia and air exchange. Temperature in “free-running” buildings is closely dependant of outside temperature because of their reliance on passive strategies [63, 64]. Thermal mass is a passive climate regulation strategy commonly found in historic buildings. Thermal mass refers to construction mass that could store heat. It is usually featured with high heat capacity materials such as bricks, natural stone and tiles [65]. A large body of literature has verified the thermal inertia effect of thermal mass and its benefits for the internal thermal comfort [66-68]. Passive cooling effect combining thermal mass and natural ventilation, especially night ventilation, could remove excess heat to maintain a comfortable temperature during summer. For example, Gagliano et al. [69] verified that thermal mass and ventilation in historic buildings could reduce cooling demand by 30% in a moderate climate. Many investigations showed the principle and effect of night cooling to reduce surface and indoor temperature [70-73]. However, this cooling system relies heavily on buildings’ thermal mass, outdoor temperature daily swing [73], solar radiation, and, ultimately, user behaviour, as it has to be appropriately managed. For example, Gagliano et al. [74] suggested a time lag of 12 to 14 hours for the east walls of a massive historic building (Catania, Italy). Values above that time lag cut down the night cooling length, and values below that weakened the thermal inertia effect. Any change in the climate and building will therefore affect the historic buildings relying exclusively on passive solutions, or imply more energy use to provide a comfortable internal climate.

2.3.1 Global warming and historic buildings

Indoor climate is the result of a complex interaction of several factors, e.g., the building geometry and envelope, HVAC system, occupants, and external climate. Despite the complexity of indoor climate, the direct correlation between internal and external climate has been previously investigated and verified. For instance, Coley et al. [75] explored the relationship between changes of internal and external temperature. The study was based on building simulation and included the dynamic representations of occupancy densities, solar gains, air densities, airflow and heating system. Despite of this complex heat flow, a direct relationship was found fitting to a linear regression with different constants of proportionality (that is, of slop) depending on the building types. Similarly, indoor daily mean temperature has a linear relationship to outdoor running mean temperature [76]. This linear relationship between internal and external temperature could be used to estimate the buildings' resilience to climate change, and it has the potential to predict future indoor climate. In the study of the relationship between indoor and outdoor humidity, it was found that indoor absolute humidity has a strong correlation with outdoor absolute humidity all throughout the year [77]. Kramer et al. [78] established an indoor climate prediction model for historic buildings. In this model, the indoor temperature is an output of outdoor temperature and solar irradiation, and then the indoor relative humidity is calculated by outdoor pressure and modelled indoor temperature. According to these research, indoor climate of historic buildings is strongly related to outdoor climate.

The impact of climate change on the indoor environment of historic buildings has been previously studied and an increase in indoor temperature is found across Europe (e.g., Netherlands and Belgium [79], Southern England [80], Croatia [81]). The changes of indoor relative humidity differ depending on the location: it rises in Netherlands, Belgium and Croatia while shows little changes in Southern England. The growth in temperature could cause both a rise in degradation of the collections and a decline in thermal comfort conditions. But these studies have focused on conservation of historic artefacts rather than thermal comfort of the occupants. Studies on future thermal comfort are still very limited in historic buildings despite the fact that the passive cooling effect of massive walls and ventilation could fail to compensate a future temperature rise. With climate change, there is a growing need for thermal mass and ventilation cooling as different studies have shown. For instance, in Istanbul, the time where ventilation, high thermal mass and evaporative cooling is needed increases from 1.4% to 5.95% [82]. In southern Spain, discomfort hours rise by more than 35% in social multi-family buildings built at post-war period due to climate change [83]. Similarly, a pre-1900 dwelling in London with high thermal mass and ventilation could effectively limit the change of indoor temperature at 2005. Yet, with the external temperature increase, average temperature of the entire house tend to be unacceptable, showing that thermal mass and ventilation cannot ensure a comfortable thermal condition any longer [84]. To add more thermal mass may not be translated to significant thermal comfort improvements [85]. Instead, an adequate ventilation strategy could make vital differences. By improving the ventilation plan, discomfort hours are cut from 53% to 7% in 2080, in a living room of a typical 1960s building in Lisbon (Portugal) [86].

2.3.2 The role of thermal mass and natural ventilation

Retrofit solutions also play a vital role in the configuration of the indoor climate. Pretelli and Fabbri [87] introduced several concepts to describe indoor microclimate of historic buildings at different use phases, which emphasized the changes in indoor climate due to the retrofit interventions. At the same time, the adjustment of indoor climate is usually one of the main aims of retrofit actions to fulfil the requirement of thermal comfort. With the increase in the adoption of retrofit solutions in historic residential buildings, occupants' thermal comfort should also be carefully evaluated.

Internal insulation is a standard solution in the energy retrofit of historic buildings [88-90]. However, the addition of insulation internally may minimise the positive effect of thermal mass and ventilation in summer. Some investigations have looked into these drawbacks. In Cirami et al.'s [91] simulation results, the operative temperature in rooms insulated with six different retrofit solutions is always higher than the un-retrofitted historic wall on the hottest day. However, night cooling could still counterbalance the adverse effect in southern Italy. Similarly, it was found that internal insulation applied to historic masonry walls leads to a temperature rise on the internal surface of up to a 3°C in a Mediterranean climate and, consequently, overheating in the building [92]. Moreover, the constant indoor temperature before retrofit, fluctuates wildly after retrofit.

In summary, previous research has already identified the potential risk of overheating in retrofitted historic building. Combined with an outdoor temperature increase, overheating risk might increase significantly in retrofitted buildings in the future. In Lee et al.'s [64] dwelling case study, overheating occurs in future climates with four different construction typologies (including masonry) due to the addition of insulation. In a retrofitted Victorian house in Birmingham (UK) [93], the overheating hours could be effectively limited to 3% of the occupied hours at present with appropriate window shading and ventilation, while in future this is limited to 10% of the hours in 2050 and 22% in 2080. Without natural ventilation or solar protection, thermal mass cannot remedy the situation. However, the implementation of new solar protection features on historic façades is, in most cases, not feasible due to the need for preservation of original historic style and features. There is still a need for further research to quantify the effect of climate change and to identify alternative retrofit solutions that prevent overheating and achieve thermal comfort both in the present and future scenarios.

2.4 Moisture dynamics in historic walls and building conservation

The hygrothermal performance of historic building materials should be assessed before any retrofit action is implemented to ensure the compatibility of the measures proposed. D'Ayala et al. [94] monitored temperature and relative humidity in two historic walls and concluded that historical brick and mortar have different moisture absorption and desorption characteristics even within the same building. Ultimately, the moisture content (MC) of historic walls with higher surface water absorption coefficients is more sensitive to exterior climate factors such as rain, wind, and solar radiation [95]. When high moisture condition persists, damages like condensation, mold growth, wood decay, and frost damage, may happen. Masonry constructions with low surface temperature are also more vulnerable to these moisture risks due to the increase of relative humidity. These low temperatures are especially found in places such as thermal bridges, corner, or cold attics [96]. Wood, generally used in historic residential buildings, is susceptible to mold growth. With suitable relative humidity and temperature, the decay process will start with mold growth and follow with the fungal attack. Moreover, if the high moisture content continues through winter, frost damage is prone to occur.

2.4.1 The implications of changing precipitation patterns

Changes in climate factors could accelerate the erosion of detailing and construction or undermine binder and coating [5, 97]. Among all climate factors, wind-driven rain (WDR) is particularly important. It can cause both surface erosion and weaken the construction. Erkal et al. [98] summarised the evidence of WDR erosion on historic façade and explored materials' response to three different diameters of rain drops. With bigger drop size, water splashes more and runs off after striking the surface. Several research studies have shown that WDR directly affects the moisture content of historic envelopes. Abuku et al. [99] compared the mold growth risk with and without WDR in a moderately cold and humid climate (Essen, Germany) on the inner side of a historic brick wall (with no insulation). The results showed a severe risk of mold growth in summer and winter when WDR loads are considered, while there is a little risk without WDR loads. In Johansson et al. [100] laboratory study, a 250 mm wall was built to represent the real historic wall situation, and it was exposed to normal rain loads from Gothenburg (Sweden) and Bergen (Norway). The study revealed that WDR is the dominant factor determining the moisture movement in the wall. Furthermore, D'Ayala and Aktas [94] not only verified the adverse impact of WDR but also inferred that more frequent rain could be even more dangerous for the historic envelope. Nik et al. [101] simulated future moisture loads in a wooden wall and found that higher amounts of moisture will accumulate in walls in the future. Beside WDR, moisture that diffuses across the wall as vapour is another main source of moisture. Diffusion across the envelope is strongly related to indoor temperature and humidity [102, 103]. In practice, moisture transport due to imperfection of vapor barrier could increase the vapor transport significantly [104]. Moisture related risks of the envelope are found in buildings with large rates of moisture production or lack of ventilation [105, 106]. Future changes in indoor climate could change the moisture states in historic walls. Physical models are established to facilitate the prediction and control of indoor climate in historic buildings [107-109], which could be an ideal method to investigate the impact of climate change on historic envelope.

Mold growth negatively affects the environmental quality of the internal climate and the durability of the envelope. Different mold risk management approaches have been developed in buildings with or without thermal active controls [110, 111]. However, climate change will impose new challenges on mold prevention. In the last 20 years, mold growth has been observed more frequently than before in ventilated attics of Sweden [112]. Temperature and humidity levels will increase in cold attics in future climate scenarios, and the risk of mold growth increases with these changes. Moreover, to retrofit the attics with insulation could decrease the condensation risk but cannot decrease the risk of mold growth. In the case of wooden structures, their durability depends on the moisture and temperature conditions as well as the exposure time. The decay of the wooden beams is usually caused by damaged downpipes, leaking roofs, and WDR [113]. With more extreme rain events in the future, the risk of water runoff along the masonries due to the unsuitable drainage system will increase, while at the same time inadequate retrofit solutions could further increase the RH in the constructions.

2.4.2 Fabric improvements and hygrothermal performance

Implementation of internal insulation usually changes the moisture dynamics in historic walls. In some cases, internal insulation brings extra vapor diffusion resistance, which will impede the inward drying of the wall. This adverse effect is especially significant in the case of vapor-tight insulation systems. Additionally, the temperature gradient across the original wall is reduced with the addition of insulation. The drying capacity of a historic wall will be drastically reduced with interior insulation, leaving higher moisture content inside historic walls [100]. For instance, Odgaard et al. [114] monitored the hygrothermal performance of a historic masonry wall (with and without diffusion-open insulation) for more than two years. They found that the relative humidity of the insulated wall was 20-30 % higher than the untreated wall. In Kehl et al. [113] simulations, moisture content of wooden beam end in masonry walls is always increased when coupled with interior insulation.

Frost damage is a mechanical weathering process caused by the water freeze-thaw cycle. Due to the changes that retrofit interventions impose on the existing structure (e.g. the lower temperature on the outer surface due to the application on internal insulation), frost damage is more likely to occur. Zhou et al. [115] proposed the number of actual ice growth and melt cycles as an indicator for freeze-thaw cycles. After simulations of uninsulated and internally retrofitted brick walls, an increase of freeze-thaw cycles is found in Switzerland after internal retrofitting. Biseniece et al. [116] studied the thermal behaviour of retrofitted historic buildings with two insulation materials and revealed a possibility of frost damages. As mentioned above, the frequencies and intensity of precipitation in winter may increase in many regions of Europe, which implies enhancing the risk of frost damage.

With moisture accumulation in historic envelopes, the durability of materials and thermal efficiency of the building may be endangered. To prevent this, some historic retrofit projects adopted capillary-active insulation systems that transport the moisture content [117, 118]. However, the results of some investigations still show scepticism about capillary-active insulation systems. Vereecken et al. [119] compared hygric performance of different internal insulation systems in the laboratory: vapor open, non-capillary active system, capillary-active systems, and vapor tight systems. Their results pointed out that, in the steady-state winter conditions, moisture captured by capillary-active systems is higher than the traditional vapor-tight system. X-ray projection analysis showed that the moisture was accumulated between the glue mortar and the insulation. Klõšeiko et al. [120] also confirmed the high humidity levels in capillary-active systems (calcium silicate, aerated concrete, and polyurethane board with capillary-active channels), which increase the risk of mold growth.

Before a retrofit, historic buildings are often sufficiently ventilated by uncontrolled air infiltration through old windows and doors. Any energy retrofit is likely to increase the airtightness of the envelope which could reduce building's capacity to remove any excess of moisture. When combined with inappropriate occupant window operation behaviour, risks of moisture damages could increase [106].

3. Methodology

In this chapter, the main methodologies used in this study are developed. Following the research structure, the first one presented here is the methodology of categorization of the historic buildings stock and the development of reference buildings for further study. Then the methodology of summarizing the current “best retrofit solutions” follows, after which is the methodology to prepare future climate projections. Finally, the simulation models and assessment models of the building performance are explained.

3.1 Building categorization

3.1.1 A Critical Review of Existing Methodologies

Building categories enable grouping different buildings that have similar or comparable features with the scope of being representative. The number of descriptive features depends on the number of target buildings, available building inventory, etc. There are no standardized characteristics; requirements and characteristics are selected for the purpose of the categorization.

In recent studies, one of the most common categorization targets was supporting the assessment of the energy consumption or emission of the building stock (Table 2), i.e., to establish a stock energy/emission model. In that case, archetypes are created representing each category before scaling their energy use according to individual impacts to model the energy use of the entire stock [121]. In previous studies, energy use-related factors such as geometrical and thermal–physical properties of the building, the heating and cooling system, the Climate zone of the building, etc. are used in the categorization [60, 122, 123]. However, selecting all the variables that are significant for building energy performance is not feasible due to limited data availability and the complexity of the energy model. Famuyibo et al. [122] attempted to define the key variables of buildings based on their impact on energy use (Table 2). Through multiple linear regression analysis, typical weekly occupancy pattern (heating season), internal temperature (°C), immersion heater weekly frequency, and air change rate (ac/h) were selected from existing inventories because they are significant variables that influence the total energy use. However, it was found that, due to the limitations of the dataset (lack of data such as occupancy behavior), more than 60% of the energy use variation could not be explained by the model. Moreover, the first three of the significant variables were excluded since occupant-related variables were standardized in the operation of a reference building.

In the case of historic buildings, categorization aims to support not only energy performance assessment but also risk mitigation and the identification of retrofit solutions (Table 2). In some cases, it is used as a process to analyze historic buildings through identifying the vernacular characteristics, cataloging the materials in different construction periods, etc. [124, 125]. Similar to non-historic building categorization, geometrical characteristics such as floor area and number of stories are adopted due to the general availability and their close relation to building energy performance. Thermal and hygrometric features such as construction materials are important for the preservation of heritage and the selection of retrofit solutions and are, therefore, generally used in categorization. In addition to that, the protection degree or other legislative requirements are included in some cases to present the historical significance or renovation limits of the buildings [126, 127]. The construction period is selected because it reveals further information about building typology, construction materials, building equipment, etc. [60, 126, 128]. It helps in the analysis of social, legislative, and technical impacts on building typology. Moreover, features on the settlement level could present the rooting of building stock. Montalbán Pozas and Neila González [124] suggested that categories of historic buildings should consider the sociocultural, economic, and historical contexts. They identified the building categories in a historic stock according to key features on four levels: territory, urban planning, architecture, and construction process, where features like the width and orientation of the streets, typical parcelling of the blocks, etc. help interpreting the development and habitability problems of the stock.

Table 2 Variables found in literature for building categorization

Study	Country	Specific to Historic Buildings	Aim of the Categorization	Key Features used to Describe the Building Categorization
[122]	Ireland	No	To support evidence-based energy and emissions policy	Air change rate, wall, roof, floor, and window U-values, dwelling type (number/area of external walls), heating and domestic hot water system, floor area
[123]	Italy	No	To assess the energy requirements of the residential stock	Construction period, geometrical properties, thermo-physical properties, heating system
[129]	Italy	No	To understand the energy performance of the building stock	Construction period
[130]	Greece	Partly	To plan and promote new energy renovation scenarios	Construction period, building use, number of floors, material
[128]	Hungary	Partly	To assess the vulnerability of building stock to increasing wind	Construction period, construction type, roof configuration, number of stories, building surroundings, materials of the building envelope
[127]	Italy	Yes	To develop energy analyses for regulation and financial strategies	Level of protection, building volume, organization of indoor spaces and adjacent constructions, thermal and hygrometric properties of envelope components
[126]	Spain	Yes	To support the energy retrofit of the building stock	Main use, number of facades, year of construction, protection degree, volume
[131, 132]	Sweden	Yes	To assess and select energy efficiency interventions	Climate zone, type of building, use, size, age of construction, aggregation with adjacent constructions, heating system
[125]	Malaysia	Yes	To improve knowledge and preservation of the built heritage	Demography, ownership, type of settlement, historical background, geographic location, landscape features, communication, accessibility, and surroundings
[60]	Eastern Europe	Yes	To assess the energy requirements and saving potential of the residential stock	Country, construction year, building size
[133]	Portugal	Yes	To support risk mitigation at urban scale	Building size, configuration, and volume, number of floors, distribution systems, building materials, construction period
[124]	Spain	Yes	To provide guidelines for the analysis of historic buildings	Features on four scales: territory, urban planning, architecture, and construction

However, data availability remains an issue [121]. Since historic buildings have a long and complex history of construction and repairs, survey work covering the whole building stock that would be needed is still infrequent. To avoid using deficient data, qualitative approaches are conducted in studies, such as expert evaluations, literature reviews, and on-site surveys [60, 124, 128, 133]. For instance, due to the lack of adequate statistical data, the categorization of Hungarian stock was based on expert judgments [128]. A qualitative study could help understanding the building typology from a genealogy point of view, focusing on how the typologies evolved [134]. It would help linking typologies with their historical context.

Once the key features are selected, the category structure could be defined. There are two main category structures: flow structure and matrix structure, as shown in Figure 1. The category process of a flow structure successively divides the whole building stock according to selected features. The matrix structure is formed with two primary key features. For instance, in the TABULA (Typology Approach for Building Stock Energy Assessment) project [135], building types (single-family houses, terraced houses, and blocks) and construction periods were selected as the two main features. Both structures have strengths and weaknesses. A flow structure allows including enough key features to establish detailed building categories. Still, the key features and intervals should be carefully determined since too many groups could be generated resulting in some categories not being representative. For the matrix structure, only two key features are involved in categorization; therefore, other features should be carefully added into the description of archetypes, without influencing the category results.

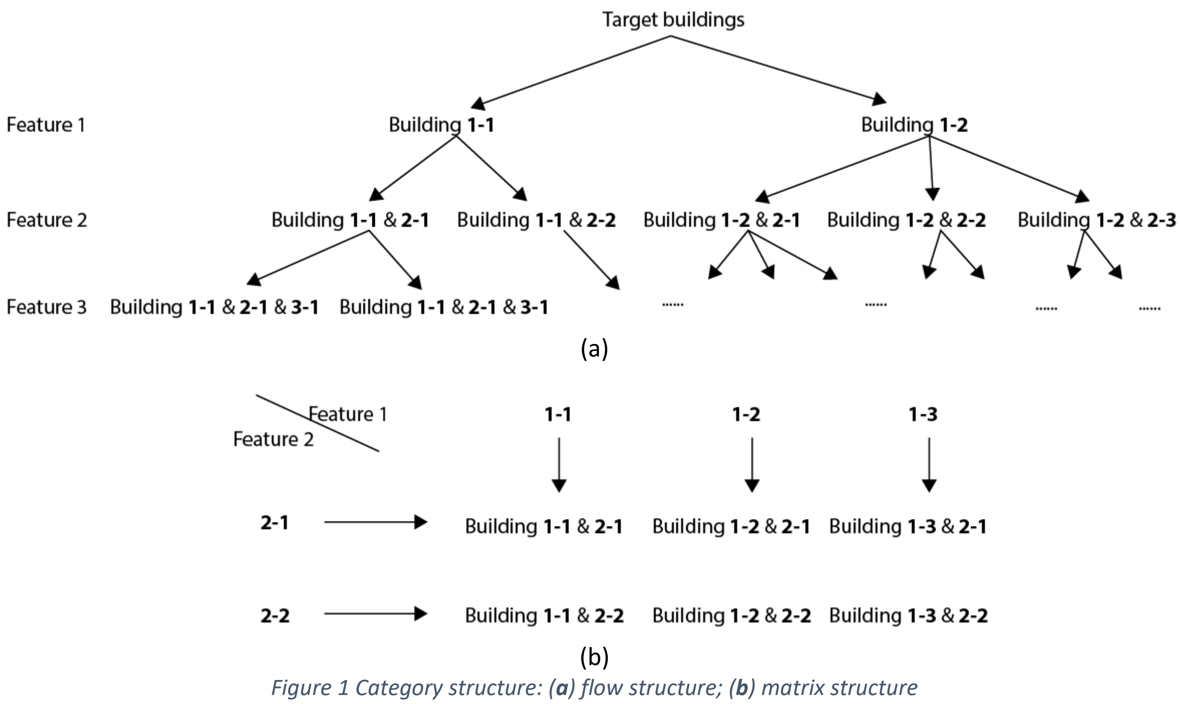


*Figure 1 Category structure: (**a**) flow structure; (**b**) matrix structure*

3.1.2 Categorization methodology

The methodology proposed in this paper is developed to allow building categories to serve as input for further risk assessment and adaptation planning while permitting the possibility to analyze the relationship between climate and building categories.

To identify the relationship between building categories and climate, the climate of South Tyrol is firstly analyzed and subdivided into three homogeneous zones: **Climate zone I, II, and III** (Figure 2, step 1).

In each Climate zone, building samples are randomly extracted from the stock of listed residential historic buildings of South Tyrol (Figure 2, step 2a). Probability sampling (more than 12% of the total stock are randomly selected) is adopted in this study to ensure the representativeness of the sample despite the limited research resources (More details about the Climate zone identification is introduced in 4.2.1, and the building stock and sampling is introduced in 4.2.2).

At the same time, key features are defined according to the aim of the categorization (Figure 2, step 2b) through a literature review, including other categorization studies and previous research on South Tyrolean residential buildings. Results are validated consulting experts on whether the key features are representative and feasible to be used in this study. The criteria to select the expert panel are as follows: people who share an interest in the research project, and who have the knowledge of South Tyrolean historic buildings or have the experience of building categorization. In this study, the expert panel includes three researchers based in South Tyrol with expertise on the energy renovation of historic buildings, as well as a local architect specialized in the conservation and adaptation of South Tyrolean heritage. Then, the defined representative features are collected for the building samples (Figure 2, step 3a), from available building inventories and the literature (step 3b).

After the dataset of key features is established, it is used in a flow structure to categorize the building samples (Figure 2, step 4). Eventually, the key features of the categories are statistically analyzed and compared among different Climate zones (step 5a, Figure 2).

The results are interpreted in the light of a qualitative study of South Tyrolean historic buildings, climate conditions, historic and social-economic events that influenced building customs, etc. (step 5b). By tracing the development of historic buildings, the relationship between climate and building categories is analyzed (step 6, Figure 2).

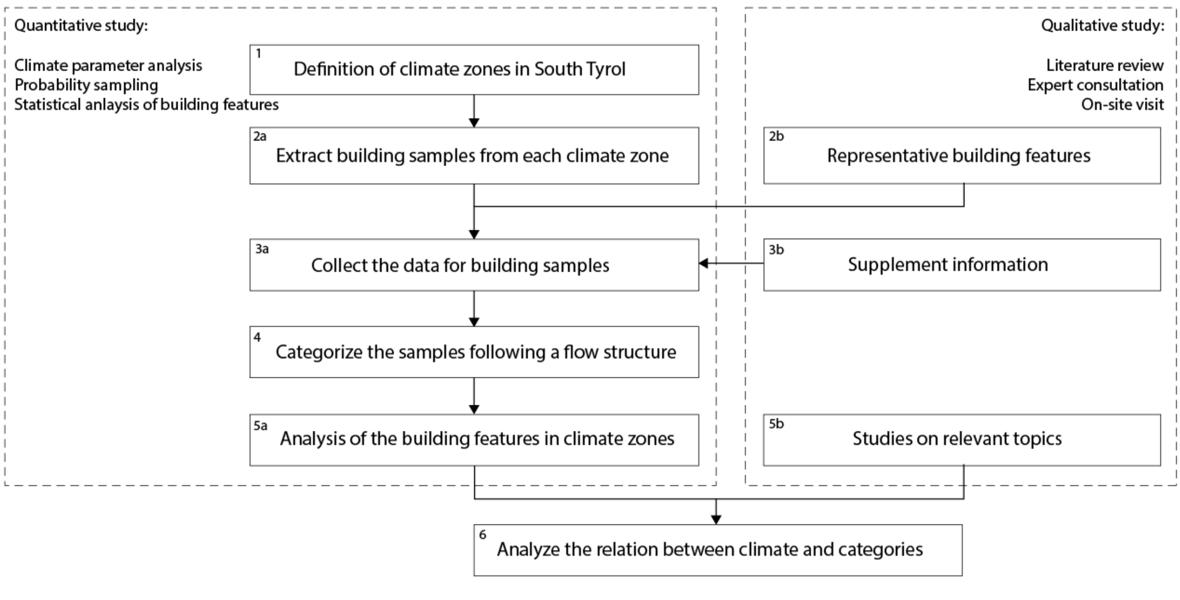


Figure 2 The methodology for categorization

3.2 Identification of current retrofit solutions

To identify current retrofit solutions, “best-practice” cases are collected and analyzed. Good examples are described as a powerful tool that has been successfully used to show what can be achieved (e.g., in terms of energy efficiency) as a way to influence mainstream retrofit practices[136]. The Directive 2018/844 calls the collection and dissemination of best practices in order to facilitate the transition to a highly energy-efficient building stock. In this study, “Best-practice” has been defined as “the best that can be achieved with present technology and methods" [137]. Best-practice examples could, therefore, be a valuable resource for decision-makers and practitioners to learn from, especially if the renovation project is presented together with an explanation of the building's heritage value and cultural significance. Explicitly articulated heritage values support a more informed selection process. As Adams et al. pointed out, "by increasing awareness of the historic features of these buildings, specifically as they relate to energy use, it might be possible to engender attitudes that promote more effective use of the infrastructural legacies of the past."

Best-practices cases are selected from implemented renovation projections of historic residential buildings in South Tyrol region. For each case, energy retrofit should have achieved notable energy-saving, and there is sufficient documentation of the technical solutions. Moreover, the retrofit plan should have considered the conservation of the historic significance of the building.

3.3 Future climate projections

3.3.1 Global & regional climate models, downscaling and bias-correction methods

To obtain climate change projections, climate models use information on greenhouse gas (GHG) emissions and land use patterns to simulate the essential processes in Earth's climate system. These processes are mathematically represented by comprehensive General Circulation Models (GCMs). Several future climate projections have been developed and integrated into IPCC Assessment Reports [1]. However, GCMs have a coarse grid (often 100-300 km), which means that it cannot be used directly for regional building simulations [138]. To obtain high spatial resolution climate change data, as needed for this study, downscaling is widely adopted. In Europe, the EURO-CORDEX initiative provides high-resolution (12.5-50 km) regional climate change simulations [139]. Within the EURO-CORDEX initiative, the GCMs from Coupled Model Intercomparison Project 5 (CMIP5) are dynamically downscaled for the European domain using different regional climate models (RCMs), and here one Representative Concentration Pathways (RCPs), RCP8.5, is used. Concentration pathways represent the GHG concentration scenarios: RCP4.5 is a moderate scenario where GHG emission peak around 2040 and declines afterward; RCP8.5 is a business-as-usual scenario with GHG emissions continuing to rise in the 21st century. There are plenty of studies of climate impact with EURO-CORDEX simulations [140-142]. In the construction field, studies are conducted to explore the changes in heating and cooling degree-days [143] and climate risk analysis [144]. While, in some cases, it is possible to do climate change impact studies directly with the coarse resolution GCMs (such as from CMIP5), here the higher resolution RCMs are used instead. They are expected to provide a more detailed view of the regional climate, which is more appropriate for local impact studies such as building simulations than the large-scale patterns in GCMs.

Statistical downscaling and dynamical downscaling are two approaches to produce higher resolution output from GCMs. Dynamical downscaling means using some physically based model (such as regional climate models) to create regionalized climate information from the GCM while statistical downscaling predict local climate variables according to their statistical relationships with the large-scale GCM data [145]. Dynamic downscaling is physically based with consistent data sets across different variables but computationally expensive and requires significant modeling effort. In the case of statistical downscaling, it is less computationally demanding. Still, it requires long-term, high-quality observation data to establish a robust mathematical relationship between local and large-scale variables.

The raw output of climate projections can show systemic biases compared to observational data since climate models are just a simplified model of the earth climate system. The errors will be introduced into subsequent downscaling chains if there are no bias adjustments towards observation. Therefore, algorithms are developed to minimize these biases. Quantile mapping (QM) is routinely applied to correct biases of regional climate model projections compared to observational data [146]. However, there are some weaknesses in the application. Firstly, quantile mapping has been found to artificially corrupt future model-projected trends in some cases, especially for precipitation [147]. Cannon et al. [148] compared QM, quantile delta mapping (QDM), and quantile detrended quantile mapping (DQM) in modifying GCMs trends in terms of mean precipitation and precipitation extremes indices. They concluded that QM could inflate the magnitude of relative trends in precipitation extremes with respect to the raw GCM, often substantially, as compared to DQM and especially to QDM. Considering this drawback, QDM is adopted in the present study. Secondly, QDM is usually applied to univariate time series and neglects the dependence between different variables [149]. Since multiple climate variables are used in the present simulations simultaneously, a multivariate bias correction was adopted instead, which preserves the correlations between the variables. It is based on QDM and an *N*-dimensional probability density function transform (N-pdf); the method is called MBCn [150].

To study climate change impact on historic buildings' performance, information on the respective climatic forcing at hourly resolution is required in many cases. Standard climate scenario products (obtained by downscaling and bias-correcting climate model information, as explained above) are, however, typically available at a daily resolution only and, hence, they need to be further disaggregated to hourly series. There are several methods to construct hourly climate series for building simulation from RCMs. Stochastic weather generators, temporal disaggregation, and dynamical downscaling are three main approaches. Stochastic weather generators calculate statistics of observed time series and apply these statistics using a random number generator to obtain a new time series with equal statistical characteristics [151]. In this approach, several sample series are selected from observed data according to its similarity to the modeled series, and one sample is randomly chosen to adopt its hourly values [152]. Dynamical downscaling is physically based and is therefore more complex and computationally expensive [153]. Temporal disaggregation is to apply deterministic equations or simple statistical models to daily time series in order to derive hourly values. This approach is simple but has the potential to include statistical evaluations of the observed data and to reconstruct the originally measured hourly values since they are forced by actual daily values [154]. In this study, temporal disaggregation is adopted. The open-source MEteoroLOgical observation time series DISaggregation Tool (MELODIST) [151], provides a robust and fully documented methodology. Its algorithms were validated against observed time series for five sites in different climates, and the results indicate a good reconstruction of diurnal features at those sites [151].

3.3.2 Climate model selection

The combination of numerous emissions pathways, GCMs, and RCMs results in a wide range of future projections. This so-called model ensemble approach is more robust than using only one single climate model. It can also quantify model uncertainty, but it can result in up to 40 different model simulations, e.g., with the EURO-CORDEX data. It is a big challenge to assess the impact of abundant climate change projections on building performance. For instance, to simulate the performance of several buildings with different retrofit solutions with the climate data from all GCM-RCM combinations and two emission pathways will be difficult and costly. The number of the GCM-RCMs multiplies the number of simulations. Therefore, there is a need to limit the number of climate models.

One method is to cluster the model ensemble through analysing their variations in future predictions [155, 156]. By cluster analysis, the ensemble can be reduced to a subset of representative models, and the computational costs of further impact study are reduced.

In the present study, model selection was based on the climate change difference, comparing the differences in seasonal temperature and precipitation from 2071-2100 to 1971-2000 for RCP8.5, for all four seasons (winter, spring, summer, and fall) and all three stations representing Climate zone I, II and III. Models are clustered using PAM (partitioning around medoids), and k=4 clusters is chosen because it produces the best visual clustering results. The medoid model is selected for further analysis. The GCM and RCM combination of these four climate models are shown in Table 3, and they represent the possible range of simulated future changes in seasonal temperature and precipitation, which is the magnitude of the expected seasonal warming as well as the different changes in precipitation (e.g., drier summers, wetter winters, no change)

Table 3 GCM and RCM combination, RCP of the selected climate models

Acronym	GCMs	RCMs	RCP
M1	ICHEC-EC-EARTH	DMI-HIRHAM 5	8.5
M2	ICHEC-EC-EARTH	SMHI-RCA 4	8.5
M3	IPSL-IPSL-CM5A-MR	SMHI-RCA 4	8.5
M4	MPI-M-MPI-ESM-LR	CLMcom-CCLM 4	8.5

3.4 Energy demand and indoor climate calculation models

Energy demand and indoor climate are calculated using EnergyPlus 8.7.0 [157], which is a whole building simulation program developed by the LBNL Simulation Research Group, the Building Systems Laboratory at the University of Illinois, the Florida Solar Energy Center, National Renewable Energy Laboratory, and others for the U.S. Department of Energy. It is validated in analytical, comparative, release, and executable tests using industry-standard [158]. The heating energy demand for the building under different climate and retrofit scenarios is calculated based on the temperature setpoint during the heating period, while indoor temperature and relative humidity (RH) in summer are calculated in free-floating conditions, without any mechanical cooling system.

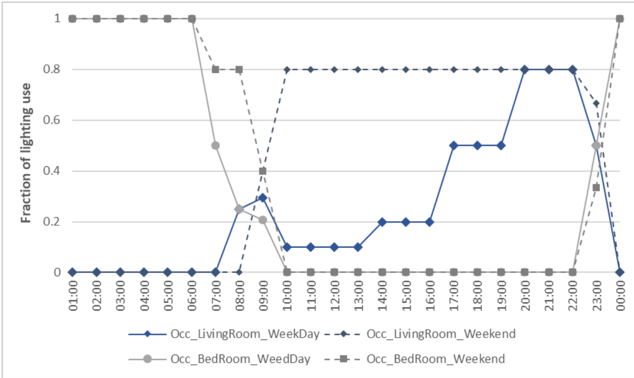
The assumptions and variables used for the simulations are reported in Table 4. The heating period of Climate zone I is defined according to the Italian requirement on Heating Degree Days (HDD): October 15th –April 15th, 14 hours/day. Since there are no limitations to heating period and heating hours for Climate zone II & III, a heating period from 15th September to 15th April is defined as resulted from comparing the HDD between Climate zone A and B, C.

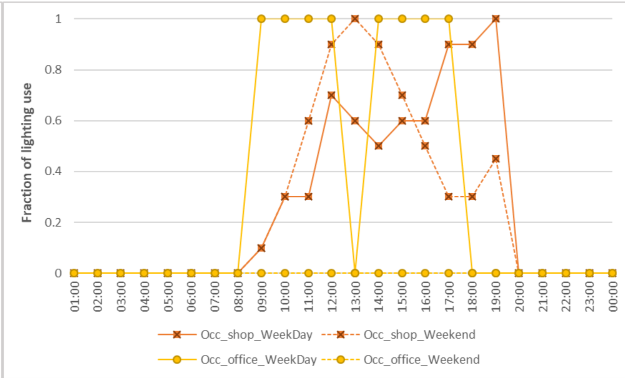
The occupancy, lighting, and electric appliances profiles are based on ISO 17772-1 [159] and the 2014 Building America House Simulation Protocols [160]. 17772-1 offers an informative occupant schedule for the energy calculations of residential buildings. However, this schedule does not differ between the living room and bedroom, which makes the comfort assessment during occupation time incorrect. Therefore, the fraction of occupants in 17772-1 is distributed for the living room and bedroom according to their ratio in the 2014 Building America House Simulation Protocols. Airtightness of the building envelope before retrofit is defined according to literature review: 10 ac/h, at 50 Pa. In the literature, the average infiltration rate of 53 historic houses from Estonia, Finland, and Sweden is 8.43 ac/h, at 50 Pa [161]. In the UK, the infiltration rate of 471 homes rages from 9.9 to 16.5 ac/h. When restricting the construction year from pre-1900 to 1949, the infiltration rate ranges from 10.5 to 16.5 ac/h [162]. The value after retrofit is defined according to CasaClima standard (A): 1.5 ac/h, at 50 Pa [163]. Natural ventilation is on when the room is occupied, the indoor temperature is higher than 24°C, and the outdoor temperature is more top than 18°C. It is modeled by simplified ventilation calculations in EnergyPlus' Wind and Stack Open Area model. Moreover, the ventilation rate is checked with the requirement of UNI 10339: 1995, based on an average ventilation level of residential buildings with a normal level of comfort expectation.

Table 4 Assumptions and variables used for the simulations

<table>
<tr><th colspan="2" rowspan="2">Parameters</th><th colspan="3">Value</th></tr>
<tr><th>Climate zone I</th><th>Climate zone II</th><th>Climate zone III</th></tr>
<tr><td colspan="2">Heating period</td><td>October 15th – April 15th, 14 hours/day</td><td>September 15th – May 15th, whole day</td><td>September 15th – May 15th, whole day</td></tr>
<tr><td rowspan="2">Setpoint temperature</td><td>Occupied hours</td><td>22°C</td><td>22°C</td><td>22°C</td></tr>
<tr><td>Un-occupied hours</td><td>18°C</td><td>18°C</td><td>18°C</td></tr>
<tr><td>Occupants profiles (occupancy profile by day type and space type)</td><td>42.5 m²/person in rural farmhouse

28.3 m²/person in Portici house

17m²/person in shops and 10m²/person in offices of Portici houses.</td><td colspan="3">


</td></tr>
<tr><td colspan="2">Infiltration rate</td><td colspan="3">Before retrofit: 10 ac/h, at 50 Pa;
After retrofit: 1.5 ac/h, at 50 Pa</td></tr>
<tr><td colspan="2">Ventilation rate (ventilation is active when:)</td><td colspan="3">1. The room is occupied
2. indoor temperature is higher than 24°C
3. the difference between indoor and outdoor temperature is higher than 3°C</td></tr>
</table>

3.5 Moisture dynamic models

The hygrothermal performance of the retrofitted wall is calculated employing numerical simulation with DELPHIN 6.0. It is a simulation program for the coupled heat, moisture, and matter transport in porous building materials [164]. It stimulates the transient transport of heat and moisture using dynamical boundary conditions. Meanwhile, thermal and hygric inertia of construction is considered. The code of DELPHIN goes back to 1987 when a transient one-dimensional (1D) heat transport is developed [165]. The software is further enhanced by upgrading of new physical models, developing algorithms for two and three-dimensional problems, etc. This simulation tool has been validated in several aspects, comparing predictions with measurements and tested in numerous studies [14, 166-169].

Both the characteristics of the wall construction and internal and external climates have a significant influence on the hygrothermal performance of the envelope. Table 5 presents the defined wall characteristics and boundary conditions. The literature review suggests that WDR is the primary source of moisture, influencing the dynamic across the wall. WDR is calculated according to EN 15927-3 [170], where the wall index is an important parameter estimating the quantity of water impacting a wall of any given orientation. It takes into account the topography, local sheltering, and the type of building and wall [170]. In the simulated reference buildings, the wall annual index is defined with the following assumptions: in Climate zone I, the reference building locates in suburban (Terrain category III) with obstructions from 25-40 m away. In Climate zone II and III, the reference building stands in a farmland with boundary hedges (Terrain category II), on flat ground, and it is a freestanding building with a distance of obstruction 60 m away. A worst-case scenario approach is used in the simulations, choosing the orientation most exposed to WDR for the calculations. Indoor temperature and humidity levels are derived from the daily mean of the external air temperature, according to EN 15026 [171].

Table 5 Parameters and values used in the hygrothermal simulations

Input parameter	Value Climate zone I	Climate zone II	Climate zone III
Wall conditions			
Wall orientation (degree from North)	180° (South)	270° (West)	90° (East)
Wall indices	0.13	0.20	0.20
Reduction coefficient of WDR	0.7	0.7	0.7
Outdoor boundary condition			
Heat conduction	Convective heat conduction exchange coefficient: 12 [W/m^{2}K] Effective heat conduction exchange coefficient: 12 [W/m^{2}K]		
Vapor diffusion mass transfer coefficient	7.5e-08 [s/m]		
Solar absorption coefficient	0.7		
Long-wave emissivity	0.9		
Indoor boundary condition			
Indoor climate	DIN EN 15026/WTA adaptive indoor climate model: temperature waves from 20 to 25°C; relative humidity waves from 35% to 65%		
Surface heat transfer coefficient	Convective + radiative: 8 [W/m^{2}K]		
Surface vapor diffusion coefficient	2.5e-08 [s/m]		

3.6 Assessment models

In order to evaluate the building's performance, assessment criteria are required. Effective assessment models offer feedbacks through evaluation criteria, which lead to a better understanding of climate change and retrofit impact, and ultimately, to better-informed solutions.

3.6.1 Indoor comfort assessment

Two approaches have been used in the evaluation of indoor overheating levels in the present study. Firstly, a deterministic approach using fixed thresholds from CIBSE Guide A [172]. Secondly, according to the adaptive thermal comfort model proposed in EN 15251 [173]. Both approaches offer temperature benchmarks in the form of operative temperature. The CIBSE Guide A recommends 23-25 °C for living rooms and bedrooms during summer and defines the overheating criterion as 28 °C for living areas and 26 °C for bedrooms. The advantage of this approach is its simplicity, but the downside is that it assumes the particular combinations of the occupant metabolic rate and clothing insulation levels. The alternative method, the adaptive approach, argues that occupants can adapt the indoor thermal conditions through window operation or clothing arrangement. It was developed from extensive field studies and defined the comfort temperature range in free-running buildings as a function of the outdoor running mean temperatures. Its upper and lower limits used in this study are:

$$\theta_{max} = 0.33\theta_{rm} + 18.8 + 3 \qquad \textit{Equation 1}$$

$$\theta_{min} = 0.33\theta_{rm} + 18.8 - 3 \qquad \textit{Equation 2}$$

where θ_{rm} is the running mean outdoor temperature.

These limits apply when $10°C < \theta_{rm} < 30°C$ for the upper limit and $15°C < \theta_{rm} < 30°C$ for lower limit. However, the outdoor running mean temperature of South Tyrol could be higher than 30°C, resulting in some overheating hours being out of the range. Therefore, it is defined in this study that when $\theta_{rm} \geq 30°C$, $\theta_{max} = 31.7°C$.

3.6.2 Condensation assessment

Condensation occurs when the water vapor pressure exceeds the corresponding saturation vapor pressure. When assessing the interstitial condensation risks in our cases, the over-hygroscopic moisture range (the moisture range above 95% relative humidity [174]) is also considered as a risk range since it is particularly relevant for the durability of any structure. Fungal degradation and mold growth occur in this range [175], and wood fibreboard used in energy retrofit is highly vulnerable to fungal and mold as a bio-based material [176]. The number of hours within the over-hygroscopic moisture range help quantifying the risk of interstitial condensation and material degradation. However, condensation can only cause substantial damages if it occurs persistently. Therefore, the risk is further divided into three levels considering the possible evaporation of the moisture content. The risk level thresholds are presented in Table 6.

Table 6 Proposed condensation risk thresholds for the hygrothermal assessment of insulated wall

	No risk	Low risk	High risk
Risk levels	Highest RH of all the simulated years is <95%	Highest RH is >95% in less than 50% of the simulated years	Highest RH is >95% in more than 50% of the simulated years

3.6.3 Mold risk assessment

Mold growth on the historic envelope and inside the construction will hamper indoor environment quality and the durability of the heritage envelope. This study uses the VTT model to assess the risk of mold growth. The model was established to measure mold growth primarily on wood and organic materials [177, 178], and was extended to other materials [179]. It is widely used in research [112, 180].

Mold growth will occur when $RH \geq RH_{crit}$. The following equation calculates the RH_{crit}:

$$RH_{crit} = \begin{cases} -0.00267\theta^3 + 0.160\theta^2 - 3.13\theta + 100, when\ \theta < 20°C \\ RH_{min}, when\ \theta \geq 20°C \end{cases} \quad \textit{Equation 3}$$

where θ is temperature, RH_{min} is depended on the base-material type, and it is 80% for sensitive materials and 85% for resistant materials.

The mold growth intensities under favorable conditions is given by [181]:

$$\frac{dM}{dt} = \frac{1}{7 \cdot exp(-0.68\ ln\ T - 13.9\ ln\ RH + 0.14W - 0.33SQ + 66.02)} k1k2 \quad \textit{Equation 4}$$

where k1 represents the intensity coefficient that depends on mold growth level, and k2 represents the moderation of the growing intensity when the mold growth index (MGI) level approaches the maximum peak value. The type of the base material influences these two factors. W (wood type, 0=pine, and 1=spruce) and SQ (surface quality, 0 for sawn and 1 for kiln dried) are factors that describe the material surface, for non-wooden materials. In this case, W=SQ=0 is used.

Under unfavorable conditions, a decline in mold growth index is given by:

$$C\left(\frac{dM}{dt}\right) = \begin{cases} -0.00133, when\ t \leq 6h \\ 0, when\ 6h < t < 24h \\ -0.000667, when\ t > 24h \end{cases} \quad \textit{Equation 5}$$

where C is the coefficient for different materials, and t is the time of unfavorable condition.

Mold growth and decay rates relate to temperature, material type, and surface quality. Depending on the mold growth initial condition and growth rate, the Mold Growth Index (MGI) represents the condition between no-mold and 100% mold coverage (Table 7).

In this study, the surface of wood fibreboard is defined as sensitive to mold growth, and the growth rate shows a relatively low decline. Climate board is defined as medium resistant to mold growth, and growth rate shows a relatively small decline. Mold risk is assumed to exist when MGI exceeds 3 [181], and if the mold growth persists over time (MGI increases or remains above 3 in more than half of the simulation years), it is further marked as high risk (Table 8).

Table 7 Mold growth index according to the coverage area [181]

Mold growth index	Coverage area
0	No mold growth
1	Small amounts of mold on a surface (microscope), initial stages of local growth
2	Several local mold growth colonies on a surface (microscope)
3	Visual findings of mold on surface, < 10 % coverage, or < 50 % coverage of mold (microscope)
4	Visual findings of mold on surface, 10 - 50 % coverage, or >50 % coverage of mold (microscope)
5	Plenty of growth on surface, > 50 % coverage (visual)
6	Heavy and tight growth, coverage about 100%

Table 8 Proposed mold risk thresholds for the hygrothermal assessment of insulated wall

	No risk	Low risk	High risk
Mold growth	Mold growth index is lower than 3	Mold growth index is higher than 3 but has an obvious decreasing tendency over time	Mold growth index is higher than 3 and the growth increases/persist over time

3.6.4 Frost damage assessment

Frost damage is a mechanical weathering process caused by water's freeze-thaw cycle. The expanse and shrinkage of water in material pores lead to material dilation and contraction. When the expansion tensile strength exceeds the tensile strength of the material, damage occurs. Moreover, the dilation effect accumulates with freeze-thaw cycles. With frequent enough cycles, cracks gradually form and enlarge.

In this study, the risk of frost damage is identified when two criteria are met (Table 9): temperature is below the freezing point of water in pores, and the degree of saturation (S) reaches the critical degree of saturation (S_{crit}). In Vereecken et al.'s risk assessment [182], the freeze-thaw point is assumed to be -2°C. Different materials have different tensile strength, and so the degree of saturation that will lead to frost damage varies. In the present study, the critical value of granite in South Tyrol is set to 80%, and the critical saturation ration of sandstone is equal to 60%, according to Franzen's study [183]. The critical saturation ratio of plaster is set to 30%, according to WTA 6-5 [184]. When the number of freeze-thaw cycles is higher than 50, it is further marked as high risk [185] (Table 9).

Table 9 Proposed frost risk thresholds for the hygrothermal assessment of insulated wall

	No risk	Low risk	High risk
Frost damage	Saturation ratio is always lower than the critical saturation ratio	Saturation ratio is higher than the critical saturation ratio, and there are less than 50 freeze-thaw cycles per year	Saturation ratio is higher than the critical saturation ratio, and there are more than 50 freeze-thaw cycles per year

4. Building typology in South Tyrol

4.1 The impact of climate on building categorizations

Building categorization allows dividing the building stock into several homogeneous building groups according to certain key features such as construction period, building volume, material, etc. Archetypes or reference buildings could be selected from each building group to represent the most significant categories/typologies of the building stock. Obviously, this is only possible within certain assumptions and limits. Yet, these simplifications of the building stock are necessary for policy development and any other activity that aims at addressing the whole built heritage stock. By offering such archetypes, building categorization supports a bottom-up analysis of the building stock that allows an assessment of the energy consumption and potential conservation threats to a large building stock [122, 124, 128].

In the case of historic buildings, however, local influences on building typology due to factors like the evolution of the economic structure, population concentration, and diffusion will challenge the generalizing approach of categorization [186]. The combination of all these factors results in an intricate history of design, construction, and renovation process of the buildings, which makes each historic building unique and hard to be grouped. However, climate change mitigation and adaptation activities require a certain generalization of the built stock.

Among the influencing factors, cultural background, social customs, and, most importantly, the climate should be emphasized. Climate variability can impact culture, landscape, and human settlement [187-189]. Moreover, many studies confirmed the relationship between building characteristics and the local climate. In fact, the morphology, the position, and size of windows, the wall material, etc. of historic buildings present climate-responsive features [190-193]. In Alpine regions, a wide range of landscapes and buildings evolved in the process of inhabitants' adaptation to the local climate. They are a constitutive and essential part of the Alpine identity, sharing similarity in reflecting Alpine living. Building settlement form, construction technique, and other morphological or technical characteristics display the logic of climate adaptation [186, 194]. For instance, the masonry wall is constructed with two external stone layer fillings with aggregates bonded with earth mortar and lime mortar to resist harsh external conditions; the compact volumes limit the thermal dispersion; the size and position of the windows are designed to minimize heat losses; the unoccupied attics reduce the heat loss through the roof thanks to the storage of hay or other fodder [195, 196].

South Tyrol is a typical Alpine region in the north of Italy. It is characterized by its mountainous topography and diverse climatic conditions. Consequently, it offers a good scenario for the analysis of the relationship between climate and building typology evolution.

In summary, climate may have formed the typology of historic buildings in South Tyrol to some extent. Considering severe climate change in the future, historic buildings that were designed, constructed, and renovated according to climatic conditions in the past may be vulnerable to new threats, which will affect their conservation or performance in terms of indoor comfort and energy consumption. Conducting a categorization with a special focus on climate allows analyzing the historical interaction between climate and human dwelling activities and, accordingly, verifying the possible effects of future climate on historic buildings. Furthermore, archetypes representing the main categories could facilitate assessing the performance of the built heritage stock and planning the adaptation strategies in changing climate context.

4.2 Categorization of the Historic Building Stock in South Tyrol

4.2.1 Climate zone of South Tyrol

The whole region of South Tyrol covers 7400 km^2 with altitudes ranging from 190 m to more than 3000 m above sea level (a.s.l.) (Figure 3). The surface area below 1000 m a.s.l. covers 14.1% of the total area, while the surface area over 1500 m a.s.l. represents 64.4% of the total area [197]. Due to the mountainous topography, diverse climate conditions can be found. To analyze the variability of the climate across the region, data of different locations in South Tyrol are required. In this paper, climate data is used from (i) Provincia Autonoma di Bolzano Alto Adige (including data of 30 representative weather stations), and (ii) results of the 3PClim project [198].

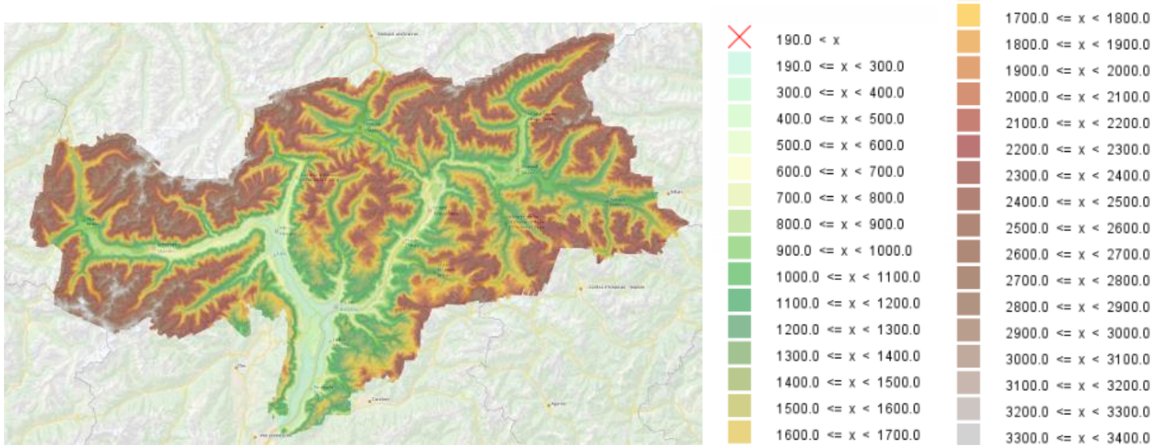


Figure 3 Elevation of South Tyrol (extracted from the digital terrain model (http://geokatalog.buergernetz.bz.it/geokatalog/#!)

Sub-climate types are defined according to criteria introduced below, which describe the similarities and distinctions in climate patterns. The Climate zones are generated based on the results of the 3PClim project, where geostatistical interpolation methods were applied with the aid of programming software and geographical information system software [198].

The descriptive criteria are firstly defined with the consideration of Köppen climate classification [199], a widely used climate classification system [200, 201]. The main parameters used in Köppen climate classification are annual and monthly sums of precipitation, and annual and monthly mean temperature. The fundamental scheme of climate classification includes five major climate types (tropical, dry, temperate, continental, and polar) covering the whole global climate. According to Köppen climate classification, the weather stations found in South Tyrol would fall into four different Climate zones: Cfa, Cfb, Dfb, and Dfc. The differences between the four climate zones are shown in Table 10, and they are all due to temperature factors. However, precipitation varies widely in South Tyrol from a regional point of view (Figure 4). Since precipitation has a significant impact on a building's hygrothermal performance, it is necessary to include precipitation in the climate zone definition in this study.

Table 10 Climate differences among four climate zones defined by Köppen climate classification. T—temperature

	Cfa	**Cfb**	**Dfb**	**Dfc**
Average T of the coldest month	0 °C–18 °C	0 °C–18 °C	≤0 °C	≤0 °C
Average T of the warmest month	≥22°C	<22°C	-	-
No. of months with average month T ≥10 °C	-	≥4	≥4	<4

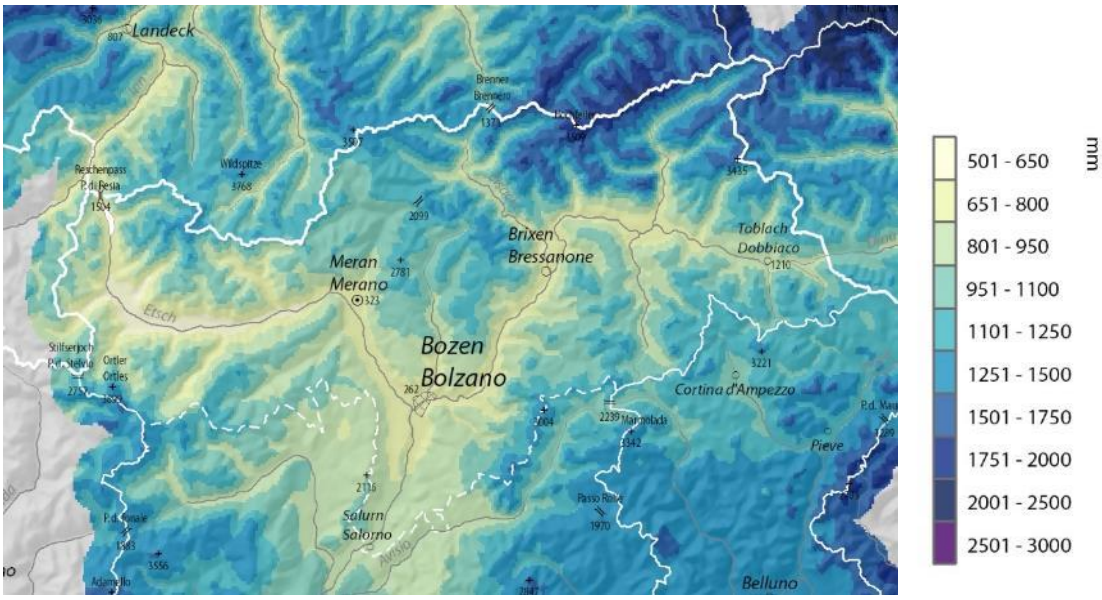


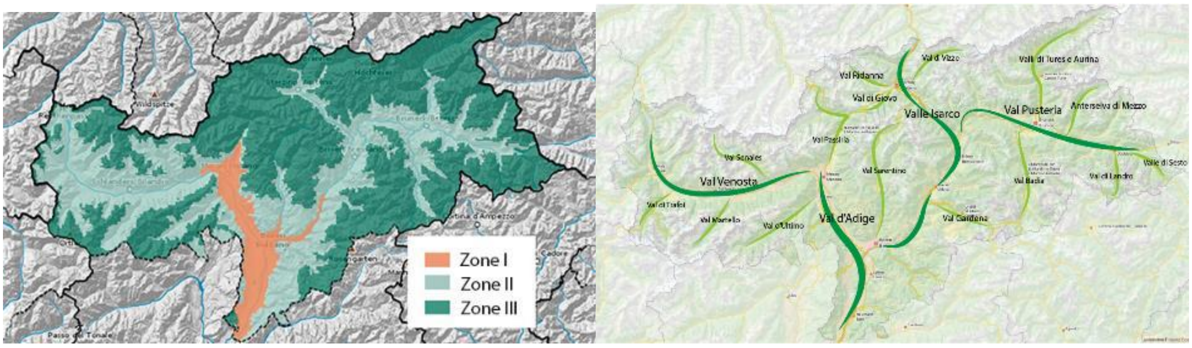
Figure 4 Mean annual total precipitation of South Tyrol (reference period: 1981–2010 (http://www.3pclim.eu/)

In this study, the average temperature of the coldest month is used to divide the relatively warm zones from the relatively cold zones. To emphasize the impact of precipitation on climate classification, the median amount of rainfall of 30 representative weather stations is introduced as a criterion to differentiate between relatively dry and relatively wet zones. According to these two criteria, four sub-Climate zones are defined (Table 11).

As shown in Figure 5, Zone I lays at the southern part of South Tyrol, covering regions with an altitude below 800 m. Zone I covers Val d'Adige that stretches from Salorno northward to Merano and runs westward along Val Venosta to Naturno. In the east, it covers a narrow strip of low land along Valle Isarco. Zone I also includes the southern part of Val Sarentino that has relatively low altitude. The climate of Zone I is characterized by relatively warm temperatures and less precipitation. Compared to Zone I, Zones II and III have lower temperatures. Zone II distributes mainly in two parts: (a) the western part of South Tyrol, which includes Val Venosta and its side valleys such as Val Senales, Val di Trafoi, Val Martello, and Val d'Ultimo below 1300 m a.s.l. in elevation, and (b) the eastern part comprising the districts of Val d'Adige and Valle Isarco, where the altitude is around 600 m–1300 m, as well as Val Pusteria and its side valleys. The climate of Zones II and III differs in precipitation (Zone II has less precipitation). Zone III includes the vast highland in central and eastern South Tyrol. A fourth Climate zone could be defined but is not included in this study due to its limited presence in the region.

Table 11 Climate differences among climate zones in this study

	Zone I	**Zone IV**	**Zone II**	**Zone III**
Average T of coldest month	0 °C–18 °C	0 °C–18 °C	≤0 °C	≤0 °C
Average annual precipitation	≤825.2 mm	>825.2 mm	≤825.2 mm	>825.2 mm
Description	Relatively warm and dry	Relatively warm and wet	Relatively cold and dry	Relatively cold and wet

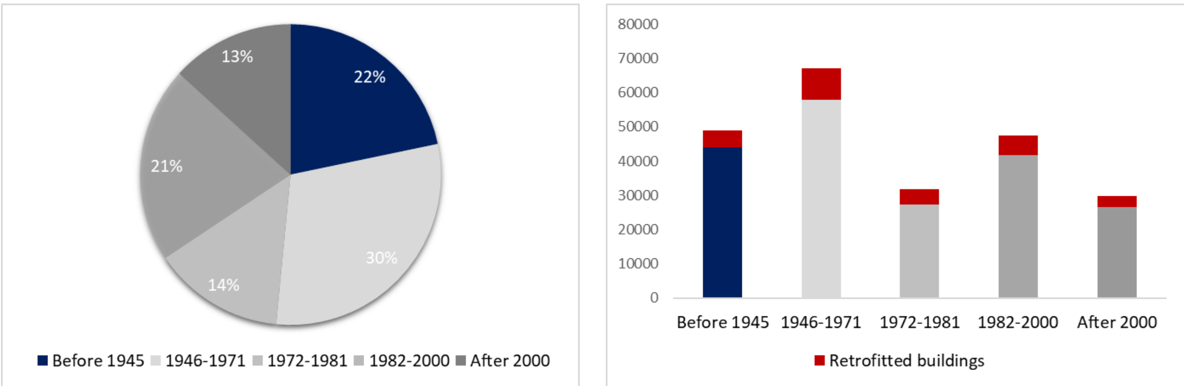


(a) (b)

Figure 5 (a) Climate zones in South Tyrol; (b) main valleys in South Tyrol

4.2.2 Historic Residential Buildings in South Tyrol

According to the 2017 population census of South Tyrol [202], the residential stock is composed of 225,483 buildings in total [202], 34,160 of which were built before 1919 and 14,840 of which were built during 1919–1945. These two parts comprise 22% of the total stock (Figure 6). Only 10.4% of this stock was retrofitted in the past ten years (Figure 6).

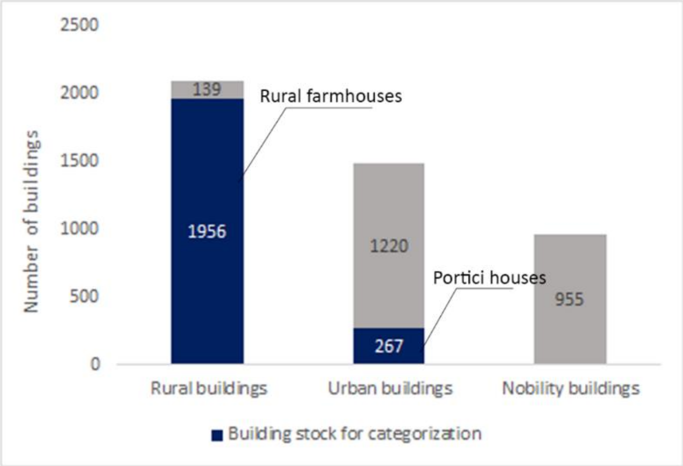


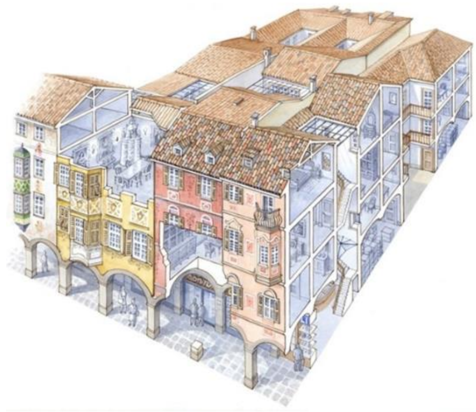
(a) (b)

*Figure 6 (**a**) Residential buildings by construction period; (**b**) residential buildings retrofitted during the last 10 years by construction period [202]*

Among the large residential stock, 4537 residential buildings in three categories (rural buildings, urban buildings, and nobility buildings, Figure 7) are listed as historic buildings under protection. Since rural farmhouses form the outstanding landscape of the Alpine space, they are selected to be studied under the category of rural buildings (Figure 7). In urban structures, the trade–residential nucleus, the Portici house (Figure 7), is studied because it is the essential urban residence in the culture, social, and economic centers of the cities in South Tyrol. They can be found in the towns of Merano, Bolzano, Egna, Bressanone, Vipiteno, and Glorenza. For rural farmhouses and Portici houses in each Climate zone, building samples are randomly extracted, ensuring a confidence interval lower than 15% and a confidence level of 95%, as shown in Table 12.

Even though the application of the proposed methodology is on listed historic buildings, it could be used for any historic building stock.





(a) (b)

Figure 7 (a) Listed residential buildings in South Tyrol, and the building stock for categorization (data source: http://www.provinz.bz.it/kunst-kultur/denkmalpflege/monumentbrowser-suche.asp); (b) scheme of a Portici house (© Antonio Monteverdi, http://www.antoniomonteverdi.com/sito/?page_id=1228).

Table 12 Information about building samples

Climate zone	Residence Type	No. of Buildings	Sample Size	Sample Size (%)	Confidence Level	Confidence Interval
I	Rural farmhouses	628	90	14.3%	95%	10%
	Portici houses	148	35	23.6%	95%	15%
II	Rural farmhouses	748	90	12.0%	95%	10%
	Portici houses	119	35	29.4%	95%	15%
III	Rural farmhouses	580	85	14.7%	95%	10%

4.2.3 Key Feature Selection

Our literature review showed that the key features used for any categorization should be selected according to the targets of the categorization. Therefore, features that are performance-related and potentially climate-responsive were selected to construct the flow structure for categorization. To better reflect the influence of climate, geographic condition, and historical context, key features were chosen in three scale levels: settlement scale, building scale, and element scale.

On the settlement scale, key features included the compactness of the settlement and the number of the adjacent walls of buildings. Here, "compactness" describes the concentration level of the buildings; a "compact" type means that most of the buildings in this settlement are surrounded by close obstacles, while a "sparse" type means that most of the buildings are exposed to wind and rain without close barriers. Close barriers are defined as obstacles with a maximum distance of 60 m, which refers to the obstruction factor of 0.6 in EN 15927-3 [170]. The number of adjacent walls expresses the density of the settlement layout. The compactness of the settlement influences a building's resilience to extreme climates. In contrast, the number of the adjacent walls affects the energy use of the building and the indoor thermal comfort.

On the building scale, the typical Alpine building forms are considered. Geometrical and thermophysical-related features, including roof projection area, floor number, window-to-wall ratio, and construction material, are collected. Data collection combined onsite and desk-based research. Data are taken from existing GIS (Geographic information system) maps from GeoKatalog of Province Bolzano [203], external inspections, and photo evaluations. Geometrical features may result in different energy performance and thermal comfort according to the literature review, and construction materials present different behaviors in terms of moisture dynamics. The building layout, which indicates the distribution of functional space, is studied from the literature as supplementary information. The layout of residential, farming and commercial spaces influences the heating patterns, i.e., the heating schedule and setpoint of the different spaces, and therefore, it affects final energy consumption.

Valuable building elements, which have historical, cultural, natural, morphological, and aesthetic value, are identified and summarized from the literature. These are the essence of historic buildings and a crucial factor in retrofit decision-making. Any retrofit solution should be compatible with the heritage elements. Therefore, they influence the performance of retrofitted buildings indirectly.

4.2.4 Building Categories

To define a reasonable number of building categories, settlement compactness, construction material, and the number of floors are used to construct the flow structure of the categorization, while other features are used as supplementary information. Eventually, 12 building categories, representing 81.6% of the building samples, are defined for the next chapters of this study (Table 13). All the key features are compared among different Climate zones in the following sections.

Table 13 Building categories of historic residential buildings

Climate zone	Residence Type	Settlement Type	Construction Material	Number of Floors	Category Code [1]	Building Layout	Adjacent Walls	Window-to-Wall Ratio (%)	Roof Projection Area (m^2)
I	Rural farmhouse [2] (R)	Compact (C)	Masonry and wood (attic only) (MW)	3 (3f)	I-R-C-MW-3f	Paarhof [3]	1	0.17-0.2	340
				2 (2f)	I-R-C-MW-2f				
		Scattered (S)	Masonry and wood (attic only) (MW)	3 (3f)	I-R-S-MW-3f		0		
	Portici house[4] (P)	Compact (C)	Masonry (M)	4 (4f)	I-P-C-M-4f	Portici house	2	0.21-0.4	447.6
				3 (3f)	I-P-C-M-3f				
II	Rural farmhouse (R)	Compact (C)	Masonry and wood (attic only) (MW)	3 (3f)	II-R-C-MW-3f	Paarhof	1	0.12-0.19	304
				2 (2f)	II-R-C-MW-2f				
		Scattered (S)	Masonry and wood (attic only) (MW)	2 (2f)	II-R-S-MW-2f		0		
	Portici house (P)	Compact (C)	Masonry (M)	4 (4f)	II-P-C-M-4f	Portici house	2	0.15-0.35	360.1
				3 (3f)	II-P-C-M-3f				
III	Rural farmhouse (R)	Scattered (S)	Masonry and wood (attic only) (MW)	2 (2f)	III-R-S-MW-2f	Paarhof	0	0.07-0.14	270
			Masonry and wood (first floor and attic) (MWW)	2 (2f)	III-R-S-MWW-2f				

[1] The category code is formed with the initials showed in brackets in the columns on the left.

[2] Elements worthy of preservation: façade decoration (e.g., fresco painting, stucco), internal fitting (e.g., carved ceiling, wood-paneled wall), historic windows, wood construction (e.g., Blockbau, Ständerbohlenbau), historic roof, vault construction, etc.

[3] By the term of Paarhof, a farm layout is described where the dwelling building and the farm building stand independently. More information could be found in 5.2.1

[4] Elements are worthy of preservation: façade decoration (e.g., fresco painting, stucco), arcades, bay windows, wrought-iron rails, stone stairs, etc.

4.3 Results and discussion: The Impact of Climate on the Development of Historic Dwelling in the Alps

In this section, the differences in the key features of historic buildings in three Climate zones are presented, as a result of the quantitative study. To interpret and discuss these differences, I make use of the qualitative information resulting from the study of building history. Discussions focus on the particularities that were historically influenced by climate to explore the possible role of climate in shaping the building categories.

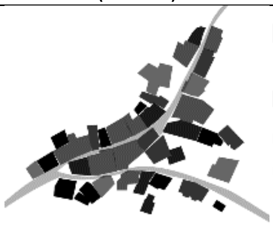
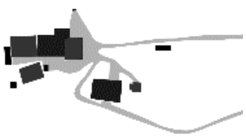
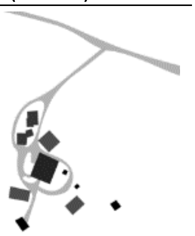
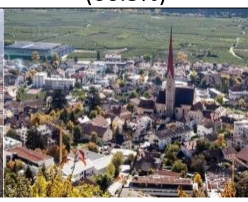
4.3.1 Settlement Level

4.3.1.1. Rural Farmhouse

- Description of quantitative results

According to the sampling survey (Table 14), in Climate zone I, 75.3% of the buildings are in compact settlements, while 44.9% of the buildings are semi-detached (one adjacent wall) and 42.7% are detached. In Climate zone II, the settlements are less concentrated, whereby 55.1% of the buildings are in compact settlements while the others are in sparse settlements. More than 66% of the farmhouses are detached. Climate zone III has 67.7% of farmhouses in sparse settlements, whereas more than 90% of the farmhouses are detached buildings.

Table 14 Rural settlement comparison in three Climate zones

Climate zone	**Zone I**		**Zone II**		**Zone III**	
Settlement type	Compact settlements (75.3%)		Compact + sparse settlements (55.1% + 44.9%)		Sparse settlements (66.7%)	
Typical Diagram						
	Termeno		Chienes	Val di Vizze	Selva dei molini	
Adjacent walls	0 (42.7%)	1 (44.9%)	0 (66.3%)	1 (28.1%)	0 (91%)	1 (9%)
Picture						
	Merano [1]		Silandro [2]	Silandro [3]	Ortisei [4]	

[1] https://pxhere.com/de/photo/1095092

[2] https://www.iha.com.de/ferienwohnungen-schlanders-silandro/ig!/

[3] Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provinz.bz.it/kunst-kultur/denkmalpflege/monumentbrowser-suche.asp?status=detail&id=17282

[4] Wolfgang Moroder, "Der Bauernhof Peza in St. Ulrich in Gröden", https://commons.wikimedia.org/wiki/File:Peza_Sacun_Urtijei_dinsta.jpg, 2016

- Discussion with consideration of qualitative results

Buildings' concentration and density of settlements decrease from Climate zone I to Zone III. This could be due to the interaction of social development, environment availability, and climate diversity. Climate and nature resources are important driving factors for settlement development, especially before modern history, when humans had less resilience against environmental changes. In the north and south of the Alps, periods of warm climate were observed to coincide with land-use expansion and increases in population, while the deteriorated climate was accompanied by land abandonment and reforestation [204]. Through influencing the land use, productivity in agriculture and pasture and the climate variety shape the socio-economic structure, which leads to the concentration of settlement in the long term. The climate in Zone I is more suitable for economic activities (viticulture, apple planting, etc.) compared to that in Zones II and III, which explains the compactness of settlement to some extent. Socio-economic activities and other anthropogenic processes that influence settlements could be seen as reactions to the climate variety [205].

However, climate is not the only factor that determined the form of settlements. Driving factors from the human culture system brought profound changes to settlements of South Tyrol. Most current settlements emerged or consolidated during the Roman dominion, before which Alpine regions were controlled by self-sufficient tribes [167, 206]. The stage stations, garrisons, and markets arranged along the Roman road became the first nuclei in Alpine cities [206]. Furthermore, the distribution of different people may have initiated the differences in settlement form and function. Two distinctive administrative structures, the Romanzo or Rhaetian-Romanzo system and Germanic system [206], resulted in two settlement forms. In the Romanzo system, new settlements emerge in a concentrated style to save space and maintain sufficient land for the whole community. In the Germanic system, the landlords manage the settlement forms and entrust the farms to the peasantry in sparsely populated areas. The settlements are scattered away from each other. In summary, the development of South Tyrolean settlements and the compactness of the settlements are the results of a mutual adaptation between the climate and culture system.

4.3.1.2. Portici House

- Description of quantitative results

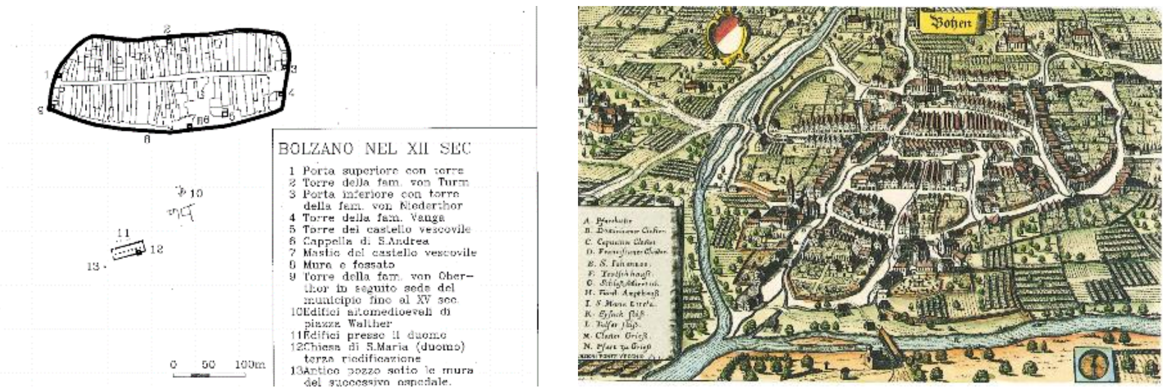
According to the sample survey (Table 15), all the settlements of the Portici house are in compact form, and most of the buildings have two adjacent walls. When comparing the size of the settlements in Climate zones I and II, the dimension of settlements is generally larger in Zone I (notice the length of the Portici district in Table 15). Furthermore, although all settlements have a high density, there is a difference in the aspect ratio (distance to height ratio, D/H) of the main street in different Climate zones (Figure 8).

- Discussion with consideration of qualitative results

The compact form of the Portici settlements is mainly attributed to the requirement of trading activities. In the late Middle ages, a significant climate warming [207] and political consolidation integrated the Alpine region into the urban expansion progress in Europe. The trading and market activities on trans-Alpine routes pushed the development of urban residences in South Tyrol. During the 11th to 13th century, several villages were chartered as cities and granted market rights, which promoted the prosperity of the city and developed local markets and crafts. In Bolzano, bishops of Trento expropriated a piece of land and divided it into parcels during 1022–1055; these trading–residential parcels are called "Laubengasse" or "Via Portici" [208] (Figure 9). These buildings are highly compact to save public land, and they have a uniform building structure, ordered ridge heights, and a controlled alignment line. Along the continuous façade, there are arcades covering the walkway on the ground floor which form an extension space for trade activities. This is a typical Romanesque building model spreading from the southeast of Bavaria to Tyrol, and westward to eastern Switzerland and southern France [209]. Around the trading district, walls, moats, and towers were built to protect the city. Two gates for the trading routes opened at the west and east ends of the "Via Portici". Outside of the walls, there are farmlands and some farmhouses. Due to wars or traffic reasons, the walls were generally demolished later, and, with city expansion, "new" buildings were built surrounding the Portici settlements (Figure 9).

The east-west axis of the Portici settlement in Bolzano and Merano could help in blocking the wind in winter and creating a comfortable local microclimate on the street. Furthermore, the low aspect ratio found in Climate zone I (Figure 8) helps in shading the street in summer, while the higher aspect ratio in Climate zone II permits more sunshine for the buildings. Further studies should be conducted on the impact of the aspect ratio on energy use. Differences are also found in the length of the Portici settlements, while there is no clear evidence that climate difference led to this phenomenon. It may be related to the trading scale and land price of the city.

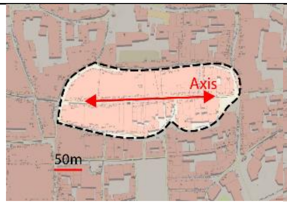
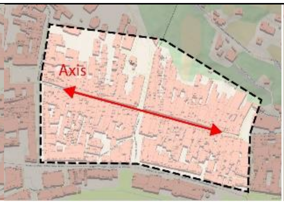
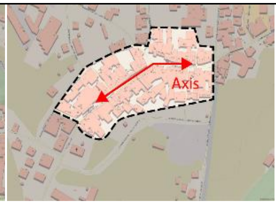
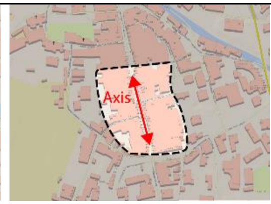
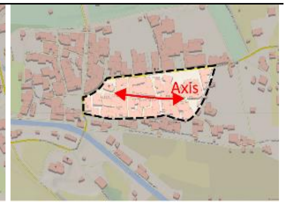
Figure 8 The aspect ratio of Portici houses, left: Bolzano (Climate zone I), right: Vipiteno (Climate zone II)



(a) (b)

Figure 9 (a) Detailed plan of Bolzano at the end of the 12th century; (b) Bolzano in 1645, copper engraving by Matthaeus Merian [208]

Table 15 “Portici” settlement comparison in different Climate zones [208, 210]

Climate zone	**Zone I**				**Zone II**	
“Portici” settlements						
	Bolzano	Merano	Egna	Bressanone	Vipiteno	Gloranza
Street width	4.8–5.8	4.5–6.8	5.2–7.1	6.2–7.2	7.3–8.3	5.2–6.6
No. of Floors	4 (72.7%), 5 (27.3%)	3 (85.7%), 4 (14.3%)	3 (74%), 4 (24%)	4 (71.4%)	4 (74%)	3 (63%), 2 (37%)
Axis	East–west	East–west	East–west	East–west	North–south	East–west
Length	~300 m	~400 m	~250 m	~200 m	~170 m	~100 m
Picture	 Portici 65–67 [1]	 Portici 110–120 [2]	 Via Andreas Hofer 14 [3]	 Via Portici Maggiori 6 [4]	 Gasthof Goldenen Adler [5]	 Via Portici 7 [6]

1 Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=13870

2 Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=15965

3 Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=16308

4 Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=14140

5 Piergiuliano Chesi, https://commons.wikimedia.org/wiki/File:Vipiteno_Gasthof_Goldenen_Adler.JPG , 2010

6 Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provinz.bz.it/kunst-kultur/denkmalpflege/monumentbrowser-suche.asp?status=detail&id=14934

4.3.2 Building Level

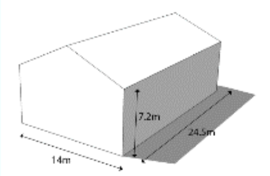
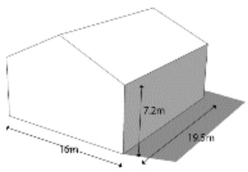
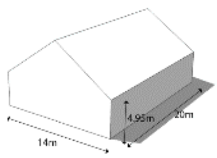
4.3.2.1 Rural Farmhouse

- Description of quantitative results

According to the sample survey, there is a significant difference in the material use between the three Climate zones. Masonry buildings are dominant in Climate zone I (Table 16), where about 77.5% of rural farmhouses are constructed entirely with masonry, and the rest of the buildings are constructed with masonry walls in the lower floors and wood for the attics. In Climate zone II, the use of wood increases. About 46.1% of the buildings are built in masonry, and 39.3% are constructed in masonry with wooden attics. Furthermore, 15.6% of masonry buildings have wooden walls. In Climate zone III, the wood ratio increases further compared to the other Climate zones. Pure masonry buildings account only for 26.7%, while 26.7% of the masonry buildings have wooden attics, and 46.7% of the masonry buildings have wooden walls and attics.

Window-to-wall ratio (W-to-W) decreases from Climate zone I to III. The dimension of the rural buildings in the three climate zones also varies (Table 16). The average area of roof projection decreases from Climate zone I to III with average numbers of 340 m^2 to 304 m^2 and 270 m^2, and the typical number of floors above ground decreases from three to two.

Table 16 Building features of rural farmhouses in three Climate zones

Climate zone	Zone I		Zone II			Zone III		
Material	M	MW	M	MW	MWW	M	MW	MWW
	77.5%	21.3%	46.1%	39.3%	14.6%	26.7%	26.7%	46.7%
W-to-W ratio	0.17–0.2		0.12–0.19			0.07–0.14		
Roof angle	25°–35°		25°–35°			25°–35°		
Floors	3	2	2	3		2		Other
	53.9%	40.4%	52.8%	37.1%		86.2%		13.8%
Roof area	340 m^2		304 m^2			270 m^2		
Main function	Fruit and crop farming, viticulture, dairy farming		Dairy farming, cereals and potato			Dairy farming		
Layout	Viticulture function: in the same building/close to each other; dairy farming: at different altitude		In the same building/close to each other			In the same building/close to each other		
Diagram								

General view			
	Amplatz, Montagna [1]	Umer, Lasa [2]	Unterleiten, Valle Aurina [3]

[1] Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=16079

[2] Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=15539

[3] Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=13640

- Discussion with consideration of qualitative results

Extensive studies showed that the choice of construction materials depends as much on their availability as on cultural reasons [211, 212]. Cultural influence was widely discussed for nationalistic purposes to trace and validate the geographical borders of different cultural regions [206]. The stone structure is deemed as a typical characteristic of Latin and Rhaetian-Romanzo influence, while wood is of Alpine Germanic influence. Dating back to the early Roman period, the Mediterranean colonialists, whose diet was based on bread, wine, and oil, tended to settle in areas suitable for these crops (low-altitude areas). The Germanic people were more dependent on milk and its derivatives, and they could, therefore, settle at higher altitudes [206]. This corresponds to what Roberti et al. [212] observed, whereby a higher elevation denoted a larger proportion of wood in a farmhouse.

In addition to cultural reasons, the material preference in Climate zones shows a correlation with climate, although the construction custom is not necessarily determined by climate. Different people divided the land into areas of different agriculture use according to climate conditions, and the function of the farmhouses followed the agriculture need. The choice of the material relates to the functional layout of the farmhouses.

The oldest type of farming building layout is mentioned in “Lex baiuvariorum”, which is called Haufenhof with multiple buildings [213] (Figure 10). The buildings were limited by construction techniques; thus, most of them were small with one function: the dwelling, the barn, the stable, the granary, the bath, and the kitchen. With technical progress, larger buildings became possible. Paarhof and Einhof evolved from Haufenhof (Figure 11). Paarhof represents the most common type of farm in the Alpine region. In the survey of South Tyrol, about 65% of rural buildings can be described as Paarhöfe [214]. Paarhof can adapt well to every terrain, even to steep ground [215]. Paarhof refers to a farm layout where the dwelling building and the farm building stand independently. In most Paarhof, the farm buildings are constructed with wood, while the dwelling buildings are built with masonry. Einhof is a farm where dwelling function and farm function are located under one roof. It represents 15% of total rural residences in South Tyrol [214]. Like the Paarhof, the farm space is generally constructed with wood. Dwelling spaces, especially the kitchen and living room, are constructed with masonry to prevent fire accidents.

Figure 10 Haufenhof in the Alpine village of Fane-Vals. (Whgler, "Fane-Alm Gesamtansicht", (https://commons.wikimedia.org/wiki/File:Fane-Alm_Gesamtansicht.jpg, 2015)

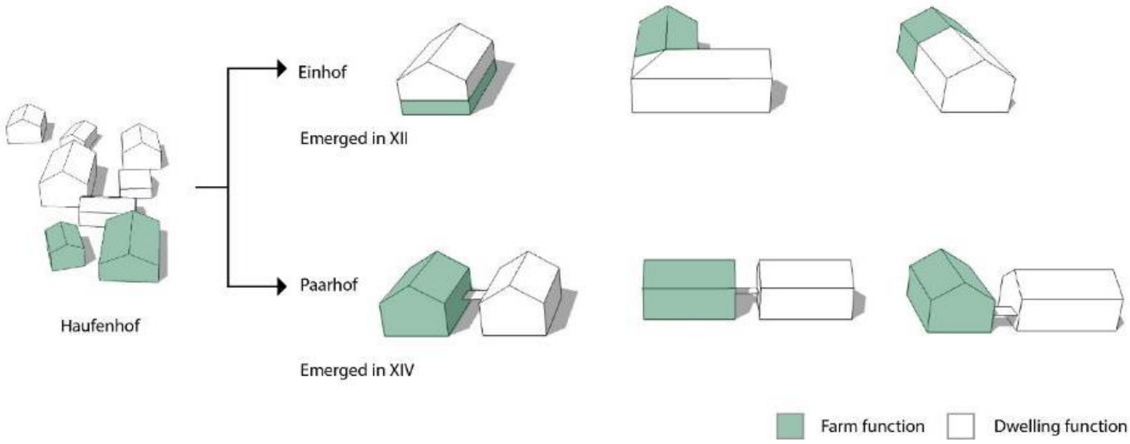


Figure 11 Farm forms and development

The function of the farm greatly depends on the climate zone where it is located. In Climate zone I, grape and other fruits (especially apple) have a long tradition. According to the report of the BLS (Business Location Südtirol) [216] (Figure 12), they grow in areas from 200 to over 1000 m in altitude, extending westward from Val d'Adige to central Val Venosta (Malles Venosta), eastward until Valle Isarco (Natz). In the past, almost every farm worked independently in viticulture. Therefore, each farmstead possessed all the facilities required for wine production: a residential building, a stable, the torggel (room for winepress), and storage [217].

In Climate zone II, the main farm function is dairy farming. Currently, fruit planting dominates the western part of Climate zone II (Figure 12). However, it is only in the last 30 years that the domain changed from dairy farming to fruit planting in Val Venosta [217]. The same change also happened in the eastern part of Climate zone II (Valle Isarco). In Climate zone III, dairy farming is predominant due to the harsh climate for other agriculture. On dairy farms in Climate zones II and III, the attics are used as drying rooms for hay and agricultural products. Therefore, the construction of the attics uses wood with unglazed openings to ensure enough air exchange.

Figure 12 Agriculture and primary production in South Tyrol (© BLS / www.farbfabrik.it) [216]

Nature and culture both lead to farm function differentiation. Fruit, viticulture, and crop farming require the warm climate of the valley or on the south-facing slopes of the mountains, while the high Alpine pastures are suitable for grazing and dairy farming. Although the climate type determines the optimum land use, the actual use of the land depends more on the farmer's responses to economic opportunities [218]. Notably, people living at different altitudes engaged in both valley cultivation and mountain grazing, but with a different focus. This combined cultivation has a long history. Dating back to the Bronze Age, the transhumance system was found in South Tyrol [219]. For the settlements at low altitudes, the function of dairy farming was placed on the mountain far away from the settlements. The stables and mountain huts were temporarily used in summer as a collective property.

The size of residences may be influenced by the economic condition of the region. Another theory for the different sizes of farmhouses is that the depth of the house is limited by the length of the tree trunks available in the area [206]. The decreased window-to-wall ratio from Climate zone I to Zone III could be a climate-responsive feature that helps to decrease the energy loss through windows in winter.

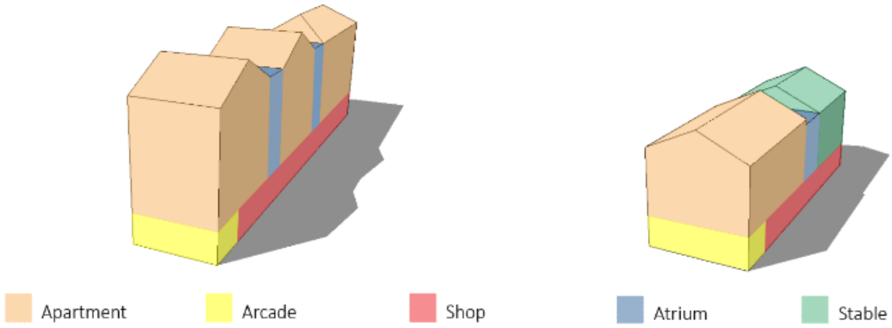
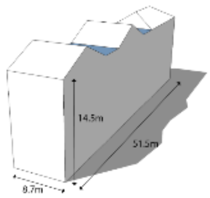
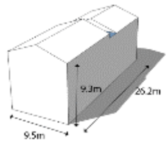
4.3.2.2 Portici House

- Description of quantitative results

According to the sample survey, all Portici houses have a similar layout: arcades facing the street, with shops occupying the ground floor and apartments located on the upper floors (Table 17). In Zone I, the shop and apartments extend toward the back, with an inner courtyard. In Zone II, on the other hand, a small yard is located behind the shop, leading to stables for livestock, with access from the back for staff and animals. The construction material is masonry in both Climate zones. The dimension of the residence is larger in Climate zone I than in Zone II, with average areas of roof projection of 447.6 m^2 and 360.1 m^2, respectively. The window-to-wall ratio is 0.21–0.4 in Zone I compared to 0.15–0.35 in Zone II.

Table 17 Construction of "Portici" buildings in different Climate zones

Climate zone	Zone I	Zone II
Material	Masonry	Masonry
W-to-W ratio	0.21–0.4	0.15–0.35
Main facade	Eaves side	Gable side
Floors	See Table 7	See Table 7

Roof area	447.6 m^2	360.1 m^2
Average Width × depth	8.7 × 51.5 m	9.5 × 26.2 m
Layout type		
Typical diagram & Picture	  Portici 45, Bolzano [1]	  Via Portici 10, Glorenza [2]

[1] Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=13862

[2] Office of Architectural and Artistic Heritage, Autonomous Province of Bolzano - Alto Adige, http://www.provincia.bz.it/arte-cultura/beni-culturali/monumentbrowser-ricerca.asp?status=detail&id=13862

- Discussion with consideration of qualitative results

The differences in building layout and roof projection area are due to the development of trading activities. When they were initially constructed, Portici houses had a fixed layout in Climate zones I and II, with the shop facing the street and the stable at the back [209]. Portici houses developed due to the prosperity of the trading and craft. The stable was abandoned since the farm is no longer a main economic income, and the building extended backward. The depth of the extension could reach up to 60 m. To ensure enough light in the residence, two or three atria were inserted in between. Compared to the depth, the width of the building structure did not change much over time. In Bolzano, each parcel had a narrow, uniformed façade of about 6 m (about three windows wide), and 12 m for the duplex façade opening to the main street. This building structure had a very low surface-to-volume ratio (S/V) ratio. This compact structure ensured equal trading opportunities to as many shops as possible, saved public farmland and investments on original walls, and decreased the heat losses through the building envelope.

Building materials changed over time to increase fire safety. Every Portici district was seriously threatened by fire accidents. It is documented that the Portici houses in Bolzano were initially built in wood on the upper floors [208]. Due to devastating fires, there was a large loss of property and lives. Masonry, therefore, became the preferred construction method for the following rebuild. In building samples, all the Portici buildings are in masonry.

4.4 Reference buildings for performance assessment

For the categorization of this historic building stock, building features are analyzed on the settlement and building level. The analysis conducted allows highlighting building features that are influenced by climate and local culture, which contributes to the state of knowledge of the historic building stock.

This methodology could be applied to different scales of historic building stock with the aim of understanding the correlation between building categories and climate.

The application of this methodology in South Tyrol shows the process in which a complex historic building stock is systematized. In addition to that, some correlations between building categories and local climate are discovered. From Climate zone I to III, the temperature decreases, and the precipitation increases as the altitude increases; the settlements of historic buildings tend to be sparser, with lower density; historic buildings tend to have smaller volumes, a lower window-to-wall ratio, less thermal mass, and different agriculture functions. These results not only show that settlements are more concentrated in regions with a climate that is ideal for agriculture, but also that they adapt to the climate in some ways. According to the analysis of the development of building features, climate is an important factor but not the only decisive one.

Considering future climate change, which could cause severe, pervasive, and irreversible impacts on historic buildings, it is necessary to study the performance of historic buildings to ensure their energy efficiency and conservation. According to the analysis of building features in three Climate zones, it is necessary to use different reference buildings to represent the typical buildings. Moreover, there is a need to carry out research to understand the capability of the climate-responsive features in future climate scenarios, as well as exploring the possible further risks and adaptation strategies.

According to the typical building features in each category, five reference buildings are selected (Table 18).

Table 18 Reference buildings for each category

Typology	Climate zone I	Climate zone II	Climate zone III
Rural farmhouse	Perlhof in Gries (I-R-C-MW-3f)	Rainer in Feldthurns (II-R-C-MW-3f)	Barteler in Jaufental (III-R-S-MWW-2f)
Portici house	Piazza Erbe 11 (I-P-C-M-4f)	Schallerhaus (II-P-C-M-3f)	---

The reference construction of Climate zone I is defined as a masonry wall, that of Climate zone II and III are masonry walls and wood walls. The stone availability usually decides the material of the masonry wall on-site — the areas in Climate zone I produce sandstone and quarzporphyr [183]. Meanwhile, in the material survey of the churches in South Tyrol, sandstone is generally used as building blocks. Therefore, the reference masonry of Climate zone I is defined as sandstone. Similarly, granite is defined as the reference masonry of Climate zone II and III.

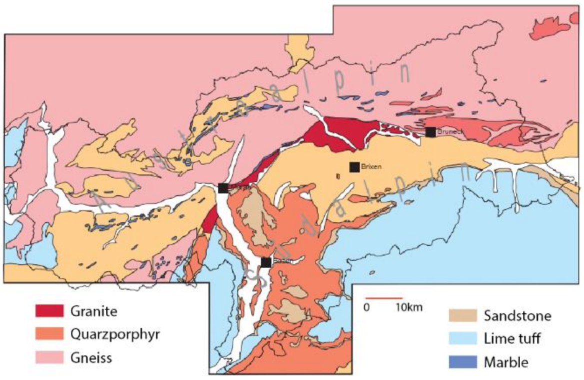


Figure 13 Simplified geological overview map of South Tyrol [183]

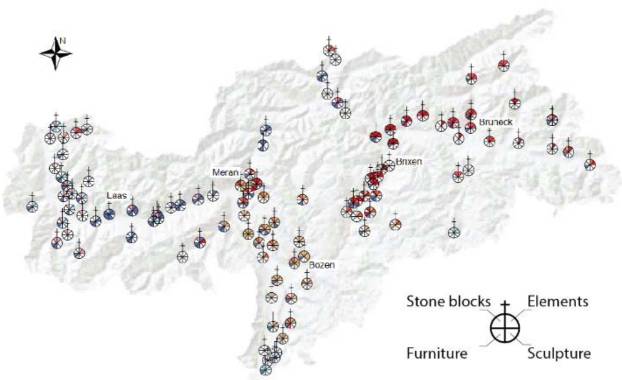
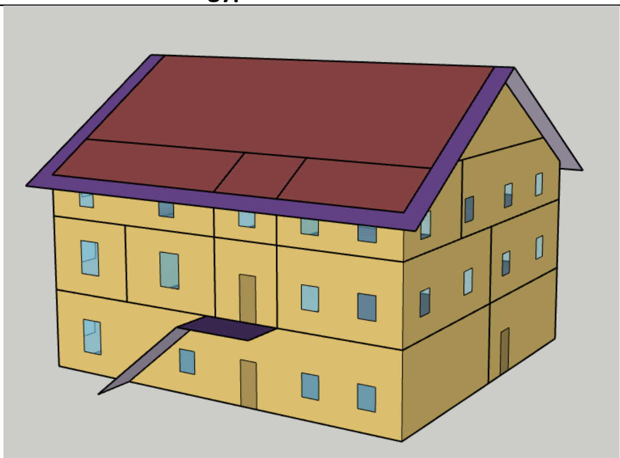


Figure 14 The material distribution of the churches in South Tyrol [220]. The color of the up-left quadrant shows the material of the building blocks

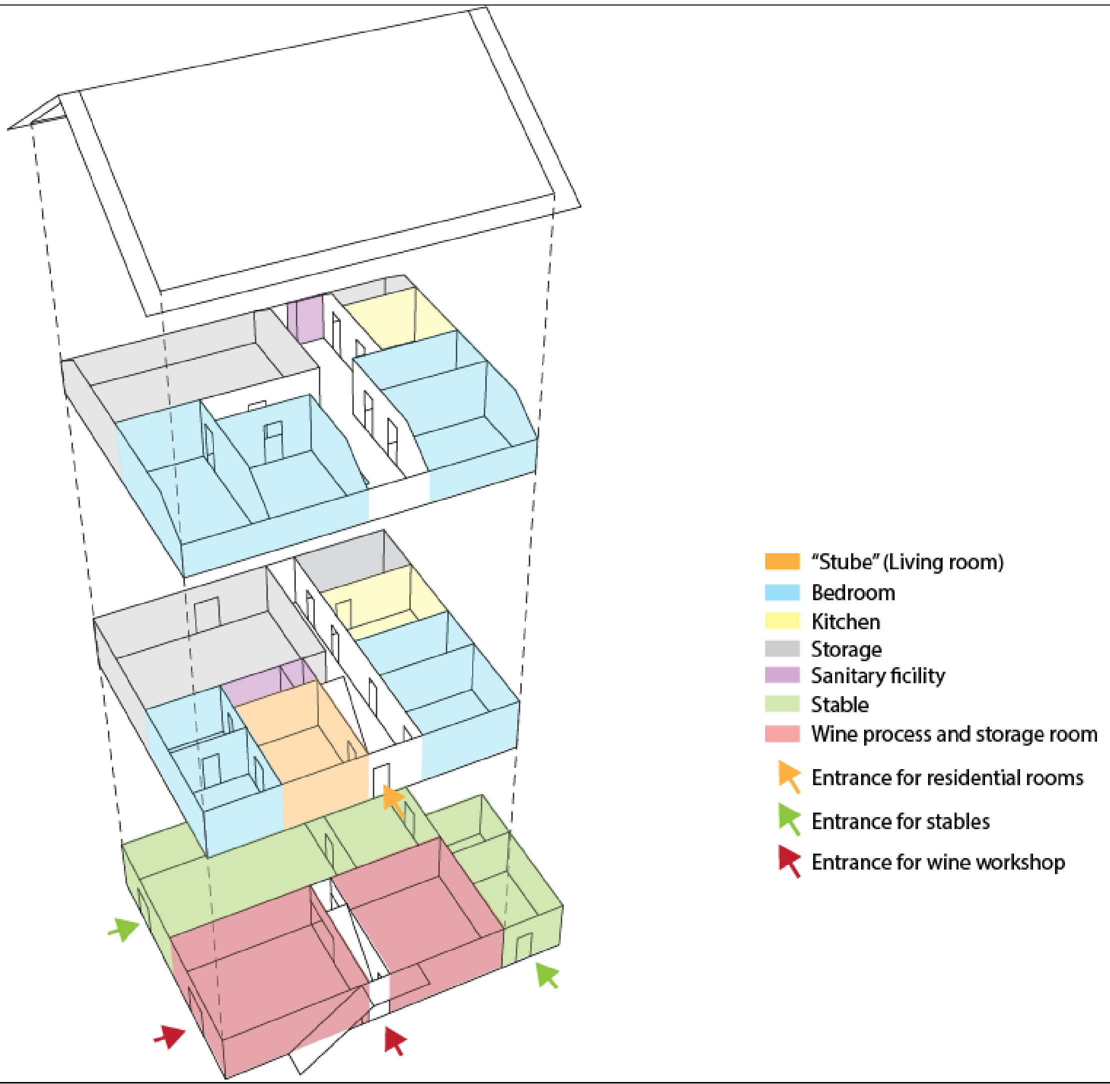
4.4.1 Perlhof

Location	Settlement type	Orientation	Period of construction
Gries	Compact settlement	North-South	Medieval

Energyplus Model & Picture



Plans and function

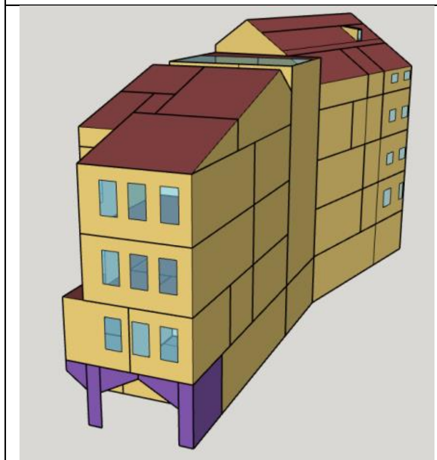


4.4.2 Piazza Erbe 11

Location	Orientation	Period of construction	Plans and function
Bolzano	North-South	12th century	

Settlement

Energyplus Model & Picture



South façade

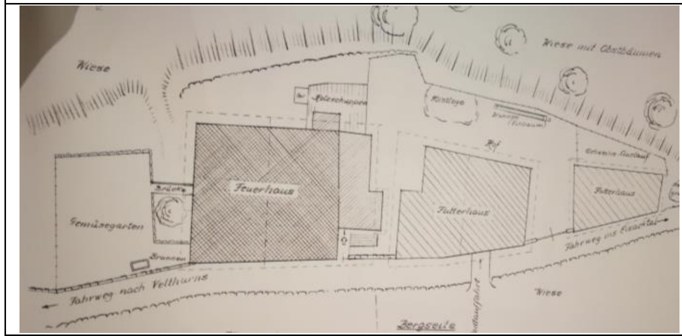
North-west façade

Plans and function

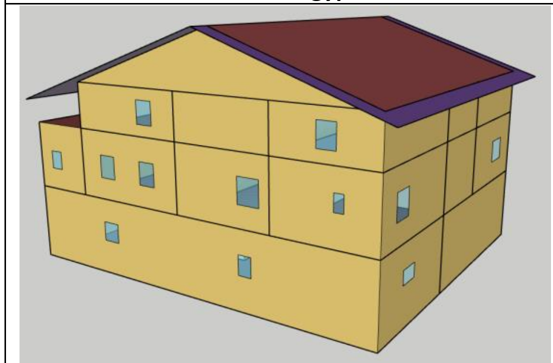
4.4.3 Rainer

Location	Orientation	Period of construction
Velturno	Southeast - Northwest	-

Settlement

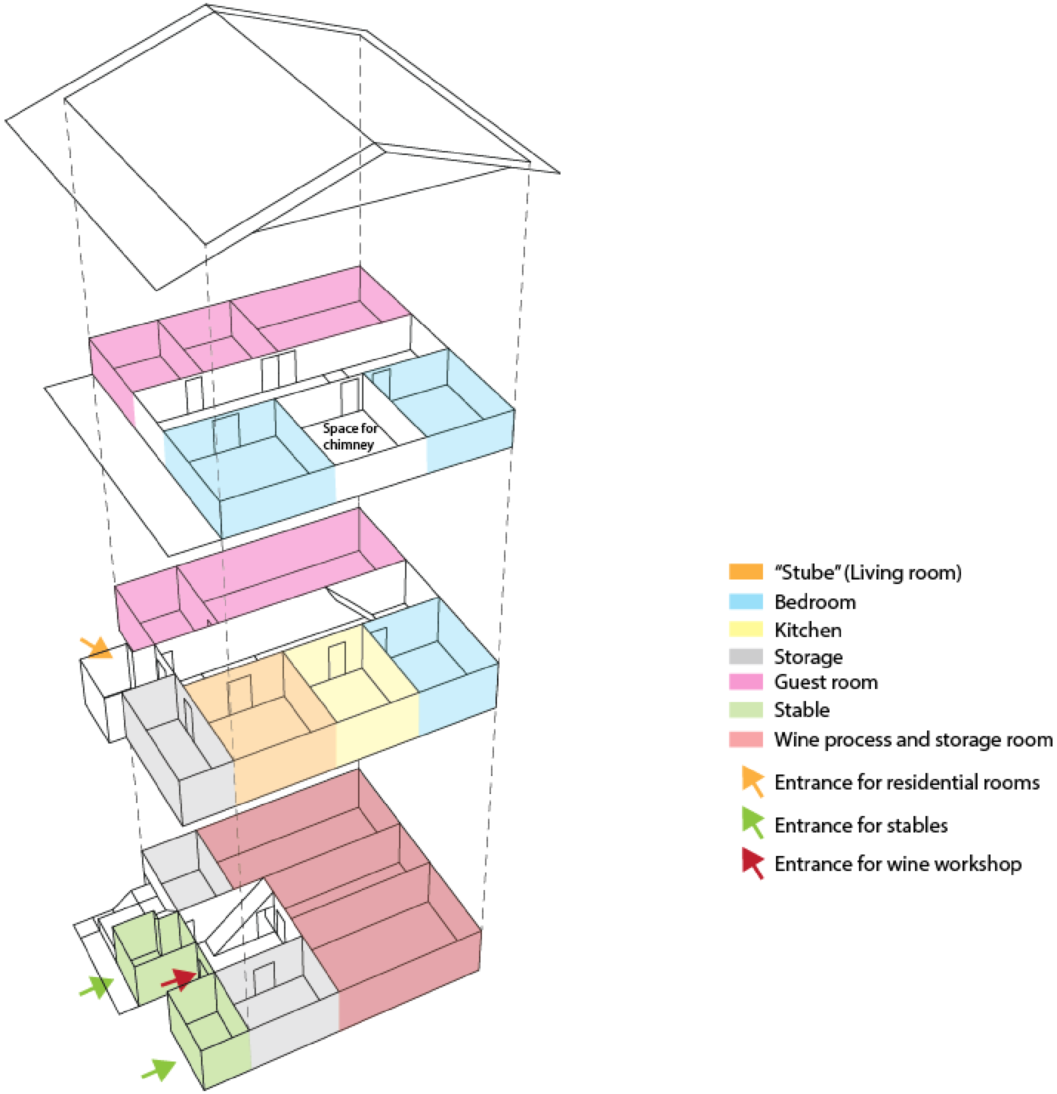


Energyplus Model & Picture



North façade

Plans and function



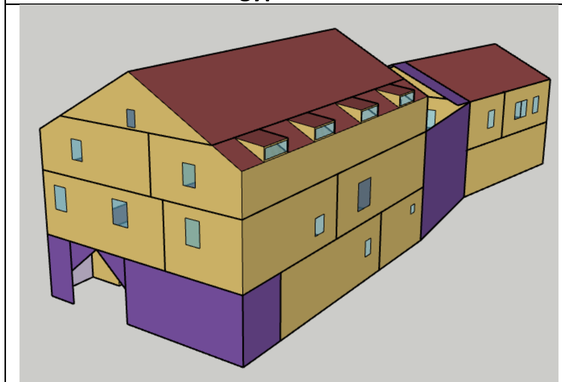
4.4.4 Schallerhaus

Location	Orientation	Period of construction
Glorenza	Southeast - Northwest	-

Settlement

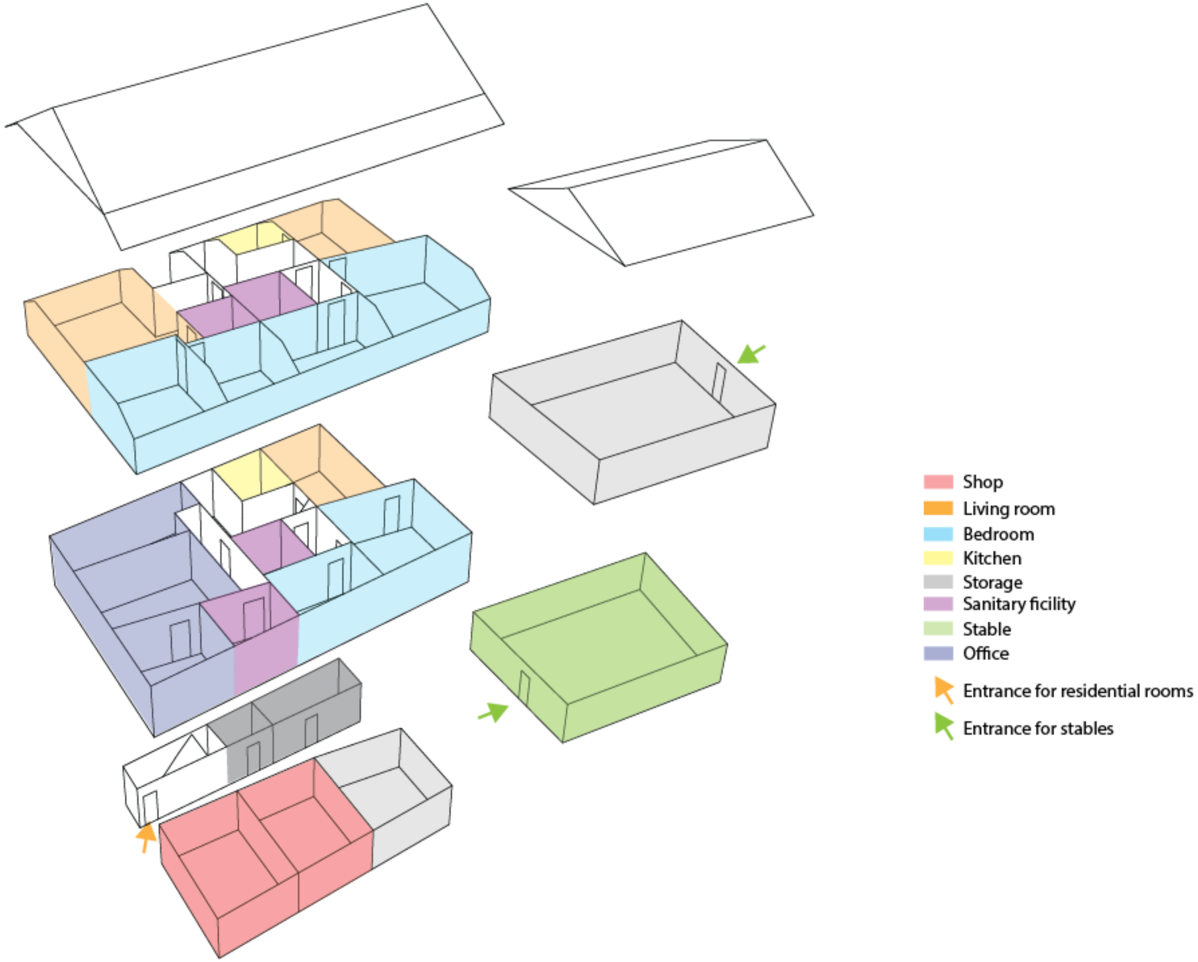
compact

Energyplus Model & Picture

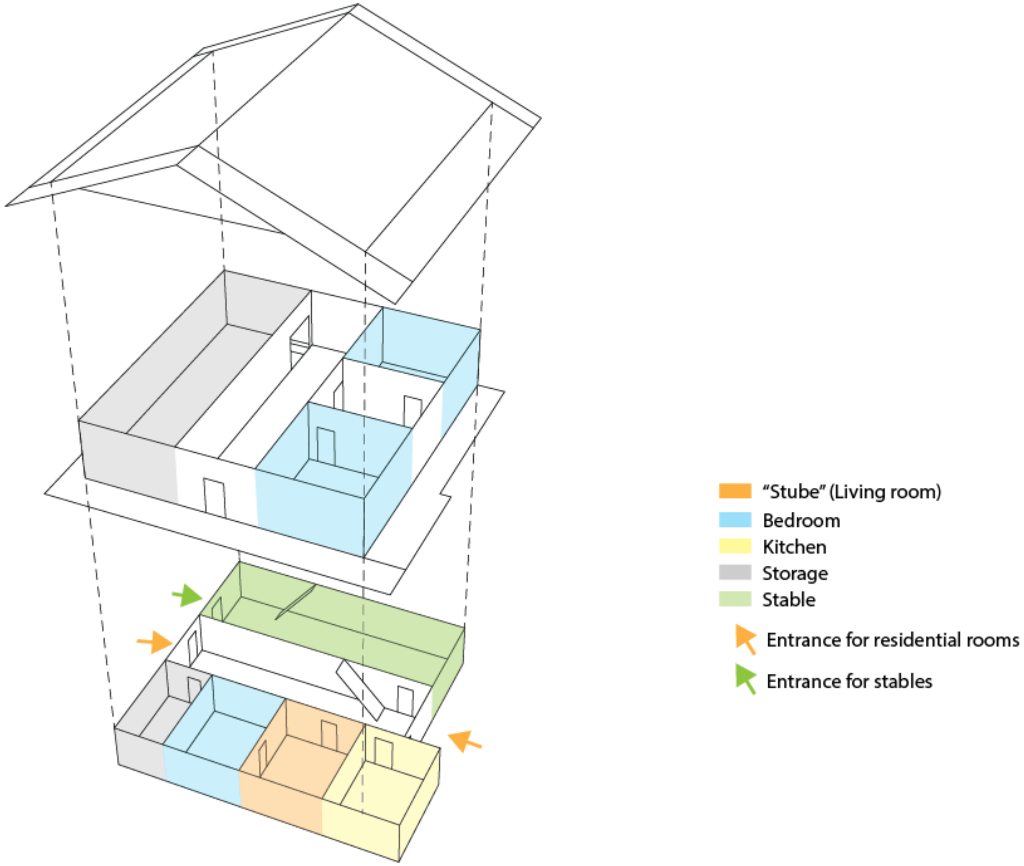
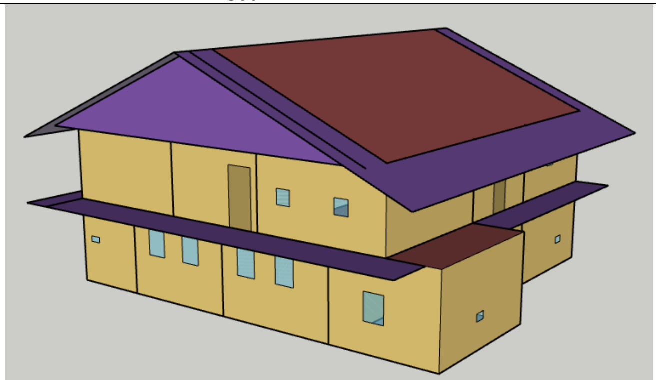


South façade

Plans and function



4.4.5 Barteler

<table>
<tr><th>Location</th><th>Settlement</th><th>Orientation</th><th>Plans and function</th></tr>
<tr><td>Val di mezzo</td><td>Sparse settlement</td><td>North-south</td><td rowspan="3">
</td></tr>
<tr><th colspan="3">Energyplus Model & Picture</th></tr>
<tr><td colspan="3">

South and east façade</td></tr>
</table>

Through the analysis of climate impacts on the development of historic buildings, it is found rural farmhouses are more influenced by climate comparing with Portici houses. The latter one is more shaped by the cultural and socioeconomic needs. With an original design closely related to local climate, whether rural farmhouses will change the performance more due to the retrofit and climate change needs further investigation.

5. Current best retrofit solutions

This chapter aims to summarize the current best retrofit solutions for further performance assessment. The historic significance of the buildings is firstly studied, which is a significant influencing factor in the decision making of retrofit solutions. Then, ten local retrofit practices, which are selected following the methodology in section 3.2, are analyzed. Eventually, the current best retrofit solutions are proposed.

5.1 Historic significance of South Tyrolean buildings

Improving energy performance is crucial to mitigate climate change and avoid the problems of emptiness and neglect of historic buildings. Renovation of the built heritage is an increasing trend in Europe [221-223]. Also, South Tyrol witnesses an increasing professional emphasis on the energy retrofit of historic buildings in recent years. Several research projects investigated how to reduce the energy demand of historic buildings in South Tyrol while preserving their heritage value [224, 225]. Several local initiatives illustrate the eagerness to foster renovation practices. For instance, the insurance company ITAS together with conservation authority and local farmer association, awards the exemplary energetic retrofit of historic farmhouses in South Tyrol on a yearly base, supporting and encouraging the practice of renovation in the rural environment [226].

Despite the benefits of energy renovation, considerations on the preservation of the historic value must not be neglected. This represents an economic, technical, and architectural challenge. In South Tyrol, the alteration of a listed historic building requires consents from the local conservation authority [227]. The conservation professionals must decide whether or not the energy improvements can be made based on their potential harm to the historic and artistic character of the building. In principle, the retrofit interventions are allowed to the extent that the peculiarities of the structures and surfaces remain unchanged [228]. Structures include walls, vaults, wood structures, beams, trusses, etc., and surfaces describe materials that complement or coat the buildings, consisting of original plasters, painting, frescoes, stucco decorations, wooden paneling, or roofs.

5.1.1 Constructive components

The structural components determine the form of a historic building, and they reflect not only the historical norms and regulations but also the construction method and aesthetic trends of that period. In principle, the preservation of the existing constructions should be given priority over changes or renewal. Constructive components refer to masonry walls, vaults, intermediate floor, arcades, fireplaces, and stoves.

External masonry walls support the floors and roof, forming the load-bearing structure of the building. The most widespread construction is stone masonry walls made of boulders of irregular size and lime mortar filling the gaps. Vault and arch constructions have a unique historical and aesthetic value in South Tyrol (Figure 15). Vaulted structures are usually constructed with masonry and lime mortar, and already since the 19th century are sometimes combined with steel rods for reinforcement (Preußische Kappen or Wiener Platzldecke) [229]. Any structure changes such as reinforcements and demolitions should be justified on a case-by-case basis. Similarly, the fillings of the vault should be kept in case of the load changes.

The stoves in South Tyrol not only serve to heat the room but are also an important piece in the decoration of the building (Figure 15). To restore their functionality, the combustion chambers are usually dismantled and repaired. In some cases, only the forms are kept, but the heating system is replaced with modern system. In any case, this solution should be carefully considered on a case by case basis.

(a) (b)

Figure 15 (a) Vaults of Rainhof, St. Magdalena. (b) A baroque stove, Tesimo (http://www.provincia.bz.it/arte-cultura/beni-culturali/stufe.asp)

5.1.2 Plasters and façade decoration

Both external and internal plasters are integral parts of a historic building. They reflect the development of material techniques and the ways of expression over centuries (Figure 16, a). Their material, structure, and color significantly shape the look of the building. Therefore, the historic plaster must be substantially preserved and, if necessary, supplemented with materials that match the original ones. In the Tyrolean region [229], lime mortar was used until 1850. Since the late 19th century, “Roman” cement spreads in Tyrol, and mixed lime and cement plasters are commonly used on the facades. From 1920 on, Portland cement substitutes the “Roman” cement due to its low cost.

Besides plasters, the paintings, stucco, and frescoes on the façade determine the appearance of a historic building and reflect the artistic and technological developments. South Tyrolean historic buildings are often decorated with wall paintings, already from the early middle ages until the 20th century (Figure 16) [230]. The term “Anstrich” (painting) refers to the manual implementation of the surface coating, which can decorate and protect the wall façade. Depending on the substrate and intentions, there are different materials and techniques for painting. On plaster, brick and natural stone facades, the coating was lime-based until the middle of the 20th century; silicate paints were used from the late 19^{th,} and cement-based paints were used in the 20th century [229].

When planning a retrofit action, all work should be carried out, aiming at minimizing the intervention and maximizing the retention of the original fabric. Moreover, since plasters and paintings are sensitive to moisture and salts changes, retrofit interventions should be preliminarily evaluated on their long term impacts on wall moisture and salts dynamics.

(a) (b) (c)

Figure 16 (a) Baroque plaster over gothic plaster with squares in Dodiciville. (b) Painting on Troyburg, Bolzano. (c) coats of arms on Portici house of Glorenza.

5.1.3 Wooden structures and surfaces

Wood is used in historic buildings for structural purposes, such as floors, walls, roof trusses, as well as finishing surfaces, such as floors, paneling, and doors. The technique and finish surface of the construction reflect the development of the buildings and characterize its historic and aesthetic value [217]. These constructions are developed over centuries of experience of carpenters.

Wooden walls have a long history in the Alpine region. Several types of wood constructions could be found: Blockbau, Ständerblockbau, and Bundwerk (Figure 17). Wooden attics were generally used for the storage of hay and cereals in the past, and because of that, they are naturally ventilated.

The wooden shingle roof is a traditional expression of historic architecture in Alpine regions where there is a great availability of wood (Figure 18). The larch shingles are hand-split [231], and triple shingle layers are placed directly on top without any additional waterproofing layer allowing the shingles to dry entirely after a rain event. When the slope of the roof is gentle, long shingles without nails (80 cm) are used. The shingles are kept in place with wood and stones laid on top of them.

(a) (b)

Figure 17 (a) The wood stand construction of the Paarhof in Antholz [213]. (b) Baroque wood constructions of Kampedeller, Kastelruth (http://www.provinz.bz.it/kunst-kultur/denkmalpflege/monumentbrowser-suche.asp?status=detail&id=15321)

Figure 18 Traditional shingle roof of South Tyrol (http://www.provincia.bz.it/arte-cultura/beni-culturali/tetti.asp)

Wooden surfaces play an essential role in the traditional South Tyrolean residential buildings. According to Joachim Hahnel, the word "Stube" originally refers to parlors, and it was first mentioned to refer to the parlors with wooden panels in the house of Adeligen Odalrich in Girlan in 1194 [213]. This wooden paneled parlor (Figure 19) appears in castles, monasteries, and ecclesiastical possessions at the beginning, and is then taken over by farmhouses, becoming a characteristic of the rural living culture in South Tyrol that has continued until the present day. The floor, wall, and ceiling are covered with wooden panels, which also serve as thermal insulation. Wood frames were laid next to each other, and the panels insert in-between. The wooden beams and panels are often artistically decorated and carved (Figure 19).

Figure 19 (a) Full paneled parlor in Ahrntal of South Tyrol. (b) Carved ceiling at Maireggerhof in St. Johann in Ahrntal [213]. (c) Heiliger Geist in Breitnerhof in St. Valentin in Villanders

To preserve the wooden structure and surfaces, any mechanical treatment (e.g., milling), must be excluded, and any removal of historic surface layers (e.g., varnishes) should require permission. If the damaged structure is load-bearing, it could be replaced or integrated with new solid wood from the Alpine area with the same quality.

5.2 Analysis of the retrofit case studies

Before any retrofit project is considered, a detailed building survey should be carried out. This should include an examination of the structure conditions, a description of the interventions done in the past, and a photo documentation of the building elements worth of preservation such as building proportions, vaults, decorations, windows, etc. [232]. Ideally, the planned retrofit interventions are then discussed among conservationists, house owners, and architects. Energy retrofit actions must abide by building conservation ethics and principles, therefore be of minimal impact and reversible without causing further damage.

In order to define the type and extent of the interventions, ten renovation cases in South Tyrol are analyzed in detail. The case studies are selected according to the criteria defined in section 3.2. Retrofit solutions are analyzed and summarized for further study. More information about the case studies can be found in Appendix A.1.

5.2.1 Masonry wall

All the analyzed cases have external masonry walls, and internal insulation is used to keep the original outlook of the building. Internal insulation is only applied to the walls without any historical painting or decorations. The inner plaster is conserved, and it is cleaned by removing the biological patinas and incoherent surface deposits, which are harmful for preserving the historic plaster. Lime mortar is used to repair any damage in the original plaster because it has a similar vapor permeability [233]. After restoring the historic plaster, the insulation panels are fixed through adhesive or mechanical fixings. These fixings should be reversible. Afterward, an internal finish is applied with or without a vapor barrier to the insulation layer.

In the retrofit of non-historic buildings, the thickness of insulation is determined by the local energy requirement. For instance, according to DM 26/06/2015 [234], the requirement of the thermal transmittance of the external walls in Climate zone I is 0.3 W/m^{2}K, whereas in Climate zone II and II is 0.28 W/m^{2}K for all the buildings. However, historic buildings are exempt from energy performance requirements. In the analyzed case studies, not all the U-values after retrofit reach the requirement (Table 19). The thickness of the insulation panel is determined by the considerations of its compatibility. For instance, when retrofitting a historic wall with wood paneling ("stuben"), the space between the wood paneling and the wall will be utilized for insulation panel installation. To keep the original wood paneling intact, the thickness of insulation should be the same as the width of the void. Moreover, the depth of insulation should not lead to moisture problems or significant loss of indoor area. The general thickness of the insulation is around 12cm, while for the external walls of a "Stuben," the thickness is about 6 cm. Stanglerhof is a particular case. It was an abandoned stable before the energy retrofit, and the owner requires the renovation to be cost-effective and simple. Therefore, straw bale is used as an insulation material, and the thickness is 36 cm.

Both vapor tight, and vapor open insulation systems are used in the analyzed cases. Therefore, both insulation systems should be studied in terms of their hygrothermal influences on historic buildings. Wood fibreboard is used in half of the analyzed cases (Table 19), and it is selected as a reference insulation material.

Table 19 Retrofit solutions on external masonry wall (VT=vapor tight insulation system, VO=vapor open and non-capillary active insulation system, C=capillary active; 1. the insulation is applied in "stuben")

Case study	Location	System type	Vapor barrier	Insulation material	Thickness [cm]	λ [W/mK]	U value [W/ m^{2}K]
Aussergrubhof	Ultental	VT	N	EPS	10	0.034	0.34
Huberhof	Rodeneck	VT	Y	Wood fibreboard	12	0.042	0.35
		VT[1]	Y	Wood fibreboard	4	0.042	1.05
Kohlerhaus	Innichen	VO	N	Reed + insulation plaster	12+3	0.081; 0.056	0.50
Rainhof	Gsies	C	N	Calsitherm plaster	5	0.059	0.85
		VO[1]	N	wood fibreboard	8	0.042	0.53
Schallerhaus	Glurns	VO[1]	N	Mineral panel	8	0.04	0.5
Ansitz Kofler	Bozen	VT	Y	Mineral wool panel/wood fiberboard	14	0.04	0.29
Laubenhaus	Bozen	---	---	---	---	---	---
Prosenhof	Truden	VO	N	Wood fibreboard + insulation plaster	10+6	0.042; 0.056	0.29
Stanglerhof	Voels	VO	N	Nature straw	36	0.095	0.26
Leimegger	Campo Tures	VO	N	Mineral foam board	16	0.045	0.28

5.2.2 Wooden wall

Similar to the external masonry wall, internal insulation is the main retrofit solution in order to preserve the original appearance. Before any retrofit, existing wooden walls are cleaned, disinfected, and disinfested in a delicate intervention that does not eliminate the patina conferred by time [227]. The wood structures are fixed or partly replaced to ensure the structural safety. After conservative restoration, a water-resistant and UV-resistant layer is applied on the inner side of the wooden wall to increase the airtightness of the wall. Then insulation panel is used with a thickness of around 12 cm (Table 20). After the insulation, a vapor barrier is adopted. The last step of intervention is to assembly a surface finish.

The thickness of the insulation is similar to that in the retrofit of masonry walls, around 12 cm. But all the cases adopt a vapor-tight insulation system, which shows the general concern about the moisture risks for wood structures.

Table 20 Retrofit solutions on the external wooden wall (VT=vapor tight, VO=vapor open and non-capillary active, C=capillary active; 1. the insulation is applied in "stuben")

Case study	Location	System type	Vapor barrier	Insulation material	Thickness [cm]	λ [W/mK]	U value [W/ m²K]
Aussergrubhof	Ultental	VT[1]	Y	Hemp fibreboard	10	0.039	0.39
Huberhof	Rodeneck	VT	Y	Wood fibreboard	12+4	0.042	0.26
Kohlerhaus	Innichen	---	---	---	---	---	---
Rainhof	Gsies	VT	Y	Wood fibreboard	12	0.042	0.35
Schallerhaus	Glurns	---		---	---	---	---
Ansitz Kofler	Bozen	---	---	---	---	---	---
Laubenhaus	Bozen	---	---	---	---	---	---
Prosenhof	Truden	---	---	---	---	---	---
Stanglerhof	Voels	VT	Y	Nature straw	36	0.095	0.26
Leimegger	Campo Tures	---	---	---	---	---	---

5.2.3 Roof

Roof structure includes the roof beams, substructures, and roof covering. Elements are joined together with wooden pegs. The preference of roof shape varies with the construction period. Generally, it has two pitches and a wide projection to protect the façade. Besides the shingle roof introduced in 5.1.2, there are the natural stone roof, beaver-tail clay roof (Biberschwanz-Tonplatten), Monk, and nun roofs (Mönch- und Nonne-Dächer), thatched roofs, etc., which differ in the covering materials [231].

During the retrofit process, the roof is firstly disassembled, and the degraded elements are replaced (Priority should always be given to repair and integration rather than a replacement). Insulation should be applied between roof beams instead of on the roof beams to avoid an excessive thickness of the roof. Therefore, flexible insulation material is filled into the void between roof beams, and another insulation layer is applied under it to prevent any thermal bridge. Wood fibreboard is commonly used due to its feasibility (Table 21). The thickness of the insulation layer is around 20 cm.

Table 21 Retrofit solutions on roof

Case study	Location	Insulation material	Thickness [cm]	λ [W/mK]	U value [W/ m²K]
Aussergrubhof	Ultental	Wood fiberboard	16	0.042	0.26
Huberhof	Rodeneck	Wood fibreboard	20	0.042	0.21
Kohlerhaus	Innichen	Wood fibreboard	24	0.042	0.18

Rainhof	Gsies	Wood fibreboard	18	0.042	0.23
Schallerhaus	Glurns	Wood fibreboard	20+6	0.042	016
Ansitz Kofler	Bozen	Mineral fiberboard	12+14	0.044	0.17
Laubenhaus	Bozen	---	---	---	---
Prosenhof	Truden	Wood fiberboard	18	0.042	0.23
Stanglerhof	Voels	---	---	---	---
Leimegger	Campo Tures	---	---	---	---

5.2.4 Floors

Wooden floors are the most common type of intermediate floors in South Tyrol. The beams are placed on the groove of the masonry walls. In the “double-deck” floor, which is usually used in living space, the first floor slab is wedged between the supporting beams, while the second floorboard is fixed to the supporting beams by means of wooden pin connectors [233]. Besides the wood floor, different stone vaults (barrel vault, cross vault, etc.) could be found in the kitchen or ground floor rooms. It has better fire resistance compared with wood floors. On the extrados (the upper/ outer curve of an arch), stone mixed with sand or earth is filled in and level up the floor to the transverse wood beams where the wood floor is paved. Ground floor is simply constructed with wood board supported upon ground or stone slab placed on the ground directly.

Floors are examined and consolidated before the retrofit: the stone vault is cleaned and rendered, fixed with compatible material. Wooden floors are cleaned, disinfected, and disinfested, and degraded elements are replaced [229]. After conservative restoration, energy retrofit could start. Floors are considered to be thermal insulated when they are adjacent to the unheated area. For instance, the ceilings to unheated attic and ground floor are generally insulated. For the ground floor, the intervention requires more exceptional thickness to construct the new floor. Therefore, excavation is carried out, and a geotextile layer and reinforced concrete are laid over successively. After another layer of the vapor barrier, insulation panels are paved. Polystyrene product is commonly used in ground floor. Finally, a bedding layer is laid for the installation of the original floor material.

Table 22 Retrofit solutions on floors

Case study	Location	Floor type	Insulation material	Thickness [cm]	λ [W/mK]	U value [W/ m²K]
Aussergrubhof	Ultental	Ceiling to the basement	Poly-foam insulation+ expanded clay bedding		0.023	
Huberhof	Rodeneck	Basement floor	insulation polystyrene	12	0.03	0.25
		Ceiling to the basement	insulation polystyrene	15	0.03	0.2
Kohlerhaus	Innichen	Ceiling to the basement	Wood fibreboard+ insulation fill	6+8	0.042	0.3
Rainhof	Gsies	Ground floor	Insulating concrete+ insulation	7+9		
Schallerhaus	Glurns	Ground floor	Expanded polystyrene	12	0.03	0.25
Ansitz Kofler	Bozen	Basement floor	XPS	20	0.027	0.135
Laubenhaus	Bozen	---	---	---	---	---
Prosenhof	Truden	Basement floor	XPS	2	0.027	1.35
		Ceiling to the basement	Stiferite	10	0.022	0.22
Stanglerhof	Voels	Ceiling to the attic	Straw	36	0.095	0.26
Leimegger	Campo Tures	Ceiling to the basement	---	5	---	---
		Ceiling to the attic	Begehbare	20	0.038	0.19

5.2.5 Windows

Windows are crucial elements of a historic building, and they are carrying information on the cultural history. Each era has different window solutions [235]: In South Tyrol, Romanesque and Gothic window openings were small for technical reasons and closed with wooden shutters, later with sliding windows. From the late 15th century, the dimension of the window increases due to the development of building techniques. From the 18th century, double-leaf windows become common. The box window developed at the end of the 19th century. It consists of two interconnected frames with single glazing.

Historic windows with delicate details must be preserved but can be improved in terms of energy performance. The energy retrofit of the window should be defined with an experience window restorer, and there is no “standard” historic window solution. In the case studies, when the historical window is single glazed, an additional window with insulating glass is attached to the interior, and the historical window can be restored. If the windows are too damaged or not worth preserving, they can be replaced. For instance, in the retrofit of Rainhof [225], a double glazed unit is installed. To preserve the original appearance of the windows, one of the original windows is used as a model for the new windows in terms of proportions and profile widths (Table 23). According to the conservation office [235], in the case of coupled windows, the outer pane is only repaired, while the insulating glass is used in the inner window. Similarly, the inner window of the box window is sealed and replaced with insulation glass while the outer pane is kept intact. If the windows are too damaged or not worth preserving, they can be replaced. New windows should be stylistically adapted to the historic building.

Table 23 Retrofit solutions of windows

Case study	Location	Old window	New window	U-value of new window
Aussergrubhof	Ultental	---	New larch wood windows with double glzing	1.1
Huberhof	Rodeneck	---	Triple glazed window	
Kohlerhaus	Innichen	---	New box window; three glazing	1.1
Rainhof	Gsies	Single glazed window	Casement window Double glazing	1.1
Schallerhaus	Glurns	Single glazed window	Triple glazed window	
Ansitz Kofler	Bozen	Box type windows	casement window with triple glazing	1-1.2
Laubenhaus	Bozen	No window	New double-glazing window	
Prosenhof	Truden	---	---	0.49
Stanglerhof	Voels	No window	Larch windows with double glazing	1.0
Leimegger	Campo Tures	---	New larch windows	1.1

5.3 Retrofit solutions for reference buildings

Based on the analysis of the case studies presented above, a selection of the retrofit measures that are going to be studied in combination with the reference buildings (see section 4.6) was made (Table 24). For external walls, two internal insulation systems are compared with respect to their hygrothermal performance: 1) wood fiberboard (vapor-open system), 2) wood fiberboard with a vapor barrier (vapor-tight system). These two insulation systems are coupled with three wall constructions (see section 4.6): 1) granite wall, 2) sandstone wall, and 3) wooden wall (pine). As shown in Figure 20, the masonry wall is composed of natural stones and mortar joints, which should be a detailed two-dimensional (2D) model in Delphin software simulations. However, a 2D simulation is a complicated and time-consuming process. For this reason, in the numerical models, composite walls are usually simplified with a one-dimensional (1D) stone layer, neglecting the mortar joints. However, the mortar joints are essential in the process of moisture storage and transport. This simplification could lead to large deviations from the real constructions [236]. Therefore, in this study, multi-component materials, which are virtual materials possessing the properties of the combination of stone and mortar, is used to simulate the moisture behavior of a real masonry wall. The properties of the insulation materials and wall materials are presented in Table 25. In addition, the sd-value of the vapor barrier used in the simulation is 7.72m.

Table 24 Retrofit solutions for reference buildings

	Retrofit solutions
External masonry wall	1. Vapor open insulation system (VO): wood fibreboard; 12 cm 2. Vapor tight insulation system (VT): same, but with vapor barrier
External masonry wall ("stuben")	1. Vapor open insulation system (VO): wood fibreboard; 6 cm 2. Vapor tight insulation system (VT): same, but with vapor barrier
External wood wall	Vapor tight insulation system (VT): wood fibreboard, 12 cm
Roof	Wood fibreboard, 20 cm
Foundation	Polystyrene, 10 cm
Window	New larch window, double glazing, U= 1.1

In this study, the hygrothermal risks in the external masonry wall and external wood wall are assessed. Condensation and mold risk are evaluated on the interface between the insulation and historic plaster of the masonry wall and between the insulation and wood wall. Frost-damage risk is evaluated in the outer historic plaster and 0.5 cm into the masonry wall (Figure 20).

Table 25 Properties of main construction materials

Materials	Thickness (mm)	λ [W/mK]	ρ [kg/m³]	C_p [J/kg·K]	Aw [kg/m²s0.5]	μ_{dry} [-]	θ_{por}[m³/m³]
Granite	580	1.718	2453	702	0.086	53.8	0.095
Granite-mortar	580	1.307	2251	750	-	35.1	0.166
Sandstone	580	0.956	1967	264	0.012	106.9	0.258
Sandstone-mortar	580	0.855	1876	405	-	51.8	0.292
Lime plaster	20	0.412	1498	802	0.019	9.3	0.435
Historic lime plaster	20	0.820	1800	850	0.127	12.0	0.302
Spruce	150/25	0.112	394	1843	0.012	186.1	0.738
Wood fibreboard.	120	0.042	150	2000	0.07	3.0	0.981

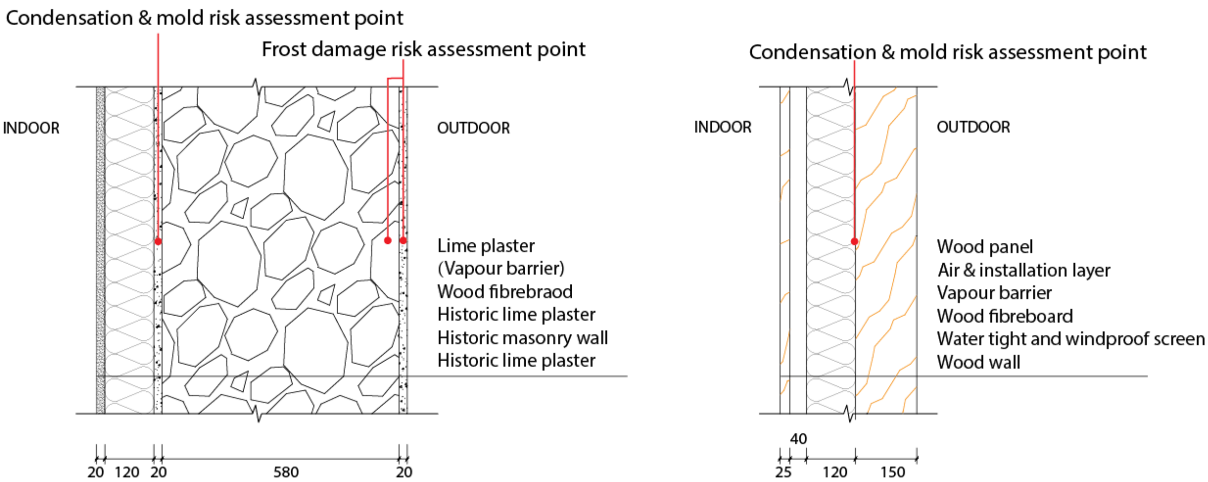


Figure 20 Reference constructions. Left: masonry wall with internal insulation; Right: wood wall with internal insulation.

6. Climate change and building performance of South Tyrol

In this chapter, future climate changes projected in climate models and the performance of retrofitted historic buildings in both present and future climate is presented. Four climate projections (M1,2,3,4) are generated following the methodology described in section 3.3. Thermal comfort of living rooms and bedrooms, moisture risks in reference constructions are simulated and assessed at present scenarios (P), near future (F1), and far future (F2) scenarios.

6.1 Future climate projections

6.1.1 Outdoor temperature conditions

Before looking into the impact of climate change on the future performance of historic buildings, the results in climate change are analyzed. Table 26 presents the temperature increase (in °C) at F1 and F2 when compared with present average values. M2 obtains the largest variation, with the highest increase of average temperature increase in all three Climate zones at F1 and F2.

Table 26 Average temperature increase compared with present scenario

	Climate zone I				Climate zone II				Climate zone II			
	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
F1	0.90	2.23	1.16	0.67	0.47	2.13	1.29	0.66	0.50	1.53	1.38	0.56
F2	3.04	6.16	5.13	3.22	2.84	6.11	5.61	3.31	3.03	5.17	5.67	3.10

6.1.1.1 Climate zone I

At the present scenario of Climate zone I, the highest temperature in summer reaches 38°C, and the lowest is -8.9°C (Figure 21). In winter, the daily average temperature ranges from -0.6 to 8.0°C, and it varies between 6.9-21.0°C, 20.1-25.9°C and 3.5-21.0°C in spring, summer, and autumn respectively (Figure 21).

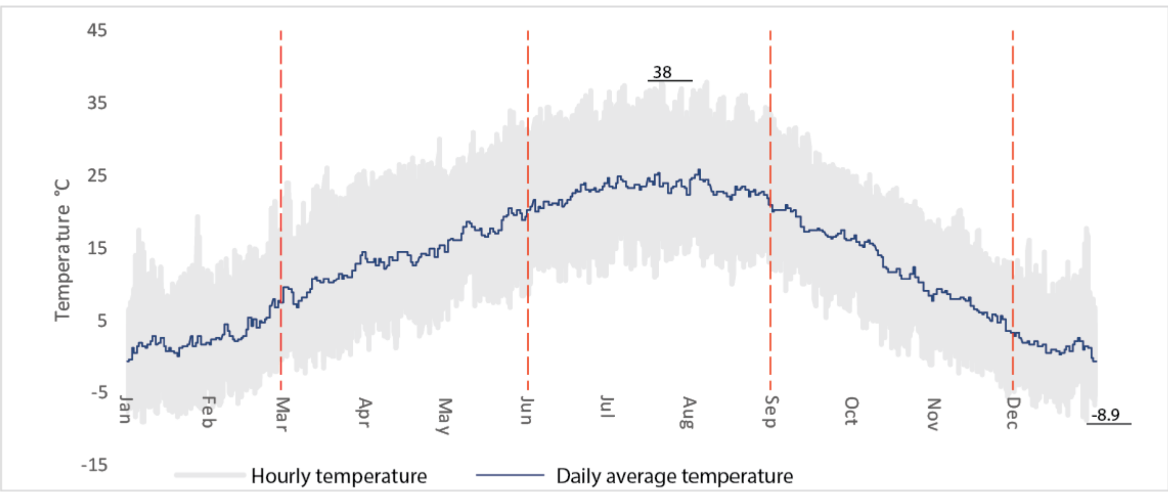


Figure 21 Hourly dry bulb temperature during 2008-2017 and Average daily temperature in Climate zone I

The frequency distribution of the hourly temperature is shown in Figure 22, where present temperature is represented by the blue dotted line, near future temperature and far future temperature is yellow and red line respectively. In addition to that, grey bars indicate the difference in frequency distribution between present and future climate.

The frequency changes marginally from P to F1 in M1,3,4, while M2 experiences a considerable change (Figure 22). In M2, the frequency of temperature below 4°C and between 12-20°C drops, while that between 4-12°C and above 20°C grows. The changes in temperature frequency are slightly different in other climate projections. Compared with the present scenario, temperature changes significantly in F2. In M2, there is no temperature below 0°C, and the frequency of temperature between 8-14°C is doubled, compared to the present scenario, and that above 22°C also increases sharply.

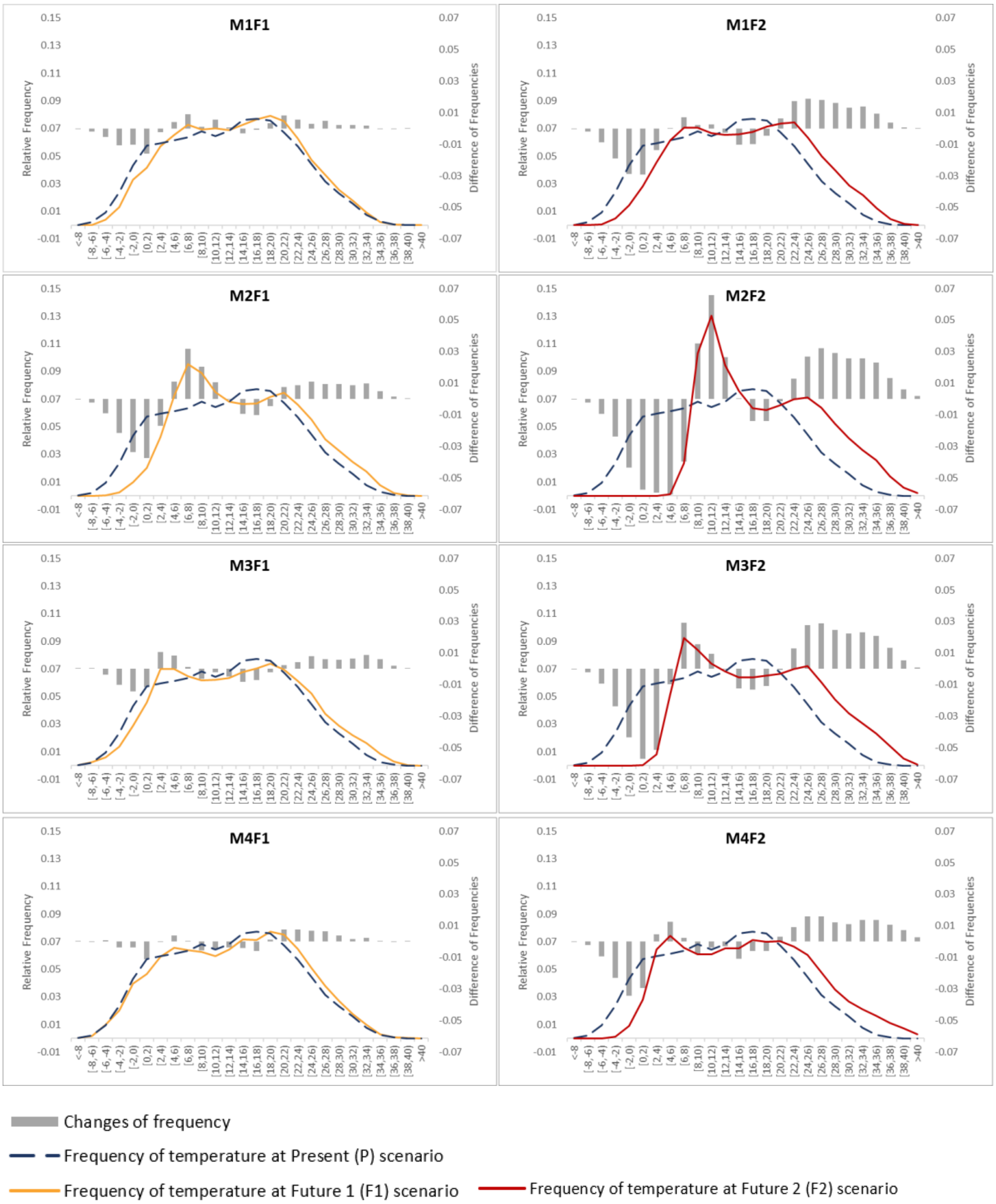


Figure 22 Changes of temperature distribution between Present and Future scenarios in Climate zone I

Temperature increase is not consistent across seasons. In Figure 23, the hourly average temperature increases in different seasons are presented, where bars with yellow-toned color are hourly average temperature increases at F1 compared with P, and bars with red-tone color are hourly average temperature increases at F2 compared with P. Winter experiences a significant temperature rise in all future projections, and the highest increase in hourly average temperature reaches to 9.2°C in M2-F2. The temperature increase in autumn is also very considerable, with 6.1°C as the highest in M2-F2. In the case of summer, the temperature grows greatly in F2 with 5.5°C in the highest, while its growth in F1 is neglectable in M1 and M4. The temperature of spring falls slightly in F1 and sees an opposite trend in F2, the highest temperature increase is 3.7°C.

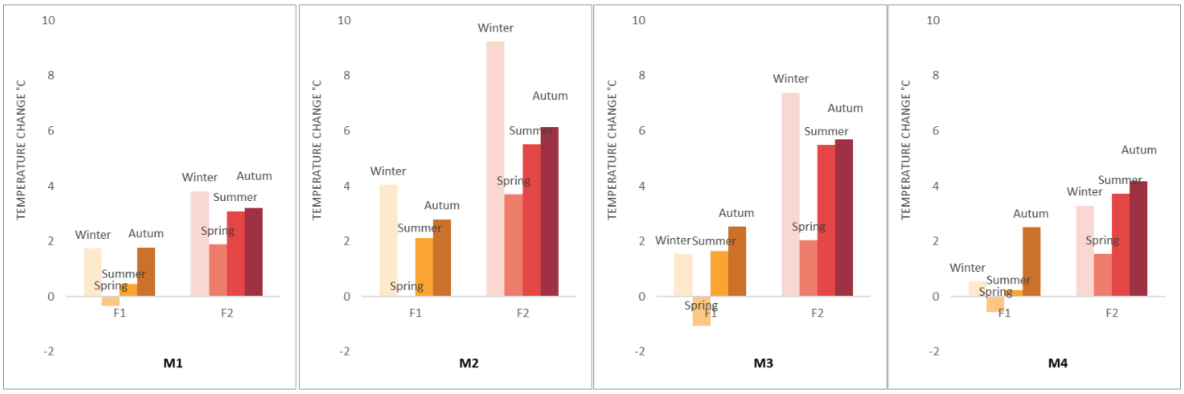


Figure 23 The changes of the hourly average temperature of seasons in Climate zone I. Bars with yellow-toned color are hourly average temperature increases at F1 compared with P; Bars with red-tone color are hourly average temperature increases at F2 compared with P

The daily temperature gradient is an important indicator in defining the potential of night cooling. Figure 24 shows the distribution of daily temperature differences during present and future scenarios. The maximum temperature difference decreases in M1, as well as the interquartile range showing a reduction in the temperature difference between the maximum and minimum daily values. In M2 and M3, the maximum daily temperature gradient rises slightly at F1 while it drops back at F2. In M4, there is a decrease in the maximum daily temperature gradient at F1, but then it increases sharply in F2.

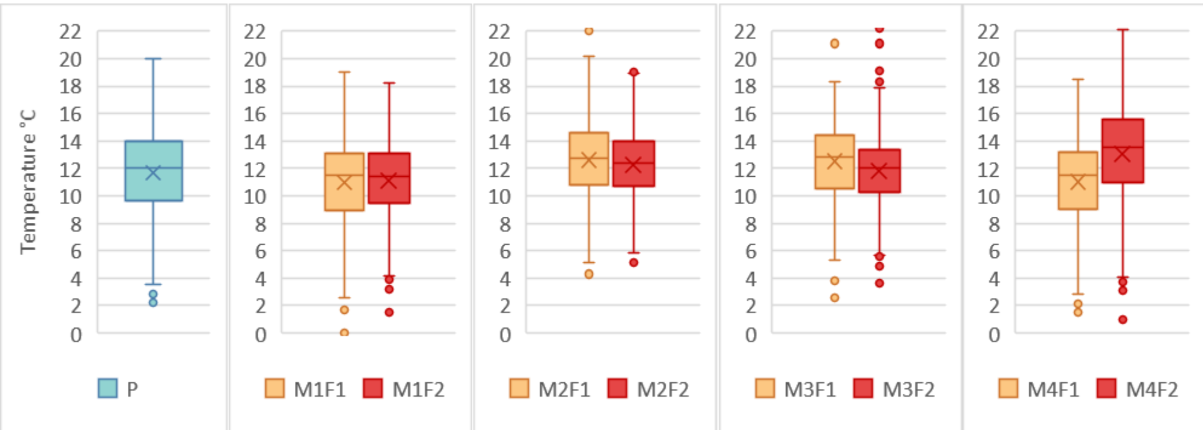


Figure 24 Distribution of daily temperature difference of summer months in present (blue) and near (orange) and far (red) future scenarios in Climate zone I.

6.1.1.2 Climate zone II

In the present scenario of Climate zone II, the highest temperature in summer reaches to 33.7°C, and the lowest is -12.8°C (Figure 25). In winter, the daily average temperature ranges from -1.8 to 5.60°C, and it varies between 4.5-17.0°C, 16.8-22.0°C and 1.42-17.6°C in spring, summer and autumn respectively (Figure 25).

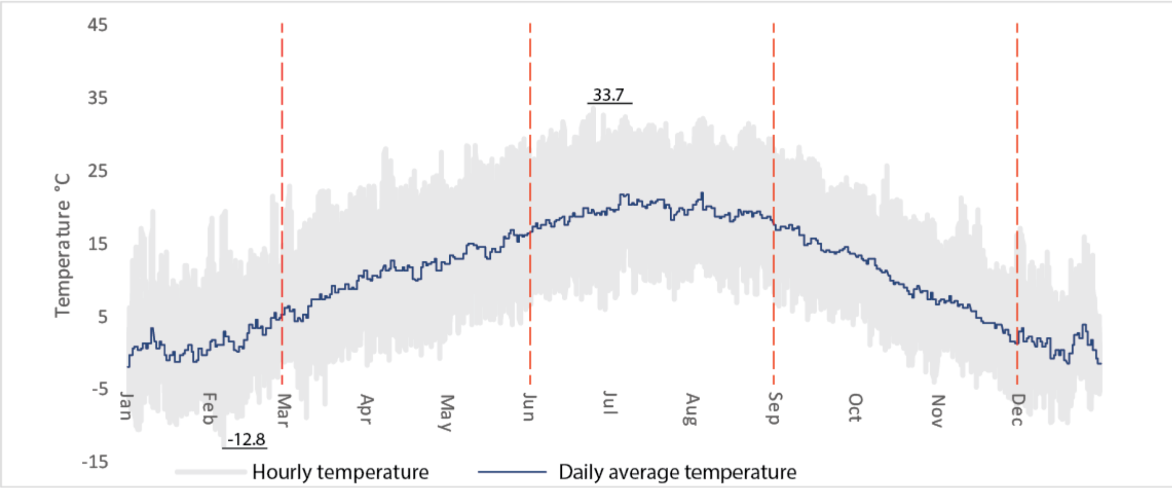


Figure 25 Dry bulb temperature during 2010-2017 and Average daily temperature in Climate zone II

The temperature distribution of Climate zone II changes marginally from P to F1 in M1,3,4, while M2 experiences a considerable temperature change (Figure 26). In M2, the frequency of temperature below 2°C and between 14-18°C falls, while that between 2-14°C and above 18°C rises. The changes in temperature frequency are slightly different in other climate projections. Compared with the present scenario, temperature changes significantly in F2. The most dramatic changes happen in M3. In M3, there is a considerable drop in the frequency of temperature below 6°C and between 12-20°C, while there is an increase in that between 6-12°C and above 20°C.

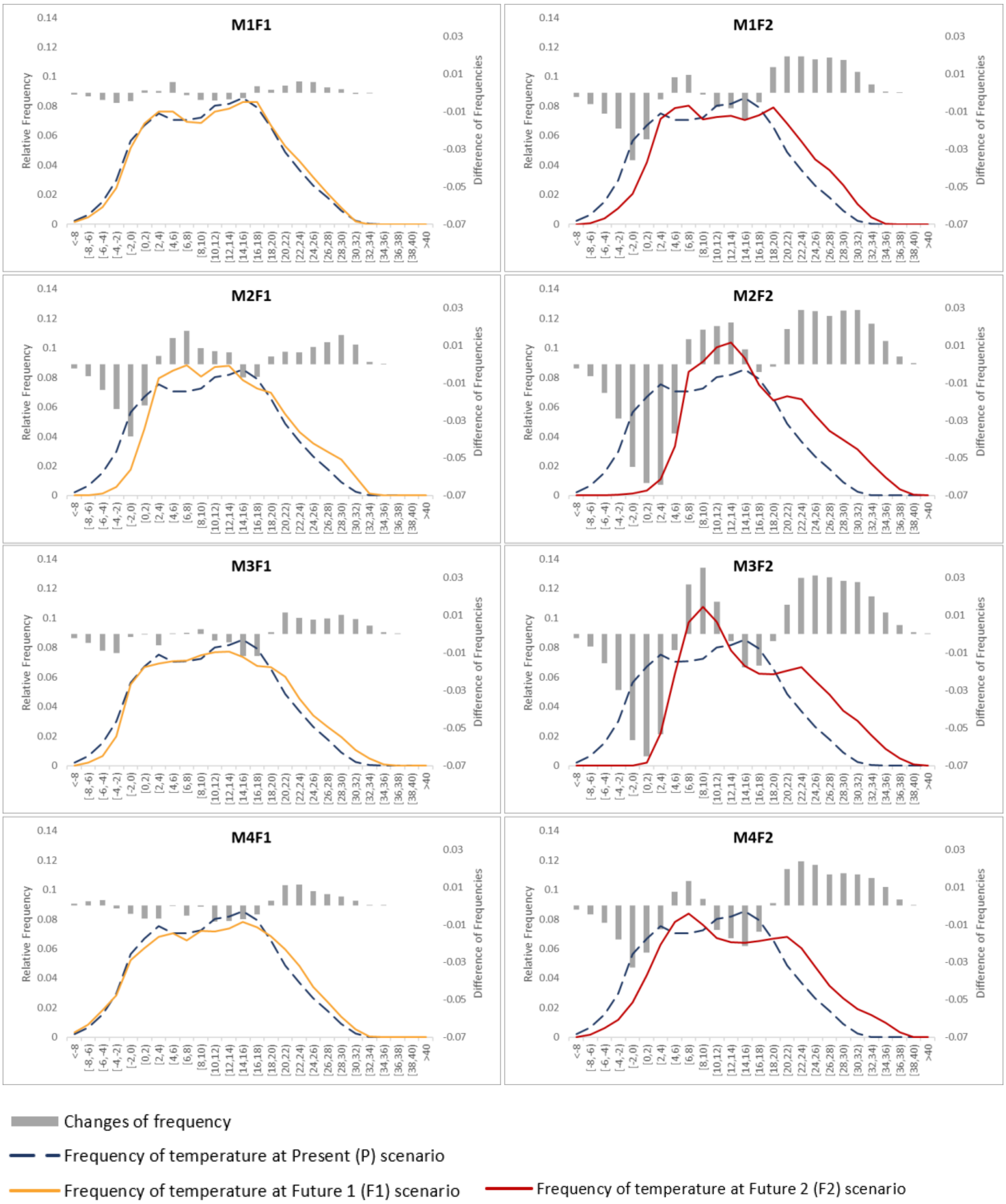


Figure 26 Changes of temperature distribution between Present and Future scenarios in Climate zone II

The temperature increase is not consistent across seasons (Figure 27). The growth of winter temperature at F1 is not obvious in M4, while in other projections, it is considerable. Winter experiences a significant temperature rise in all future projections at F2, and the highest increase in hourly average temperature reaches to 7.8°C in M2-F2. The temperature increase in autumn is also very considerable both at F1 and F2, with 7.0°C as the highest in M2-F2. In the case of summer, the temperature grows greatly in F2 with 6.3°C in the highest, while its growth in F1 is neglectable in M1 and M4. The temperature of spring falls at F1, by 1.8°C in M3, and sees an opposite trend in F2, the highest temperature increase is 3.5°C.

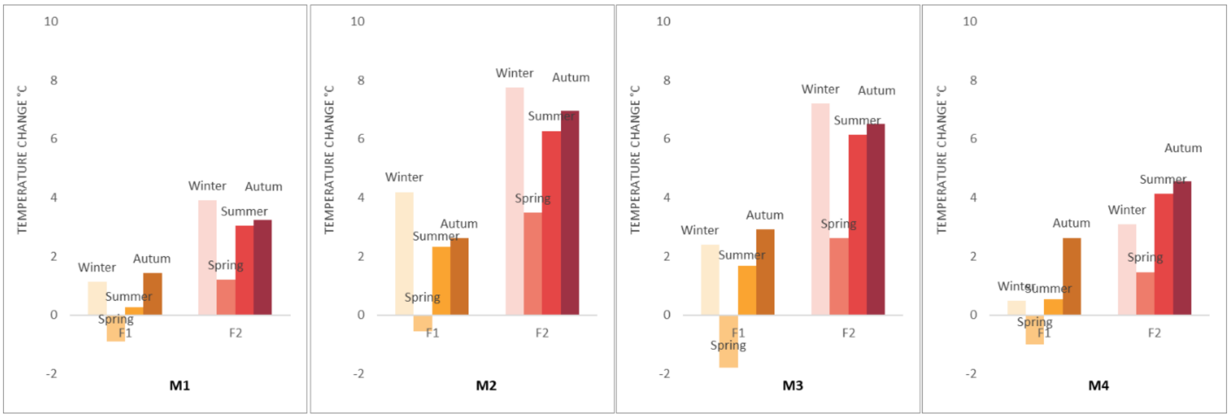


Figure 27 The changes in hourly average temperature of seasons in Climate zone II. Bars with yellow-tone color are hourly average temperature increases at F1 compared with P; Bars with red-tone color are hourly average temperature increases at F2 compared with P

Figure 28 shows the distribution of daily temperature differences during present and future scenarios in Climate zone II. At F1, the average temperature difference decreases in M1 but increases in other projections. At F2, there is a general rise in the average temperature difference.

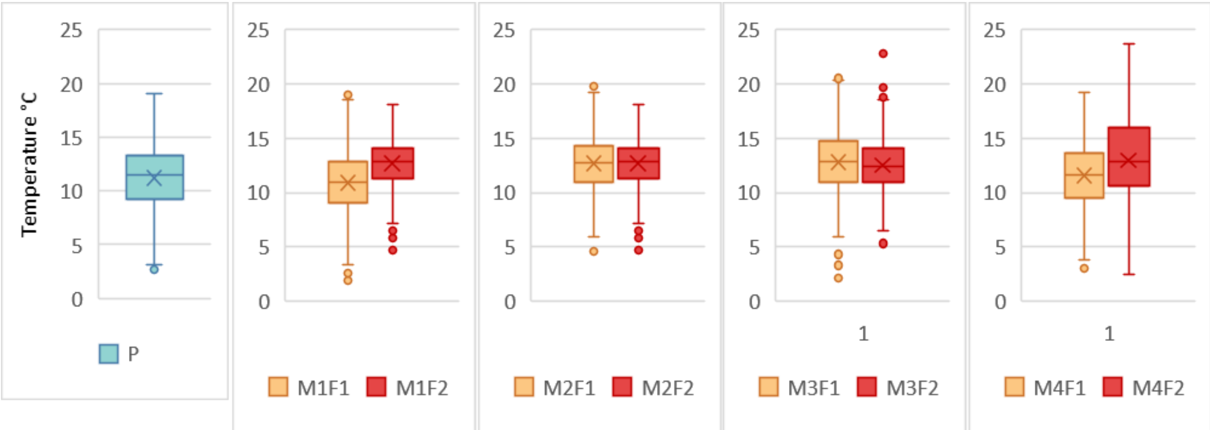


Figure 28 Distribution of daily temperature difference of summer months in present (blue) and near (orange) and far (red) future scenarios in Climate zone II.

6.1.1.3 Climate zone III

At the present scenario of Climate zone III, the highest temperature in summer reaches to 29.1°C, and the lowest is -21°C (Figure 29). In winter, the average temperature ranges from -5.7 to 0.3°C, and it varies between -1.0-11.1°C, 11.0-17.1°C and -2.0-12.7°C in spring, summer and autumn respectively (Figure 29).

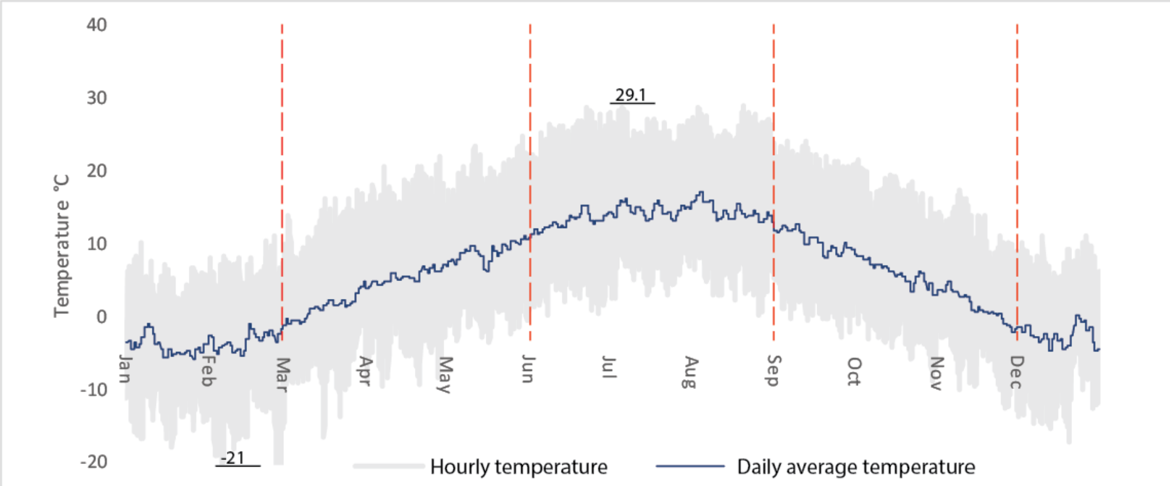


Figure 29 Hourly dry bulb temperature during 2011-2018 and Average daily temperature in Climate zone III

The temperature distribution of Climate zone III changes marginally from P to F1 in all the projections (Figure 26). In M1, the frequency of temperature below -6°C and above 12°C grows, while that between -6-12°C drops. The changes in temperature frequency are slightly different in other climate projections. Compared with the present scenario, temperature changes significantly in F2. The most dramatic changes happen in M3. In M3, there is a considerable drop in the frequency of temperature below 2°C and between 8-14°C, while there is an increase in that between 2-8°C and above 14°C.

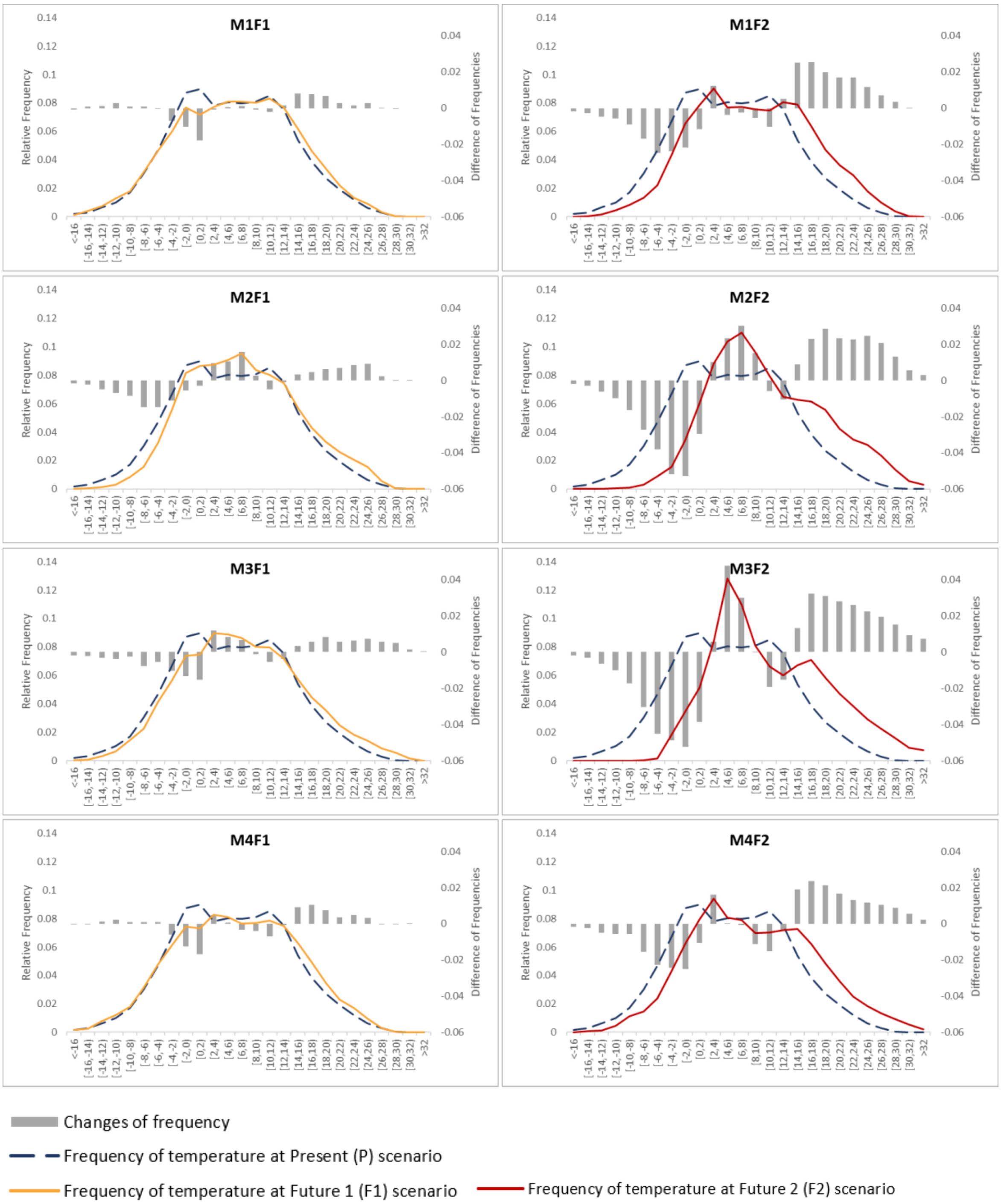


Figure 30 Changes of temperature distribution between Present and Future scenarios in Climate zone III

The temperature increase is not consistent across seasons (Figure 31). The growth of winter temperature at F1 is not obvious in M1 and M4, while in other projections, it is considerable. Winter experiences a significant temperature rise in all future projections at F2, and the highest increase in hourly average temperature reaches to 6.6°C in M3-F2. The temperature increase in autumn is also very considerable both at F1 and F2, with 5.9°C as the highest in M2-F2. In the case of summer, the temperature grows greatly in F2 with 6.6°C in the highest, while its growth in F1 is neglectable in M1 and M4. The temperature of spring falls at F1, by 1°C in M3, and sees an opposite trend in F2, the highest temperature increase is 3.7°C.

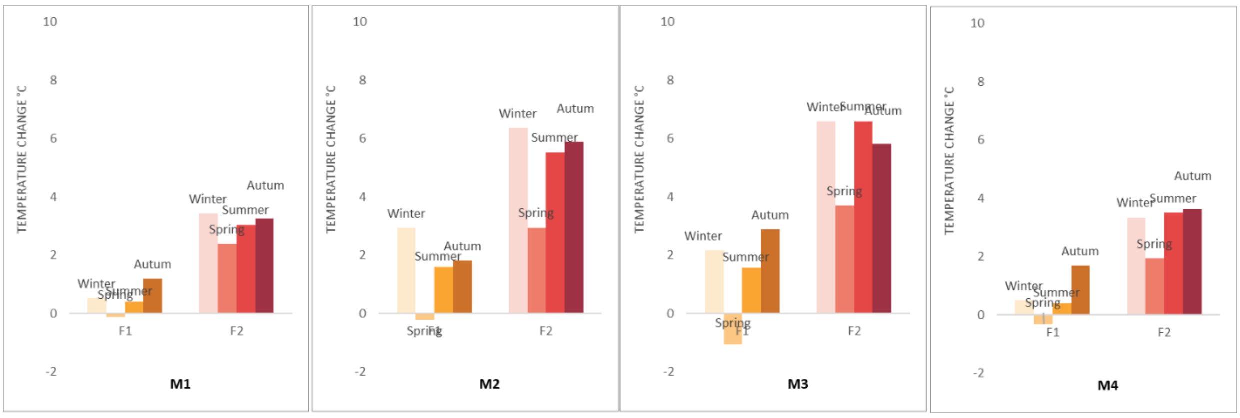


Figure 31 The changes in hourly average temperature of seasons in Climate zone III. Bars with yellow-tone color are hourly average temperature increases at F1 compared with P; Bars with red-tone color are hourly average temperature increases at F2 compared with P

Figure 32 shows the distribution of daily temperature differences during present and future scenarios in Climate zone III. The average temperature difference decreases in M1 and M4 but increases in other projections both at F1 and F2.

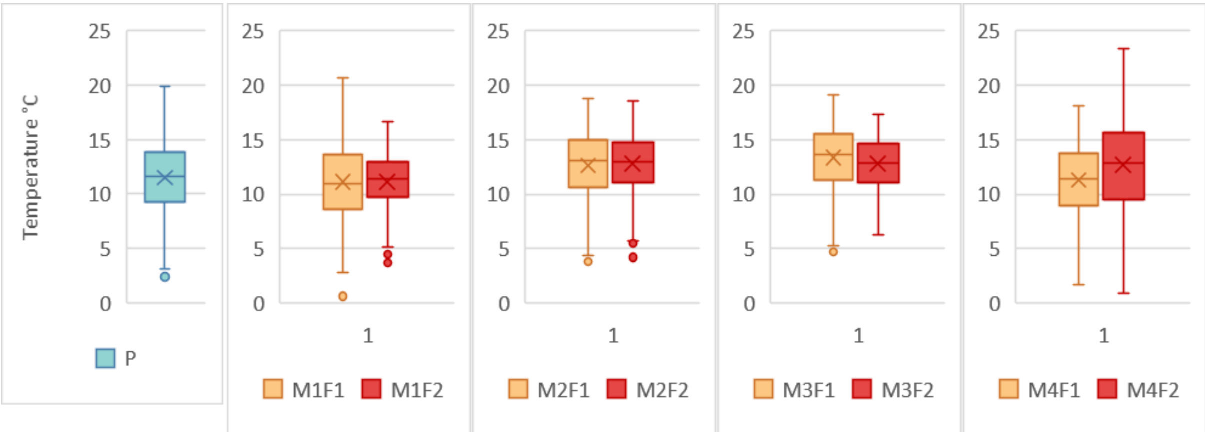


Figure 32 Distribution of daily temperature difference of summer months in present (blue) and near (orange) and far (red) future scenarios in Climate zone III

6.1.2 Precipitation conditions

The total amount of annual precipitation (Pr) increases from the present scenario to F1 scenarios in all three Climate zones, while the annual precipitation event number decreases, meaning that the amount of rainfall per event will increase considerably at the F1 scenario in all three Climate zones. At F2, a similar trend occurs in Climate zone II and III results in more precipitation in each event compared with F1. Meanwhile, Climate zone I witnesses a fall in both total annual precipitation amount and event number, which leads to a constant precipitation amount in each event compared with F1.

Table 27 Precipitation conditions in the present and future scenarios in three Climate zones

	Climate zone I			Climate zone II			Climate zone III		
	P	F1	F2	P	F1	F2	P	F1	F2
Average Pr amount per year[mm]	784	904	662	583	724	715	926	1049	1054
Average No. of Pr events per year	79.6	79.2	59.9	86	77.2	77.3	107	103	102
Average Pr amount per event per year [mm]	9.8	11.4	11.1	6.8	9.4	9.2	8.7	10.1	10.3

6.1.2.1 Climate zone I

At F1, all the future projections have more annual precipitation, as well as the precipitation events, and eventually more precipitation in each rain event. At F2, M1 and M2 see the opposite trend in annual precipitation amount and events number but still have intense rain amount per event.

Table 28 Precipitation conditions in the present and future scenarios in Climate zone I

	P	F1				F2			
		M1	M2	M3	M4	M1	M2	M3	M4
Average P amount per year[mm]	**784**	929	1010	890	787	466	369	998	814
Average No. of P events per year	**79.6**	80.2	78.5	78.9	79.1	43.6	34.2	83.2	78.5
Average P amount per event per year [mm]	**9.8**	11.6	12.9	11.3	9.9	10.7	10.8	12.0	10.4

The changes of precipitation amount in seasons differ greatly depending on future climate models (Figure 33). In M1, there is a mild rise in precipitation amount in all seasons at F1 before it falls at F2. M2 experiences a rapid increase of precipitation amount in winter, spring and autumn at F1, while that in summer decreases greatly. However, precipitation amount drops abruptly in all the seasons at F2. The precipitation increase in winter and the decrease in summer are both intense in M3. On the contrary, precipitation changes in M4 is mild.

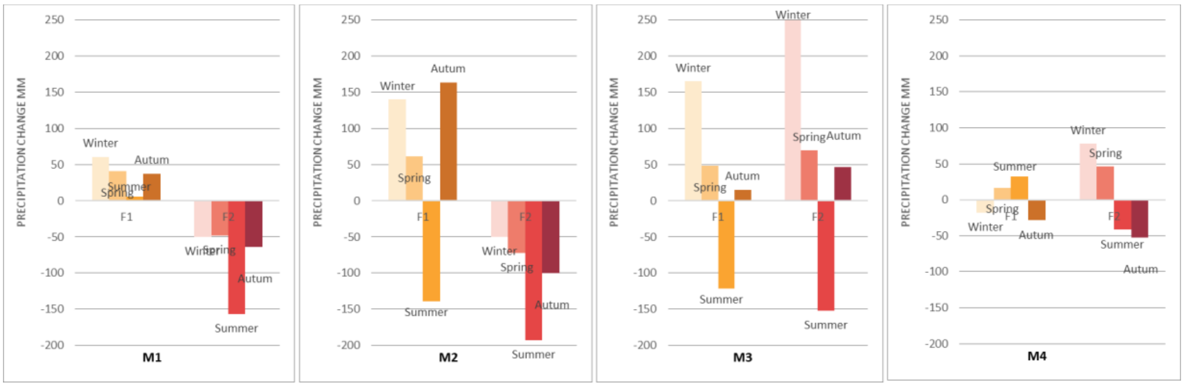


Figure 33 The changes in annual precipitation amount in seasons. Bars with yellow-toned color are annual Pr increases at F1 compared with P; Bars with red-tone color are annual Pr increases at F2 compared with P

Wind-driven rain (WDR) is an import moisture source influencing the moisture state in the historic constructions. According to EN15927-3, the amount of the WDR is influenced by the precipitation amount, wind speed, the terrain of the location, the geometry and orientation of the construction, etc. In Climate zone I, the west wall (270) is most exposed to WDR at present scenario and at most future projections (Figure 34). The amount of WDR on west wall drops from present to future scenarios. At F1, M1 has the most WDR while M4 gets the most WDR at F2.

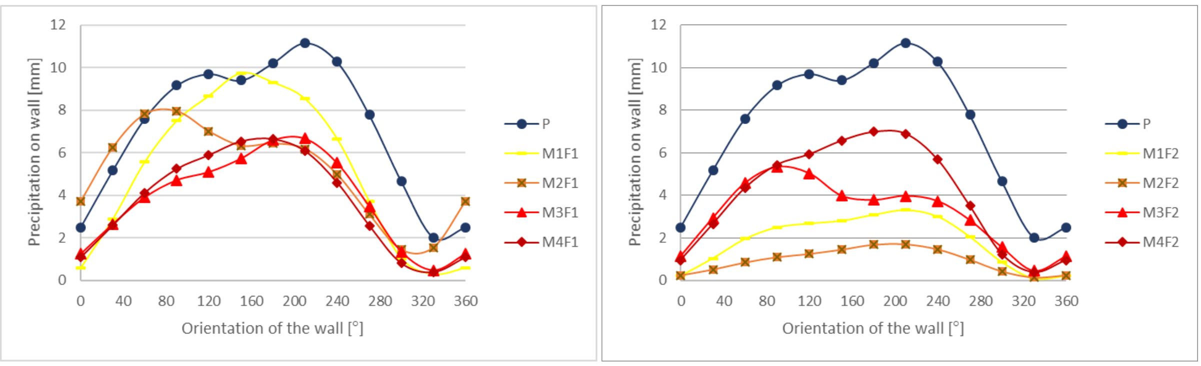


Figure 34 Amount of wind-driven rain on walls with different orientations (0° corresponds to the north). Left: Present and F1 scenarios; Right: Present and F2 scenarios

6.1.2.2 Climate zone II

In Climate zone II, the annual precipitation amount grows in all the future projections, while the number of precipitation events drops, resulting in more rainfall in each event. Among all the projections, M1 has the most precipitation.

Table 29 Precipitation conditions in the present and future scenarios in Climate zone II

	P	F1				F2			
		M1	M2	M3	M4	M1	M2	M3	M4
Average P amount per year[mm]	**583**	829	725	747	595	934	629	704	591
Average No. of P events per year	**86**	77.1	78.1	76.7	76.7	78.3	74.8	78.5	77.4
Average P amount per event per year [mm]	**6.8**	10.8	9.3	9.7	7.8	11.9	8.4	9.0	7.6

The changes in precipitation amount in seasons differ greatly depending on future climate models (Figure 35). In M1, there is a rise in precipitation amount in all seasons at F1 and F2. The precipitation grows more than 150mm in autumn at F2. M2 and M3 experience an increase of precipitation amount in winter, spring, and autumn, while that in summer decreases greatly both at F1 and F2. The precipitation changes are marginal in M4 at F1. At F2, there is a rise in winter and spring precipitation during a drop in summer and autumn.

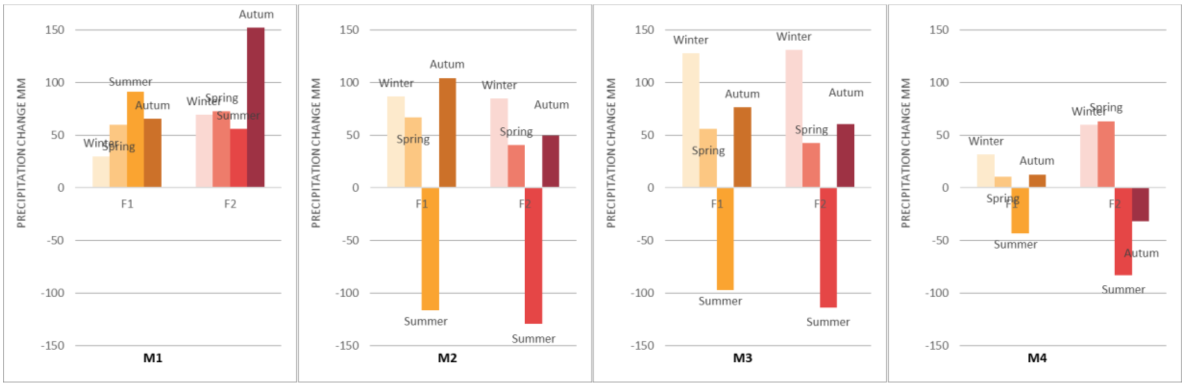


Figure 35 The changes in annual precipitation amount in seasons. Bars with yellow-tone color are annual Pr increases at F1 compared with P; Bars with red-tone color are annual Pr increases at F2 compared with P

The west wall (270°) is most exposed to WDR in Climate zone II (Figure 36). Compared with the present scenario, the amount of WDR on the west wall of M1 and M3 increases at both F1 and F2. Therefore, these two projections may introduce more moisture into historic constructions. The amount of WDR in M3 rises at F1, and then it decreases at F2. The WDR is always less in M4 when compared with the present scenario.

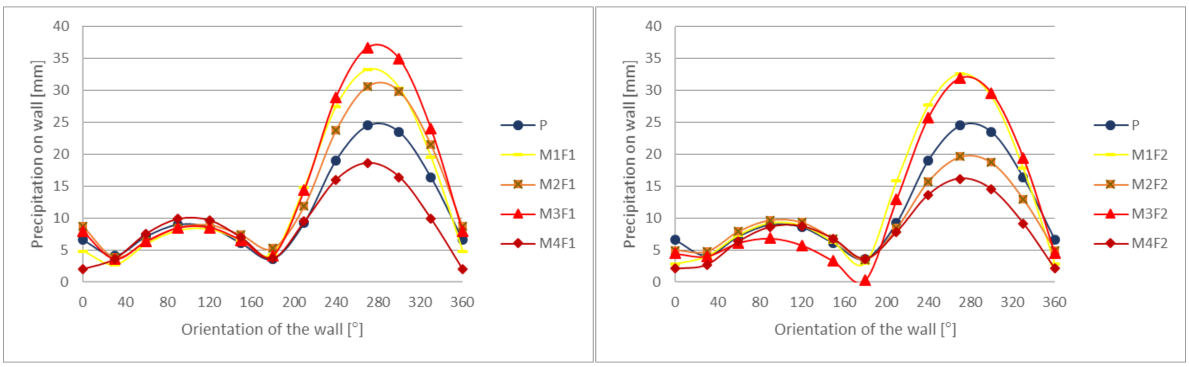


Figure 36 Amount of wind-driven rain on walls with different orientations (0° corresponds to the north).Left: Present and F1 scenarios; Right: Present and F2 scenarios

6.1.2.3 Climate zone III

In Climate zone III, the annual precipitation amount grows in all the future projections, while the number of precipitation events drops, resulting in more rainfall in each event. Among all the projections, M2 has the most precipitation in each event.

Table 30 Precipitation conditions in the present and future scenarios in Climate zone III

	P	F1				F2			
		M1	M2	M3	M4	M1	M2	M3	M4
Average P amount per year[mm]	**926**	1073	1097	1045	980	1104	1071	1032	1009
Average No. of P events per year	**107**	104.9	100	103.1	104.2	103.2	99	101	102
Average P amount per event per year [mm]	**8.7**	10.2	11.0	10.1	9.4	10.7	10.8	10.2	9.9

The changes in precipitation amount in seasons has a similar pattern in future climate models (Figure 37): precipitation sees a rise in all seasons except summer. The rise in precipitation amount of winter is intense in M1, M2, and M3. M2 and M3 also experience a significant decrease in precipitation amount in summer. The precipitation changes are marginal in M4.

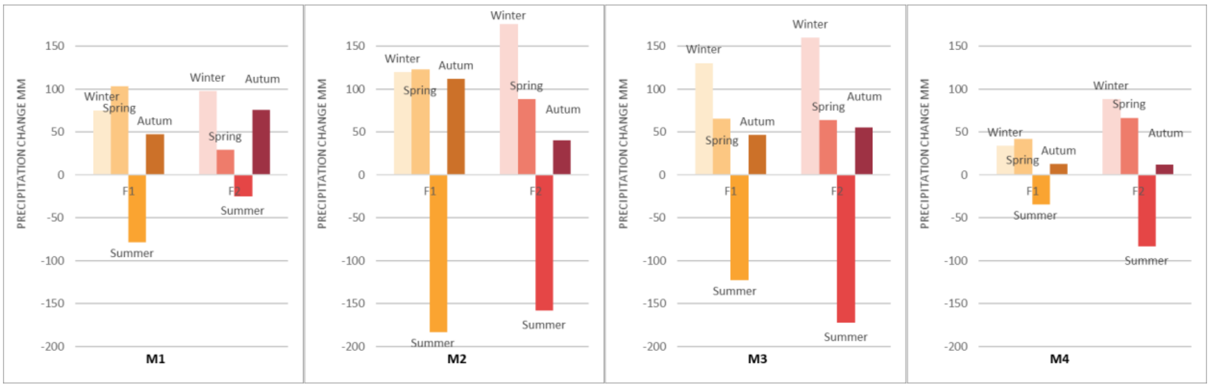


Figure 37 The changes of annual precipitation amount in seasons in Climate zone III. Bars with yellow-tone color are annual Pr increases at F1 compared with P; Bars with red-tone color are annual Pr increases at F2 compared with P

The east wall (90°) is most exposed to WDR in Climate zone III (Figure 38). Compared with the present scenario, the amount of WDR on the east wall of M2and M3 increases at both F1 and F2. Therefore, these two projections may introduce more moisture into historic constructions. The WDR is always less in M1and M4 when compared with the present scenario.

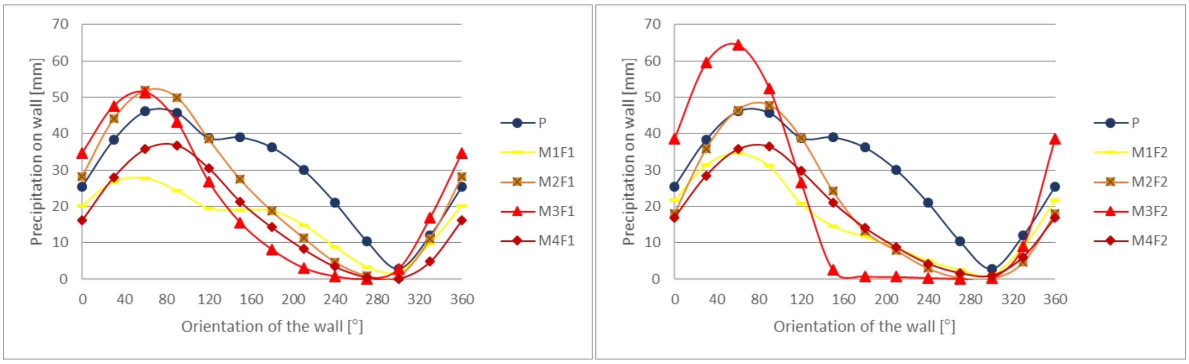


Figure 38 Amount of wind-driven rain on walls with different orientations (0° corresponds to the north). Left: Present and F1 scenarios; Right: Present and F2 scenarios

6.1.3 Potential impacts of climate changes on building performance

In Climate zone I, the hourly winter temperature rise in M2 is most notable compared with other climate projections. Therefore, the heating energy use of M2 projection could be the lowest and followed by M3, 1, and 4. Hourly summer temperature of M2 and M3 grows significantly, which could lead to overheating problems in Living rooms. However, the daily temperature difference of summer months in M2 and M3 increases, meaning that the night cooling could effectively reduce the heat during the night. Therefore, the bedrooms may perform well in thermal comfort with M2 and M3 projections. Even though there is more precipitation in the future, especially in winter, the quantity of WDR decreases in all the climate projections. This is due to the drops in wind speed in the future. Therefore, there may be less moisture risks compared with present in Climate zone I.

In Climate zone II, the hourly winter temperature rise in M2 is the highest among other climate projections, similar to Climate zone I. It is again hypothesized to achieve the lowest energy use in heating. Moreover, the increase in the hourly summer temperature of M2 is sharp. However, considering the relatively low temperature of Climate zone II, whether this increase will lead to overheating is debatable. There will be more WDR in M1 and M3. Since temperature rise in M1 is marginal, condensation is relatively easier to form. Therefore, M1 is assumed to have the most moisture risks.

In Climate zone III, M2 and M3 have the highest hourly winter temperature increase. Therefore, the future heating energy reduction in M2 and M3 should be the most. The hourly temperature in summer witness a rapid growth in M3. However, the hourly average temperature of summer in Climate zone III is rather low. Therefore, overheating should not happen regardless of the temperature rise. A considerable growth in the annual precipitation takes place in the future winter. Even so, the quantity of WDR changes on the east walls is marginal. Therefore, it is presumed that moisture risks will be at the same level in the future as at present.

6.2 Building energy use

The average annual heating energy use of the reference buildings is presented in Figure 39, where the heating energy use at F1 and F2 is the average energy use of the four future climate projections. The average heating energy use increases from Climate zone I to II and III, and Portici houses require more heating energy use per square meter than rural farmhouses. However, it should be emphasized that the different characteristics of reference buildings (differences in building function, layout, volume, etc.) may prevent the direct comparison of their energy performance. Figure 40 shows the specific heating energy use in each future projection of the three Climate zones.

Current best retrofit solutions reduce the heating energy use significantly in all three Climate zones. In Climate zone I, energy retrofit has a higher efficiency in Portici house than rural farmhouse, and it could save 92.2% of the heating energy at the present scenario, and 93.4% at F1 scenarios and 95.8% at F2 scenarios. On the other hand, energy saved in rural farmhouses constitutes 85.4% of the original energy use at present scenario and 86.4% at F1 and 90% at F2. Even though the ratio of energy saving increases from present to future, from rural farmhouse to Portici house, the absolute use of the energy in kWh/m^2 witnesses the opposite. In Climate zone II and III, energy retrofit is slightly less effective compared with Climate zone I in terms of the ratio of energy saving. However, the absolute energy saving of Climate zone II and III is higher than Climate zone I. In summary, retrofit solutions have a substantial impact on heating energy use, and it could achieve better effects in a warmer climate and in Portici houses when comparing the energy-saving ratio.

Future climate change can also lessen the heating energy use, but its impact is only substantial at F2 when the building is not retrofitted. In Climate zone I, the average heating energy use drops by 12.7% at F1, and 39% at F2 compared with P, in Portici house. In rural farmhouse, the reduction ratio is slightly higher: 13.6% at F1 and 42.2% at F2. The impact of climate change is less intense in Climate zone II compared with Climate zone I, from the perspective of energy reduction ratio. The temperature rise reduces 10.0% of the average heating energy use in Portici house at F1, and 33.5% at F2. Different with Climate zone I, the decrease ratio of the heating energy of rural farmhouse is slightly lower than Portici house: 8.9% at F1 and 32.4% at F2. The impact of climate change is the least in Climate zone III. It leads to 6.1% reduction of the heating energy at F1 and 21.5% at F2. In the case of retrofitted buildings, climate change causes less reduction in the absolute heating energy use, since it is already low. However, the reduction ratio is high in Climate zone I and II. For instance, in the retrofitted Portici house, there is 67.7% of the heating energy saved due to climate change at F2 in Climate zone I, and 57.0% in Climate zone II. To sum up, the impact of climate change on building energy use is more obvious in a warmer climate and in retrofitted historic buildings when using energy reduction ratio as an indicator. In un-retrofitted buildings, the impact is substantial at F2.

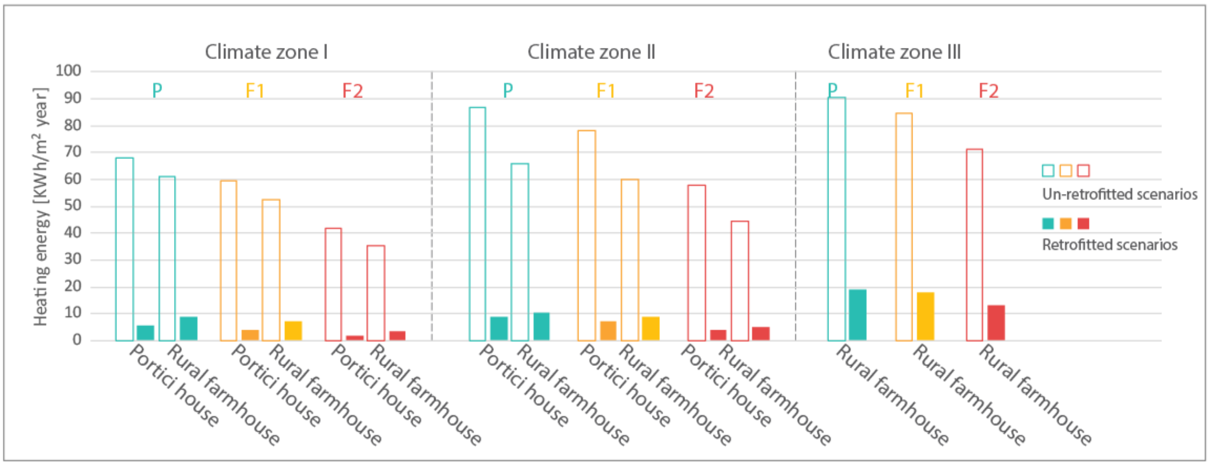


Figure 39 Average annual heating energy consumption of whole building in KWh/m²

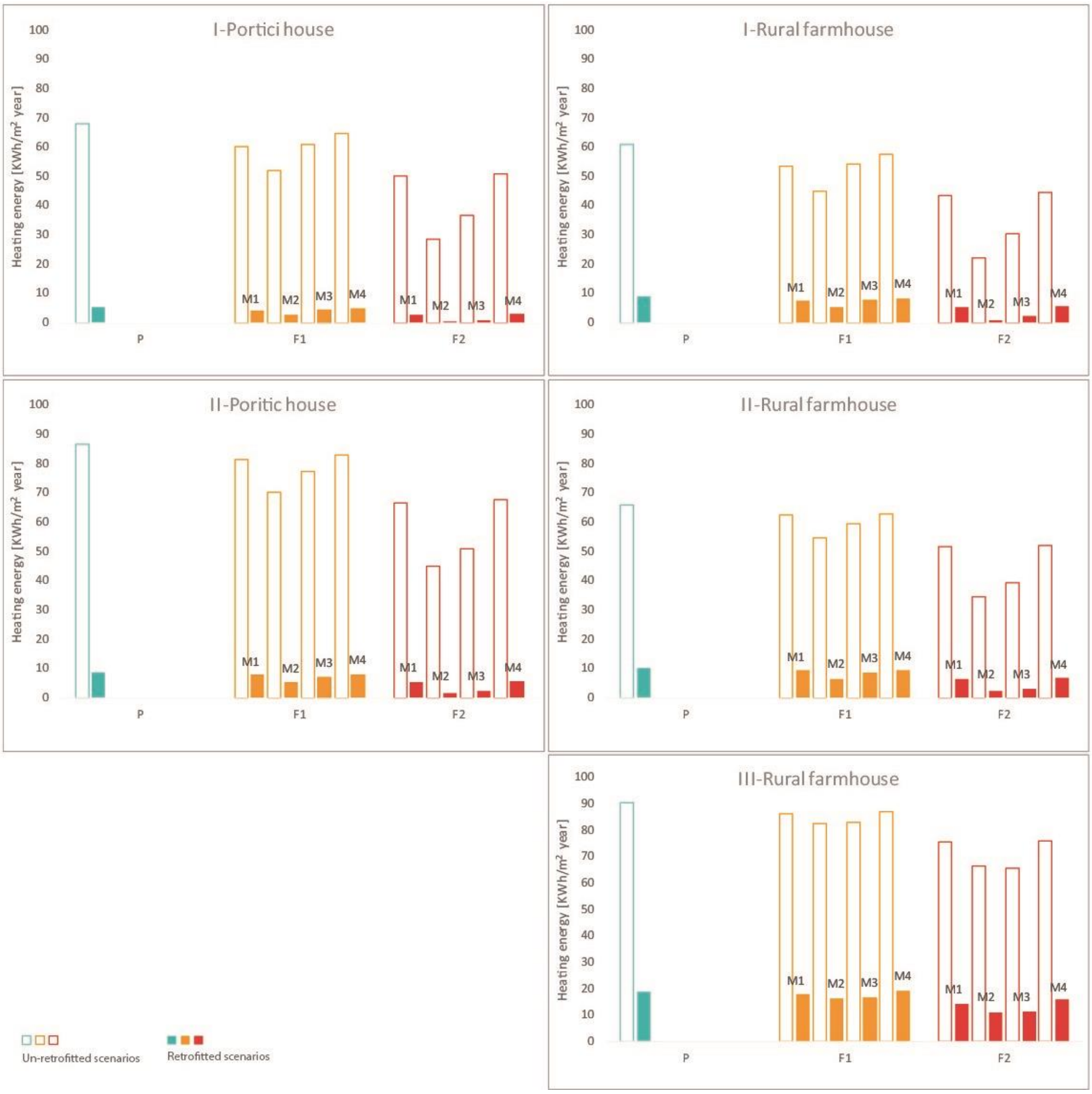


Figure 40 Average annual heating energy consumption of the whole building in kWh for retrofitted/un-retrofitted and present/future scenarios. left: Portici house; right: Rural farmhouse

6.3 Thermal comfort assessment

6.3.1 Comfort assessment with fixed operative temperature threshold

Both retrofit and climate change alter the distribution of indoor operative temperature. In the living room of Portici house of Climate zone I (Figure 41), the most frequent temperature interval is 20-22°C before retrofit, which consists of the heating setpoint temperature in winter. The impact of future climate change at F1 is rather limited, while at F2, it increases more than 10% of the operative temperature above 28°C with M2 climate projection. The impact of retrofit on operative temperature is substantial. At present, the most frequent temperature interval is still 20-22°C as in un-retrofitted scenario. However, retrofit interventions double the frequency of temperature between 22-28°C. Moreover, it increases the frequency of temperature above 28°C by 22%. In the retrofitted scenario, the impact of climate change on operative temperature is more visible than in un-retrofitted scenario. For instance, with M2 climate projection, the most frequent temperature interval shifts from 20-22°C at present to 22-24°C at F2, indicating climate change influence the operative temperature during the heating period. Furthermore, the frequency of temperature between 26-32°C reduces while that above 32°C rises.

The changes in other reference buildings are presented in Appendix A.

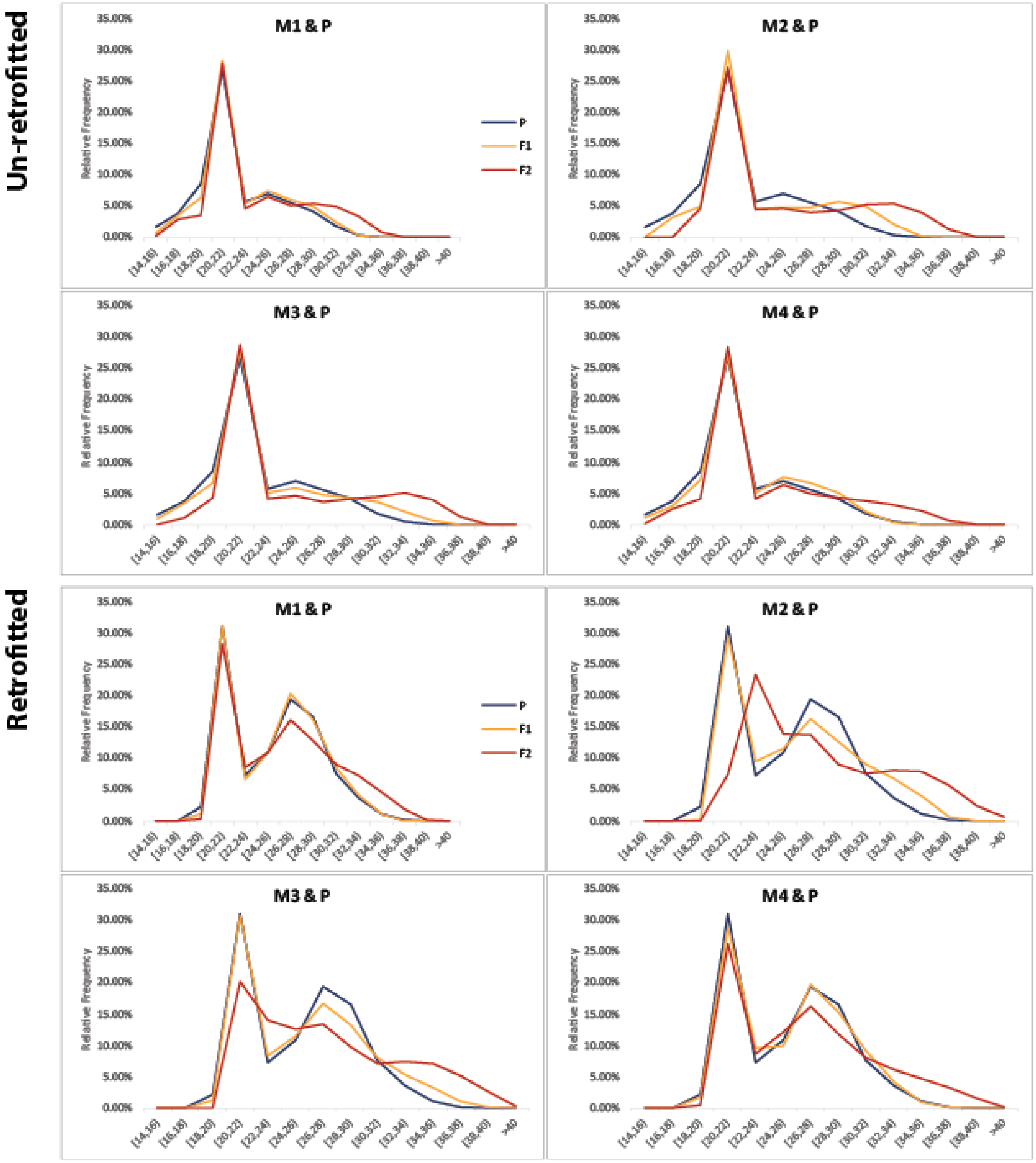


Figure 41 Operative temperature distribution of the living room of Portici house in Climate zone I

CIBSE guild A is used to characterize overheating in the living rooms and bedrooms. The operating hours when the temperature exceeds 28°C in the living room and 26°C in the bedroom are quantified. As shown in Figure 42, there are 5736 operating hours every year. In the Portici house of Climate zone I, overheating hours exist even in the un-retrofitted scenario at present. Both climate change and retrofit interventions aggravate the overheating risk. To further analyze the impact of climate change and retrofit interventions on overheating, three parameters are defined: In un-retrofitted buildings (Figure 43), Δ1= number of overheating hour in the **future** scenario - number of overheating hour in the **present** scenario, and it indicates the overheating hours caused by climate change in un-retrofitted buildings; In retrofitted buildings, Δ2= number of overheating hour in the **future** scenario - number of overheating hour in the **present** scenario. Therefore, it is the overheating-hour due to climate change in retrofitted buildings; Δ3= number of overheating hour in the **retrofitted** scenario - number of overheating hour in **un-retrofitted** scenario at the same time period, so it could show the impact of retrofit interventions on overheating hours.

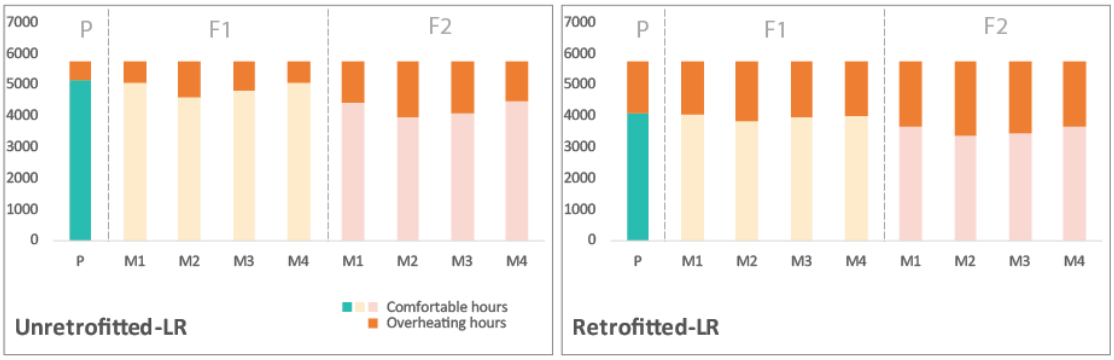


Figure 42 The thermal comfort state in Living room of Portici house in Climate zone I

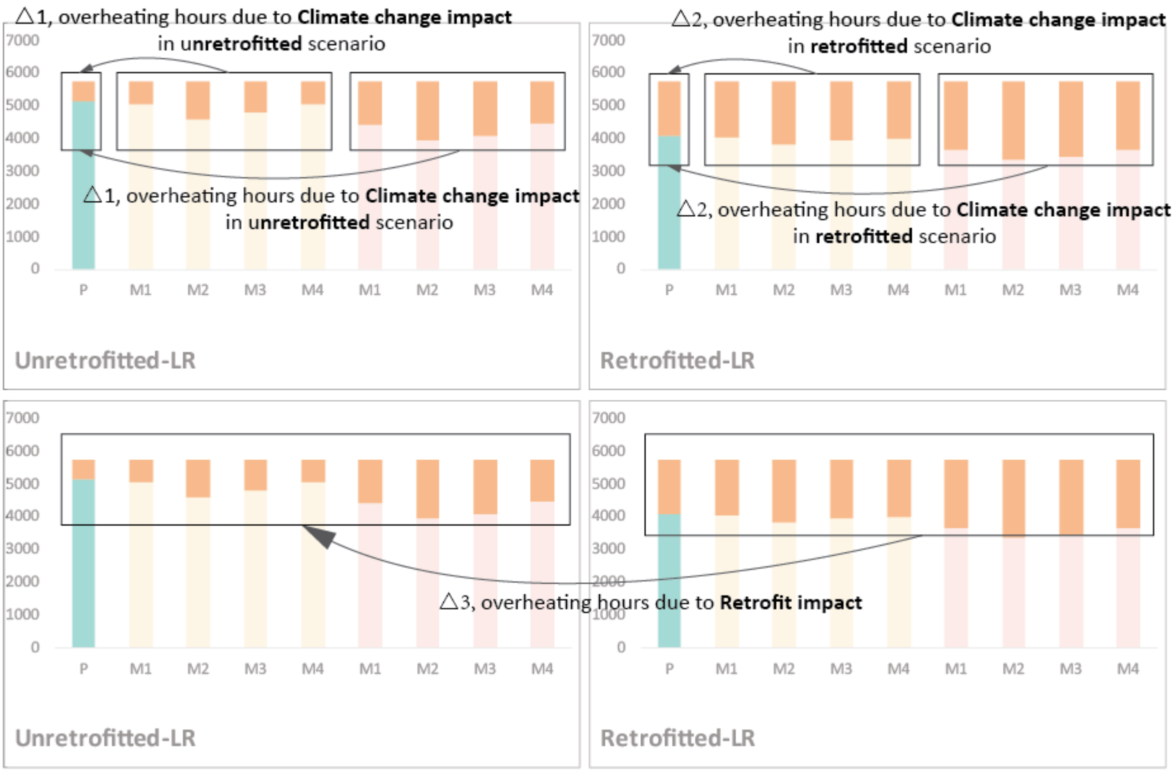


Figure 43 The meaning of Δ1- Δ3

Table 31 shows a comparison of the number of overheating-hour in living rooms due to climate change and retrofit between different scenarios. In Climate zone I, Δ1 is generally higher than Δ2, meaning that retrofit interventions could slightly mitigate the impact of climate change. Even though the retrofit action presents this mitigation effect, it brings much more overheating risk since Δ3 is very high in Climate zone I. On the contrary, Δ2 is always higher than Δ1 in Climate zone II. Therefore, climate change leads to more overheating risks in the retrofitted scenarios. Bedrooms shows the same trend as in living rooms (Table 32).

*Table 31 The number of overheating-hour per year of **Livingroom** due to climate change/retrofit intervention.*

			P	F1				F2			
				M1	M2	M3	M4	M1	M2	M3	M4
Climate zone I	Portici house	Δ1	-	112	571	379	100	725	1230	1098	691
		Δ2	-	55	228	137	62	399	730	611	409
		Δ3	1090	1033	747	848	1052	764	591	603	809
	Rural farmhouse	Δ1	-	125	594	463	149	814	1380	1282	846
		Δ2	-	135	560	449	280	751	1254	1070	819
		Δ3	615	625	581	601	745	552	489	404	588
Climate zone II	Portici house	Δ1	-	65	521	427	114	611	1373	1317	849
		Δ2	-	200	803	676	378	847	1576	1569	1210
		Δ3	228	363	510	476	492	465	431	480	589
	Rural farmhouse	Δ1	-	11	260	264	40	345	1220	1178	667
		Δ2	-	121	689	585	276	754	1577	1588	1149
		Δ3	161	272	590	482	397	571	519	572	643

*Table 32 The number of overheating-hour per year of **bedroom** due to climate change/retrofit intervention.*

			P	F1				F2			
				M1	M2	M3	M4	M1	M2	M3	M4
Climate zone I	Portici house	Δ1	-	69	448	301	113	541	914	811	546
		Δ2	-	62	-9	-59	22	128	223	103	124
		Δ3	1753	1747	1296	1393	1662	1340	1062	1045	1332
	Rural farmhouse	Δ1	-	84	444	326	158	578	976	885	605
		Δ2	-	181	279	231	161	517	700	460	433
		Δ3	971	1069	806	876	974	909	695	546	799
Climate zone II	Portici house	Δ1	-	32	316	268	46	353	927	887	540
		Δ2	-	75	183	157	176	264	613	494	441
		Δ3	1221	1264	1088	1110	1351	1132	907	828	1122
	Rural farmhouse	Δ1	-	0	105	114	6	162	805	782	400
		Δ2	-	212	412	373	297	423	893	855	691
		Δ3	655	867	963	914	946	916	743	729	946

6.3.2 Comfort assessment with adaptive model

6.3.2.1 Thermal comfort in Living room

According to the adaptive thermal comfort model of EN15251, current retrofit solutions change the thermal comfort state of the living rooms in all three zones. Its impact on overheating risk is most pronounced in the Portici house in Climate zone I (Figure 44): The main uncomfortable state changes from under-heating in un-retrofitted scenarios to overheating in retrofitted scenarios not only in future scenarios but also in the present scenario. Despite the Portici house of Climate zone I, retrofit interventions do not lead to substantial overheating hours at present and F1 (Figure 44-Figure 46). Moreover, in the rural farmhouse of Climate zone III, under-heating hours account for more than 85% of the total applicable hours. Retrofit improves the under-heating state remarkably and does not introduce overheating risk.

When comparing the overheating hours increased by retrofit interventions (Δ3 in Table 33), there are more overheating hours induced by retrofit in Climate zone I than II due to the warmer climate in zone I. In the Portici house of Climate zone I, Δ3 decreases slightly from present to F2. This phenomenon indicates that the negative effect of retrofit interventions falls slightly in future scenarios. However, in other reference buildings, Δ3 rises at F2, meaning that the negative impact of insulation escalates with temperature increases.

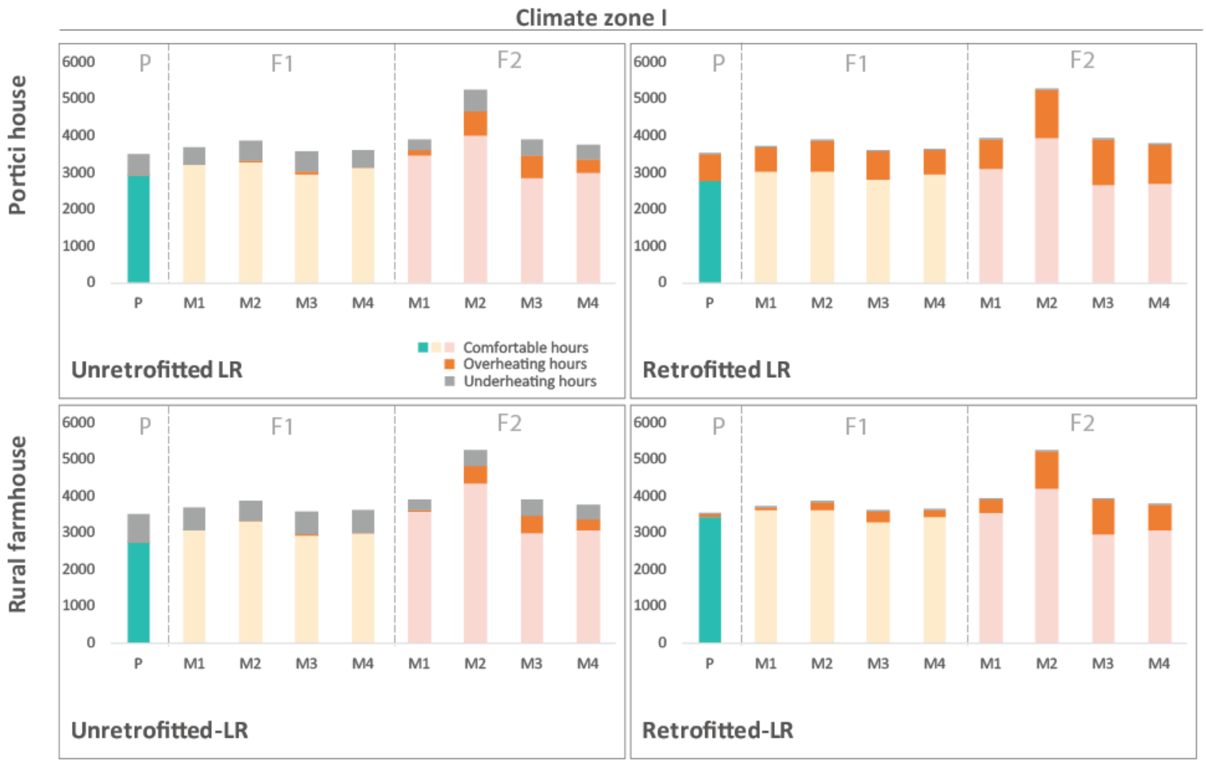


Figure 44 Thermal comfort state in Livingroom of reference buildings in Climate zone I

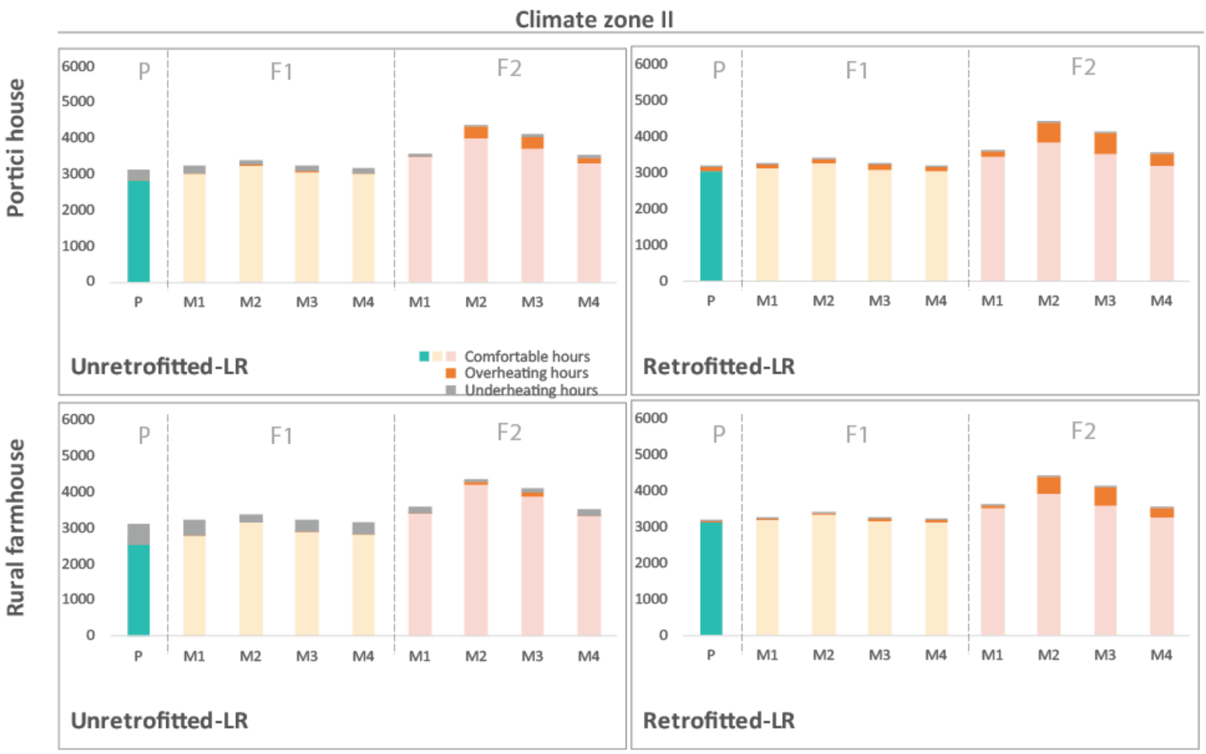


Figure 45 Thermal comfort state in Livingroom of reference buildings in Climate zone II

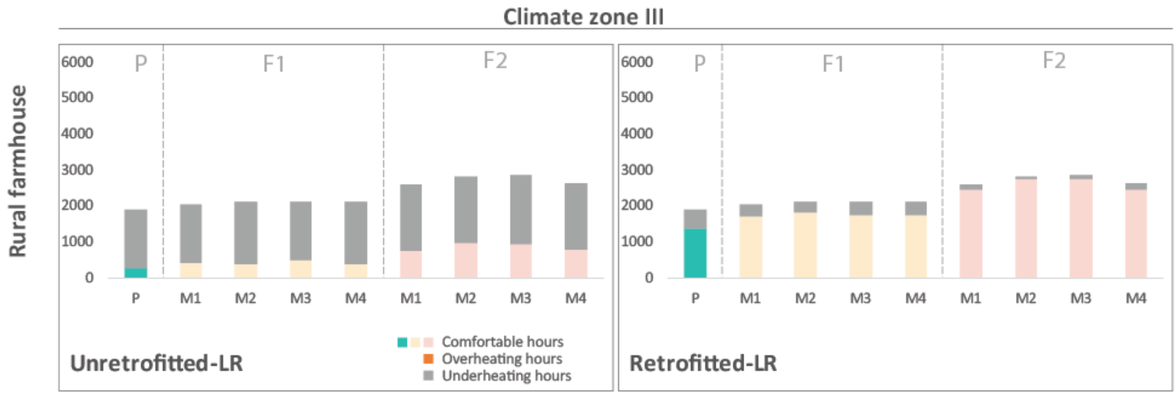


Figure 46 Thermal comfort state in Livingroom of rural farmhouse in Climate zone III

Table 33 The number of overheating-hour per year of ***Livingroom*** *due to climate change/retrofit intervention*

			P	F1				F2			
				M1	M2	M3	M4	M1	M2	M3	M4
Climate zone I	Portici house	Δ1	-	2	34	90	10	138	650	624	384
		Δ2	-	-59	87	27	-77	90	584	519	333
		Δ3	715	654	767	652	627	667	648	690	664
	Rural farmhouse	Δ1	-	-1	6	33	0	57	453	473	262
		Δ2	-	-22	172	193	92	270	956	846	612
		Δ3	73	51	239	233	165	286	576	446	422
Climate zone II	Portici house	Δ1	-	0	21	29	0	17	318	318	130
		Δ2	-	25	39	61	42	26	446	471	234
		Δ3	91	116	109	123	132	99	219	244	194
	Rural farmhouse	Δ1	-	0	0	0	0	0	64	96	1
		Δ2	-	18	33	61	59	36	447	482	247
		Δ3	15	33	48	76	74	51	398	400	261

Due to future temperature increase, the applicable hours of thermal comfort assessment grow, meaning that there is more outdoor running mean temperature above 15°C. Climate change leads to the most overheating hours in Climate zone I, in the rural farmhouse (Δ2 in Table 33). This is because the rural farmhouse is not shaded as the Portici house, and is more sensitive to climate change. The impact of climate change differs on whether the building is retrofitted or not. In the portici house of Climate zone I, Δ1> Δ2, showing that climate change leads to more overheating hours in un-retrofitted scenarios. However, other reference buildings experience the opposite: Δ2> Δ1, meaning climate change leads to more overheating risks in retrofitted scenarios.

6.3.2.2 Thermal comfort in Bedroom

Current retrofit solutions change the thermal comfort state of the bedrooms in all three zones, and its impact on overheating risk of bedrooms is most pronounced in the Portici house in Climate zone I (Figure 47), where the main uncomfortable state changes from under-heating in un-retrofitted scenarios to overheating in retrofitted scenarios. Retrofit interventions lead to overheating at all time scenarios. Still, the present scenario results in more overheating hours than future scenarios in Climate zone I. In Climate zone II, retrofit interventions do not cause substantial overheating risks until F2 (Figure 48). In Climate zone III, retrofit actions improved the under-heating state (Figure 49).

When comparing the overheating hours increased by retrofit interventions (Δ3 in Table 34), Portici houses are more impacted. In Climate zone I, Δ3 drops from present to F2. This phenomenon indicates that the negative effect of retrofit interventions decreases in future scenarios. However, other reference buildings witness a rise in Δ3, suggesting that the negative impact of retrofit on overheating risk grows with future climate change.

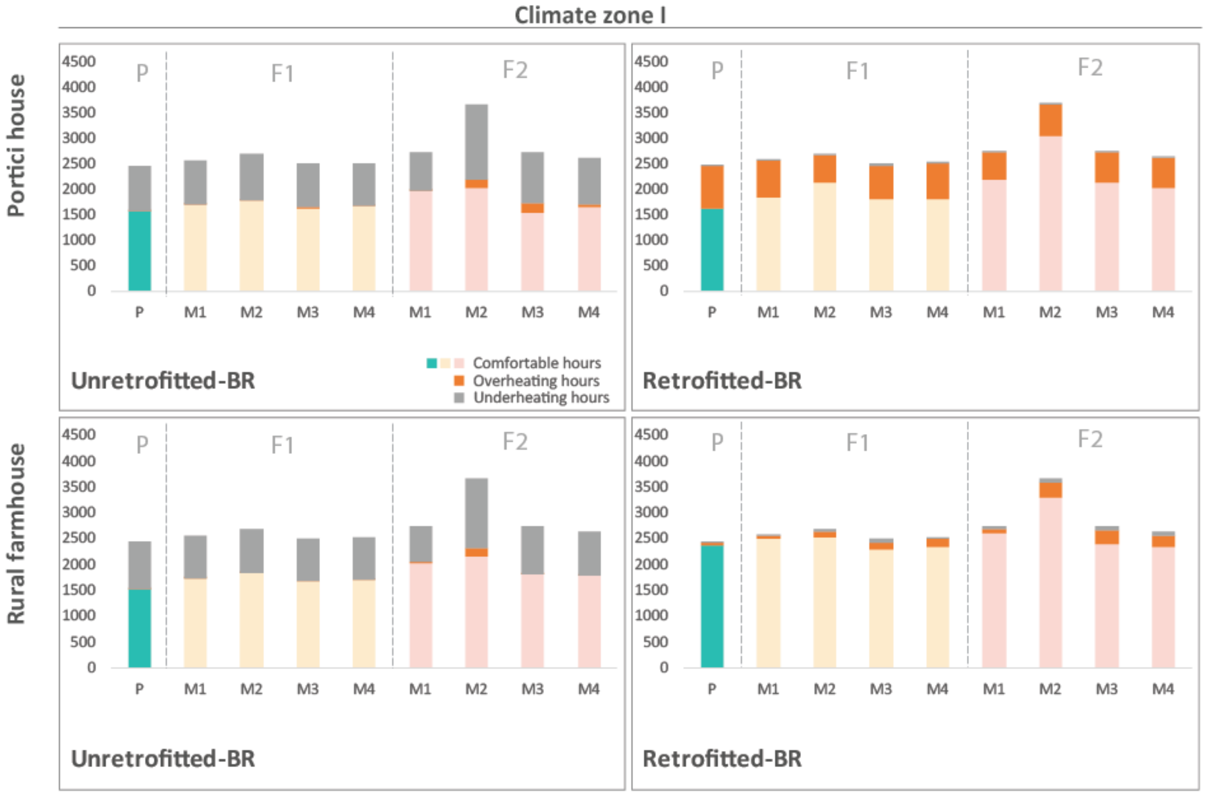


Figure 47 Thermal comfort state in Bedroom of reference buildings in Climate zone I

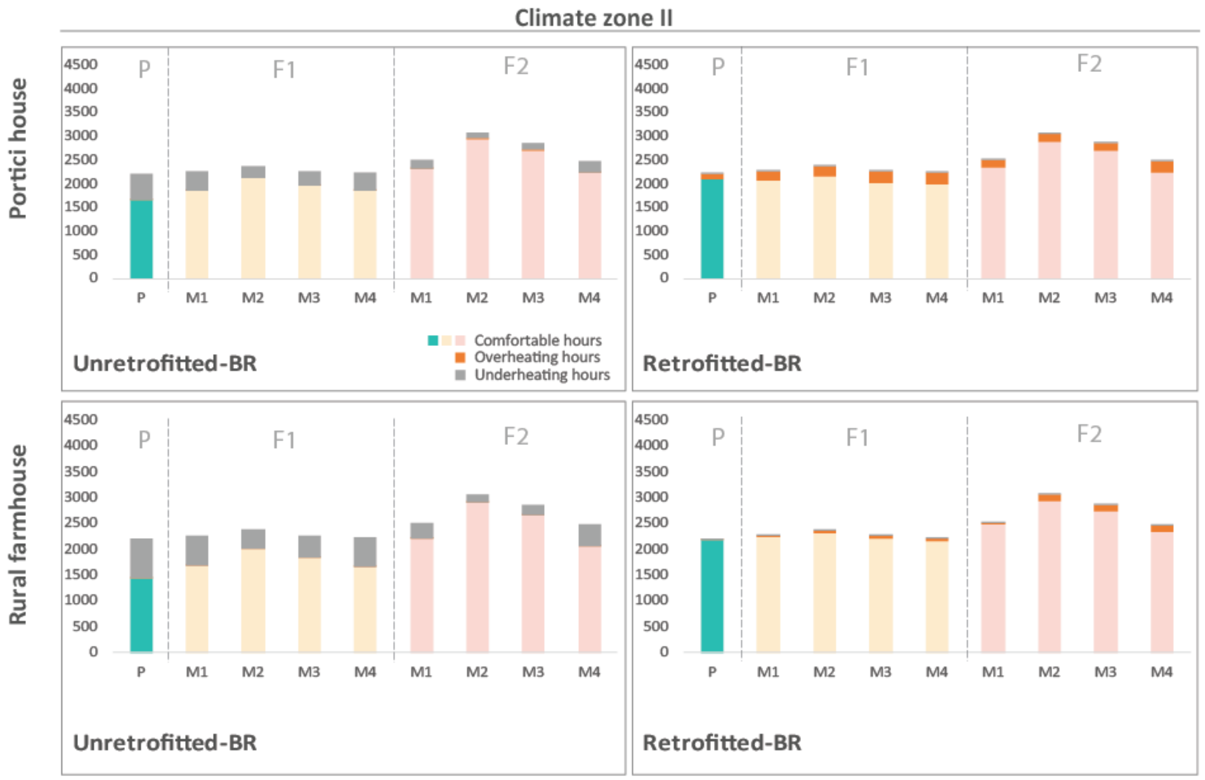


Figure 48 Thermal comfort state in Bedroom of reference buildings in Climate zone II

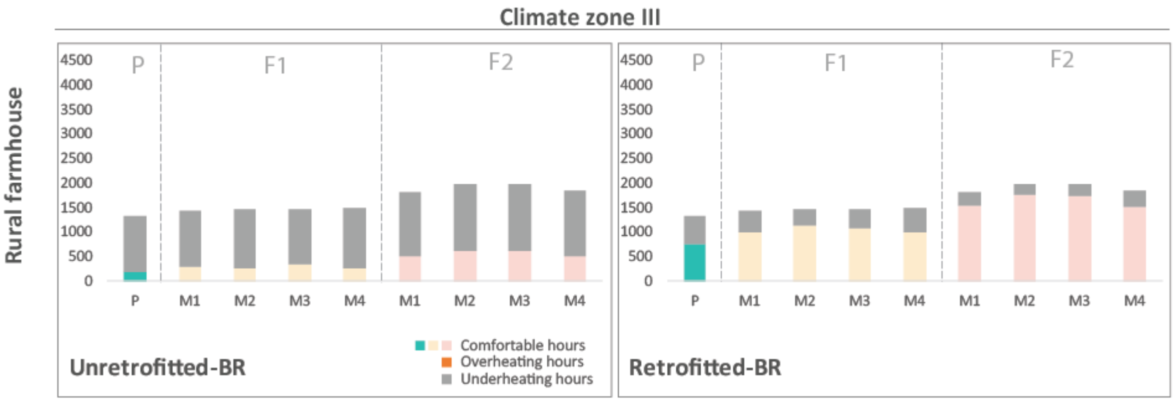


Figure 49 Thermal comfort state in Bedroom of reference buildings in Climate zone III

Table 34 The number of overheating-hour per year of ***Bedroom*** *due to climate change/retrofit intervention*

			P	F1				F2			
				M1	M2	M3	M4	M1	M2	M3	M4
Climate zone I	Portici house	Δ1	-	0	1	5	0	16	164	189	68
		Δ2	-	-98	-265	-174	-130	-291	-202	-237	-247
		Δ3	821	724	553	635	690	501	370	306	462
	Rural farmhouse	Δ1	-	0	1	0	0	15	154	0	0
		Δ2	-	-18	31	74	84	-9	219	201	154
		Δ3	72	53	101	146	155	47	137	272	225
Climate zone II	Portici house	Δ1	-	0	0	0	0	0	14	26	0
		Δ2	-	81	98	139	131	41	68	58	127
		Δ3	113	195	211	252	244	154	167	145	240
	Rural farmhouse	Δ1	-	0	0	0	0	0	5	8	0
		Δ2	-	8	49	58	54	25	105	110	128
		Δ3	3	11	52	60	57	28	103	105	130

Future climate change leads to more overheating hours. The impact of climate change differs on whether the building is retrofitted or not, and on the Climate zones. In un-retrofitted reference buildings, Δ1 increases from F1 to F2, showing the overheating risk grows due to climate change. However, in retrofitted Portici houses of Climate zone I and II, Δ1 drops from F1 to F2. Therefore, the retrofit interventions seem to mitigate the negative impact of climate change on overheating.

6.4 Moisture risks in envelopes

6.4.1 Condensation risk

A summary of the obtained results is presented in Table 4. In Climate zone I, the RH of all the retrofitted walls is in the safe range in all studied scenarios.

In Climate zone II, the granite wall retrofitted with a vapor-open insulation system (VO) shows no condensation risks at present scenarios. However, there is a condensation risk in the near future (F1) under all climate projections. In the far future (F2) scenarios, condensation risk only appears with M1 climate projection. When looking at the number of risk-hours, it decreases from F1 scenarios to F2 scenarios in all the climate projections. It could be assumed that the VO is an appropriate retrofit option for the granite wall at present, from a moisture risk point of view, but it will lead to risks within the service life of the insulation. And yet, it becomes a safe retrofit solution in the far future again. No condensation risk appears in granite walls retrofitted with vapor-tight system (VT) at the present scenario, while a low risk is present in most of the future climate projections. Compared with the vapor-open system, the vapor-tight system could lead to condensation risk even in F2 time scenarios.

In Climate zone III, the vapor-open system could cause very high condensation risk at P and F1 scenarios. The risk-hours decrease by 16.5% from P to F1 scenarios on average. At F2 scenarios, the risk-hours further decrease. M2 and M3 show low risk while M1 and M4 remain at high risk. According to the results of these simulations, the vapor-open system should not be used in the case of granite walls in Climate zone III neither in present nor F1 scenarios. Simulated RH in granite walls with a vapor-tight system is in the safe range at P scenario but could have high condensation risk at F1 and F2 time scenarios. M4 presents the most risk-hours achieving 3252 h/year (37.1%) at the F1 scenario. At F2, the number of risk-hours with M4 decreases the least compared to other climate projections.

Table 35 Condensation risk-hours in reference constructions

Climate zone	Wall construction	Insulation systems	Average No. of hours above 95% per year								
			P	*F1M1*	*F1M2*	*F1M3*	*F1M4*	*F2M1*	*F2M2*	*F2M3*	*F2M4*
I	Sandstone wall	VO	0	0	0	0	0	0	0	0	0
		VT	0	0	0	0	0	0	0	0	0
II	Granite wall	VO	0	1182	133.3	348.9	741.2	44	0	0	0
		VT	0	285.9	84.3	182.4	289.2	110.4	0	53	199.5
	Wood wall	VT	0	0	0	0	0	0	0	0	0
III	Granite wall	VO	2711	2373	2066	1818	2799	916	66	63	2021
		VT	0	2558	3538	2625	3252	1840	1287	1419	2531
	Wood wall	VT	0	0	0	0	0	0	0	0	0

*The colours of the table correspond with the threshold defined in section 3.5.2.

6.4.2 Mold risk

Mold risks are summarized in Table 36. In Climate zone I, there is no mold risk in all the studied scenarios.

In Climate zone II (Figure 50), the granite wall currently retrofitted with a vapor open insulation system remains low mold risk in the first three years. However, the mold growth index (MGI) increases close to the critical threshold in the following years. The MGI is higher in the future compared with P. In all the future climate projections, high mold risk appears at F1, and M1 is the most mold-risk vulnerable projection. At F2, the mold risk of all climate projections drops compared with F1, but MGI of M1 and 4 is still higher than the critical MGI threshold.

Table 36 Mold risks in reference buildings

Climate zone	Wall construction	Insulation systems	Peak mold growth index								
			P	*F1M1*	*F1M2*	*F1M3*	*F1M4*	*F2M1*	*F2M2*	*F2M3*	*F2M4*
I	Sandstone wall	VO	0	0	0	0	0	0	0	0	0
		VT	0	0	0	0	0	0	0	0	0
II	Granite wall	VO	3	4.4	3.7	4	4.1	3.7	2.1	2.8	3.1
		VT	0	3.7	3.5	3.6	3.4	3.5	3.4	4	3.2
	Wood wall	VT	0	0	0	0	0	0	0	0	0
III	Granite wall	VO	3.6	4.4	4.3	4.3	4.7	4.2	3.8	3.8	4.4
		VT	0	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
	Wood wall	VT	0	0	0	0	0	0	0	0	0

*The colors of the table correspond with the threshold defined in section 3.5.3.

The development of the mold growth index is different in granite walls with different systems of insulation. The decline of the mold growth index during each year is more notable in the granite wall with a vapor open insulation system. In granite wall with a vapor-tight insulation system, there is no mold risk at the present scenario, but the mold growth index surges beyond the critical threshold in the first year in all the climate projections at F1. The high mold risk persists in M1 and M2, while in other climate projections, the MGI drops below the critical threshold. At F2, the mold growth index rises above the critical threshold in the first year, but that of M1, 2, and 4 drops year by year and goes below the critical threshold. However, the high mold risk remains in M3.

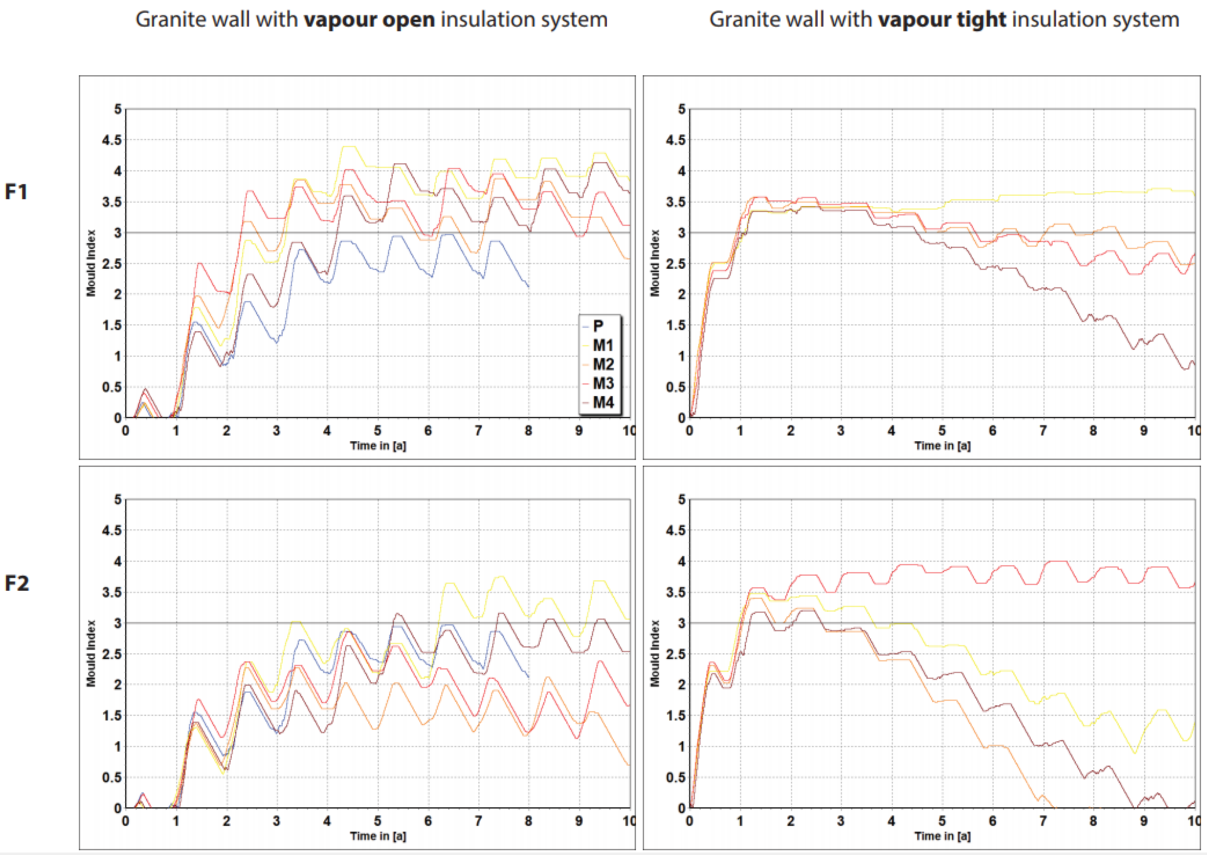


Figure 50 Mold growth index of retrofitted granite wall in Climate zone II

In Climate zone III (Figure 51), granite wall currently retrofitted with vapor open insulation system will have high mold risk from the fifth year on, and the MGI increases over time. At F1, MGI grows over time, and high mold risks appear in the fourth year in all climate projections. M4 is the most mold-risk vulnerable projection. Mold growth index at F2 is lower than that at F1 in all the climate projections. However, the high mold risks persist at F2.

The decline process of mold during each year is more notable in the granite wall with a vapor open insulation system compared with the vapor-tight insulation system. In granite wall with vapor-tight insulation system, there is no mold risk at the present scenario, but at F1 and F2, the mold growth index surges beyond the critical threshold in the first year in all the climate projections. The MGI witness a mild decline overtime at future scenarios. However, by the end of the simulation, there remains a high mold risk in all the climate projections.

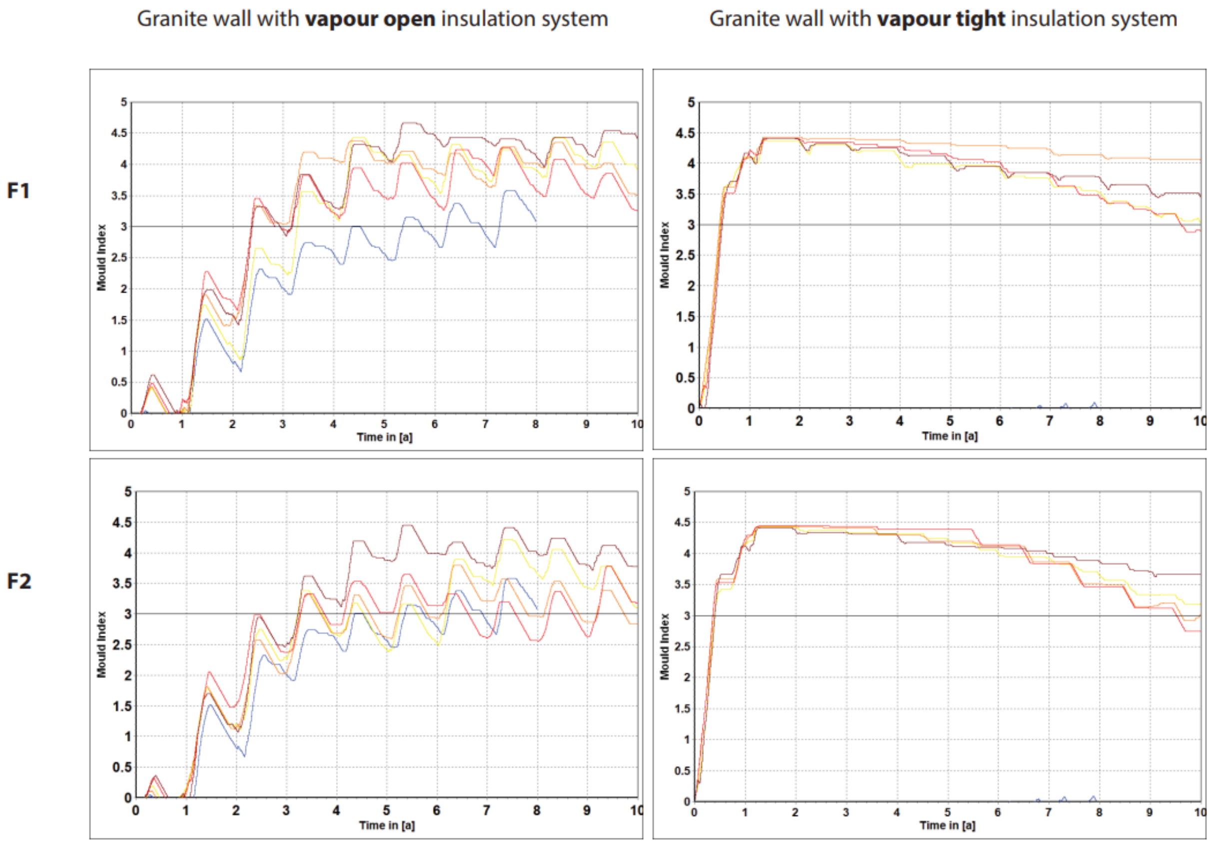


Figure 51 Mold growth index of retrofitted granite wall in Climate zone III

6.4.3 Frost-damage risk

The freeze-thaw cycles per year in all the studied scenarios are summarized in Table 37. It is found that there is no frost damage in the masonry walls with or without insulation systems of all three Climate zones. However, freeze-thaw cycles are frequent in the external plasters.

Table 37 Freeze-thaw cycles per year in reference constructions. (N=without insulation systems, VT=vapor tight insulation system, VO=vapor open and non-capillary active insulation system)

Climate zone	Wall construction	Insulation	Freeze-thaw cycles per year								
			P	*F1M1*	*F1M2*	*F1M3*	*F1M4*	*F2M1*	*F2M2*	*F2M3*	*F2M4*
I	Plaster	VO, VT &N	0	0	0	0	0	0	0	0	0
	Sandstone wall	VO, VT &N	0	0	0	0	0	0	0	0	0
II	Plaster	N	0	10.1	1.6	15	1.8	1	0	0	1
		VO	1.6	38.1	5.5	40.2	6.4	8.1	0	0	2.2
		VT	1.6	38.2	5.6	40.6	6.5	8.2	0	0	2.2
	Granite wall	VO, VT &N	0	0	0	0	0	0	0	0	0
III	plaster	N	25.6	0	32.4	19.4	51.1	26.3	19.3	5.8	14.8
		VO	183.8	53.3	99.5	58.2	129.2	121.5	55.6	48.4	36.7
		VT	194.1	54.7	100.3	58.6	132.2	123.7	56.2	49.3	37.1
	Granite wall	VO, VT &N	0	0	0	0	0	0	0	0	0

*The colors of the table correspond with the threshold defined in section 3.5.4.

In Climate zone II, there are no freeze-thaw cycles in the plaster of un-retrofitted construction at present. The number of freeze-thaw cycles rises slightly at F1. Moreover, the plaster in retrofitted construction suffers more freeze-thaw cycles at F1. Different insulation systems do not cause notable differences. In Climate zone III, the plaster of the un-retrofitted structure is constantly in low frost-damage risk from present to future. The retrofit actions increase the frost-damage risk significantly. After the retrofit, the freeze-thaw cycles experience a rise from 25.5 to 183.8 at the present scenario. Even though it drops from present to future, it remains at high risk in most of the future projections.

7. Adaptation strategy

7.1 Interpretation of the simulation results

7.1.1 Thermal comfort

Through a comparison of Δ3 (number of overheating hour in the retrofitted scenario - number of overheating hour in un-retrofitted scenario at the same time period) in different scenarios with different assessment methods, the effect of the retrofit could be analyzed. The results show that: (i) retrofit interventions increase the operative temperature and cause significant overheating risk in the Portici house in Climate zone I (relatively warm), even though this negative impact decreases slightly in the future; (ii) in rural farmhouses of Climate zone I and II and Portici in Climate zone II, retrofit interventions only lead to severe overheating risk in scenarios with climate change; and (iii) retrofit interventions improve the thermal comfort conditions of the reference building in Climate zone III under all climatic scenarios.

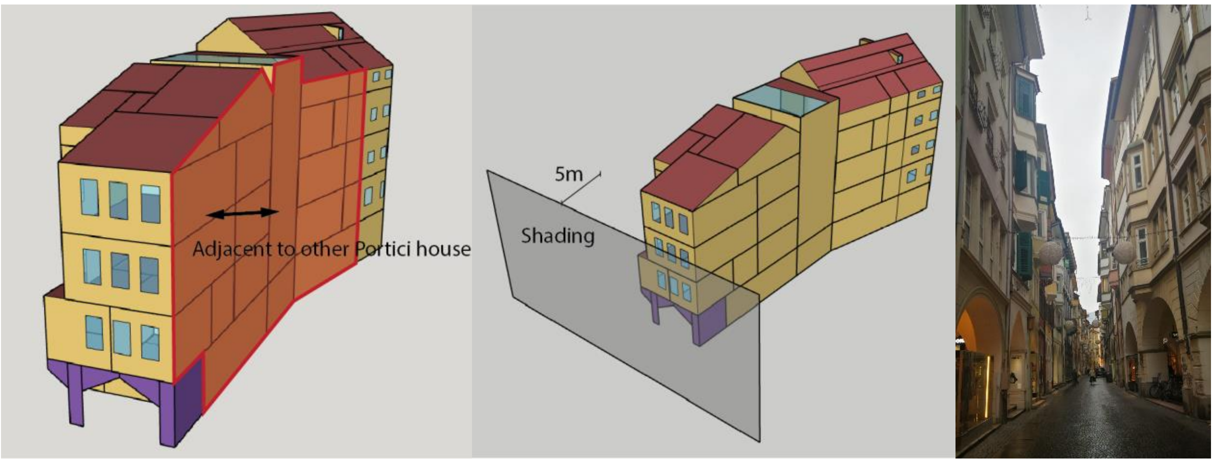
Through the analysis of Δ1 and Δ2 in different scenarios with different assessment methods, the impact of climate change could be concluded: (i). In living rooms of un-retrofitted buildings, climate change does not bring substantial overheating hours until F2 in Climate zone I and II. Moreover, it does not harm the thermal comfort Climate zone III. (ii). Retrofit enlarges the negative impact of climate change on overheating risks in living rooms. However, in bedrooms of Portici houses, retrofit solutions could help mitigate climate change impacts on thermal comfort.

To further interpret the difference in thermal comfort conditions across reference buildings, it is necessary to investigate the characteristics of these buildings and their impact on the internal climate.

In the Portici house of Climate zone I, under-heating is the main comfort problem, and the underheating hours are more than that in Climate zone II. This is due to the differences in the heating schedule. According to Italian regulation, the maximum heating days of Climate zone I is from October 15^{th} to April 15^{th}, with 14 heating hours per day. However, the heating days are not limited in Climate zone II and III. In our simulations, the heating schedule is set according to the heating degree day of Climate zone II and III: from September 15^{th} to April 15^{th}, with no limitations of heating hours.

Current retrofit interventions improve the under-heating condition of present scenarios remarkably. It does not lead to serious overheating problems in most of the reference buildings, except the Portici house of Climate zone I. Retrofit interventions could lead to overheating hours accounts for 20% of the total applicable hours in the Portici house of Climate zone I even at present. This is due to its low surface-to-volume ratio (S/V) ratio. Since the building is adjoining to other Portici houses (Figure 52), the heat cannot be diffused as well as isolated buildings. The overheating hour of insulated Portici house will be reduced by 46% in the living room and 50% in the bedroom at the present scenario if the building is isolated.

The S/V ratio is not the only decisive factor. The Portici house is shaded by the opposite building. In the case of Climate zone I the width of the street is around 5 m (Figure 52). If this shading is removed, the number of overheating hours increases by 83%. Moreover, it is found that if the energy retrofit does not improve the airtightness of the building, there will be minimum overheating risks in retrofitted scenarios. For instance, in the Portici house of Climate zone I, increased air exchange ration reduces overheating hours more than 90% in the present scenario and 49% at F2.



(a) (b) (c)

Figure 52 Portici house of Climate zone I. (a) the boundary conditions (b) the shading from the opposite (c) picture of the Portici house

In the literature review (section 2.3.1), there are studies that confirm the linear relationship between internal and external temperature, and differing typologies have differing constants of proportionalities (that is, of steepness). This linear relationship between indoor and outdoor temperatures could be used to estimate the buildings' resilience to climate change. Here the hourly indoor operative temperature is averaged against the hourly outdoor running mean temperature. Figure 53 shows the results for Portici house of Climate zone I (Results for other reference buildings are shown in Appendix A.3). The graphs show that the relationship between internal temperature and external temperature fits a linear regression in both retrofitted and un-retrofitted scenarios, although different reference buildings show different dependence on the external conditions (illustrated by the different steepness of the regression lines). Retrofit solutions at all time scenarios considerably increase the living room temperatures during occupied hours. In the present scenario, overheating would occur in retrofitted Portici house when the outdoor running mean temperature is higher than

25°C, while it does not happen until 30°C in un-retrofitted scenario. These temperature thresholds could be considered as indicators for the use of adaptation solutions.

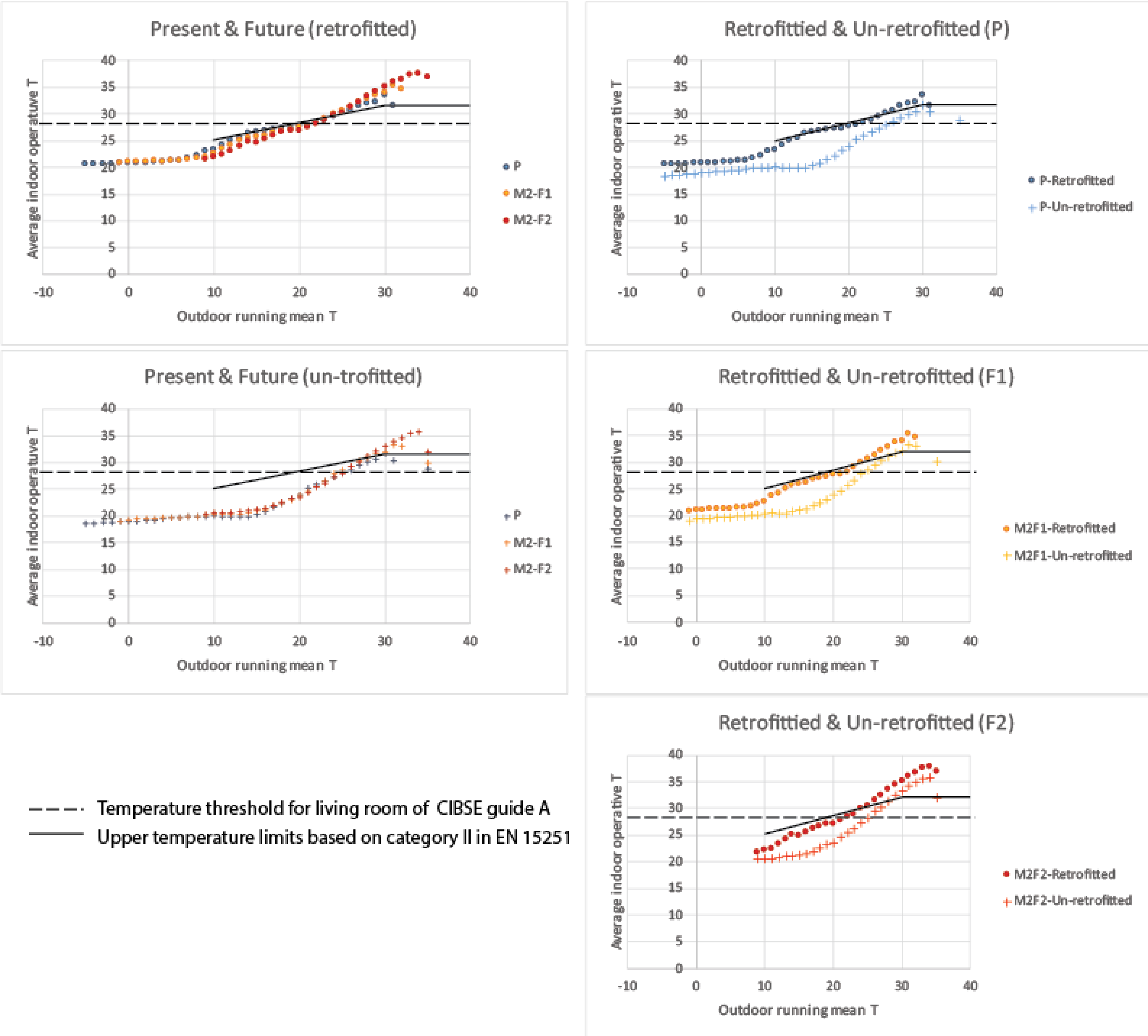


Figure 53 Average operative temperature as a function of outdoor running mean temperature in the living room of Portici house of Climate zone I

7.1.2 Moisture risks

7.1.2.1 Condensation risk

According to future hygrothermal performance of insulated walls, the risks imposed by climate change will not be homogenous but very much dependent on the different Climate zones. In Climate zone I, the moisture content in the wall decreases in the future as a result of less WDR and more evaporation due to temperature increase. In Climate zone II, the number of hours above the 95% threshold in retrofitted masonry walls increases from P to F1 and then decreases from F1 to F2 scenario. This trend is a combined result of external temperature and precipitation changes, which influence the moisture transport and storage in the construction.

The main moisture sources in the wall are WDR and vapor diffused across the wall. To distinguish the most influencing moisture source on the risk of condensation behind the insulation, external climate scenarios with and without WDR are tested in the simulations. It is found that the impact of WDR on the RH behind the insulation is quite limited in all the time scenarios (Figure 54). However, WDR changes the RH on the external side of the wall remarkably (Figure 55). The literature review has shown (section 2.4.1) that WDR has a significant impact on RH of the interior surface of un-retrofitted walls in Essen (Germany), and in the middle of un-retrofitted walls in Gothenburg (Sweden) and Bergen (Norway). This is due to the substantial quantity of the WDR in these locations. When simulating the RH in insulated (VO) granite walls with the climate of Essen, it is found that WDR changes the RH in the middle of the wall notably (Figure 56). Moreover, its influence on RH behind insulation is larger than that in South Tyrol (Figure 57).

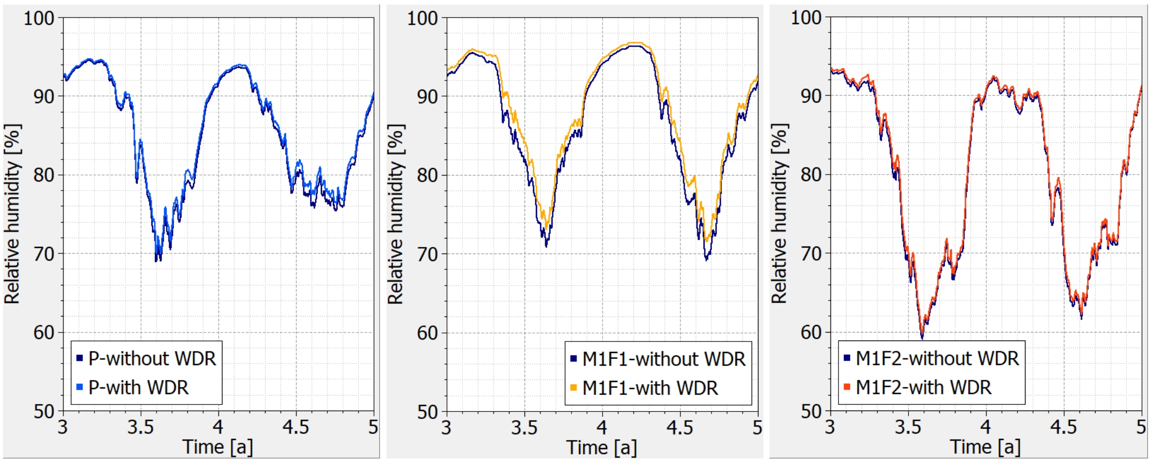


Figure 54 RH in granite walls (behind insulation) retrofitted with a vapor open insulation system at three time scenarios in Climate zone II with/without WDR. Left: present scenario; middle: F1-M1 scenario; right: F2-M1 scenario

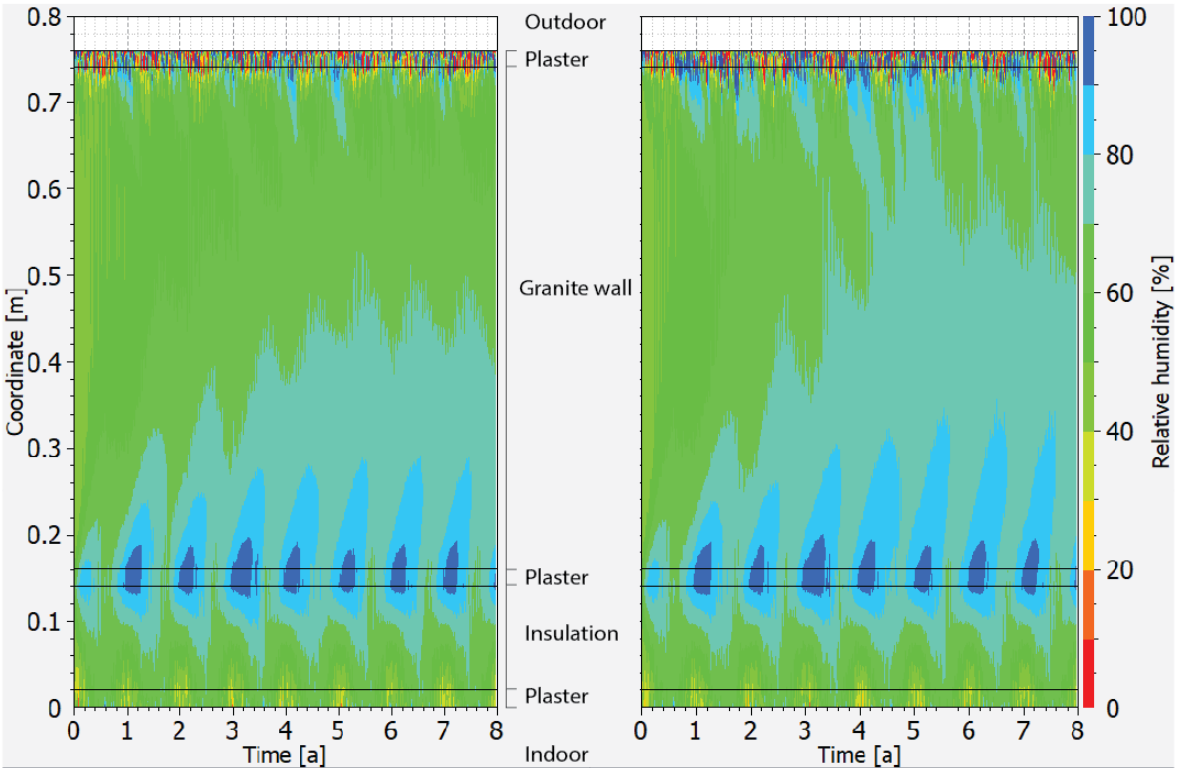


Figure 55 RH profile of granite walls retrofitted with vapor open insulation system in Climate zone II with/without WDR. Left: present scenario without WDR; Right: present scenario with WDR

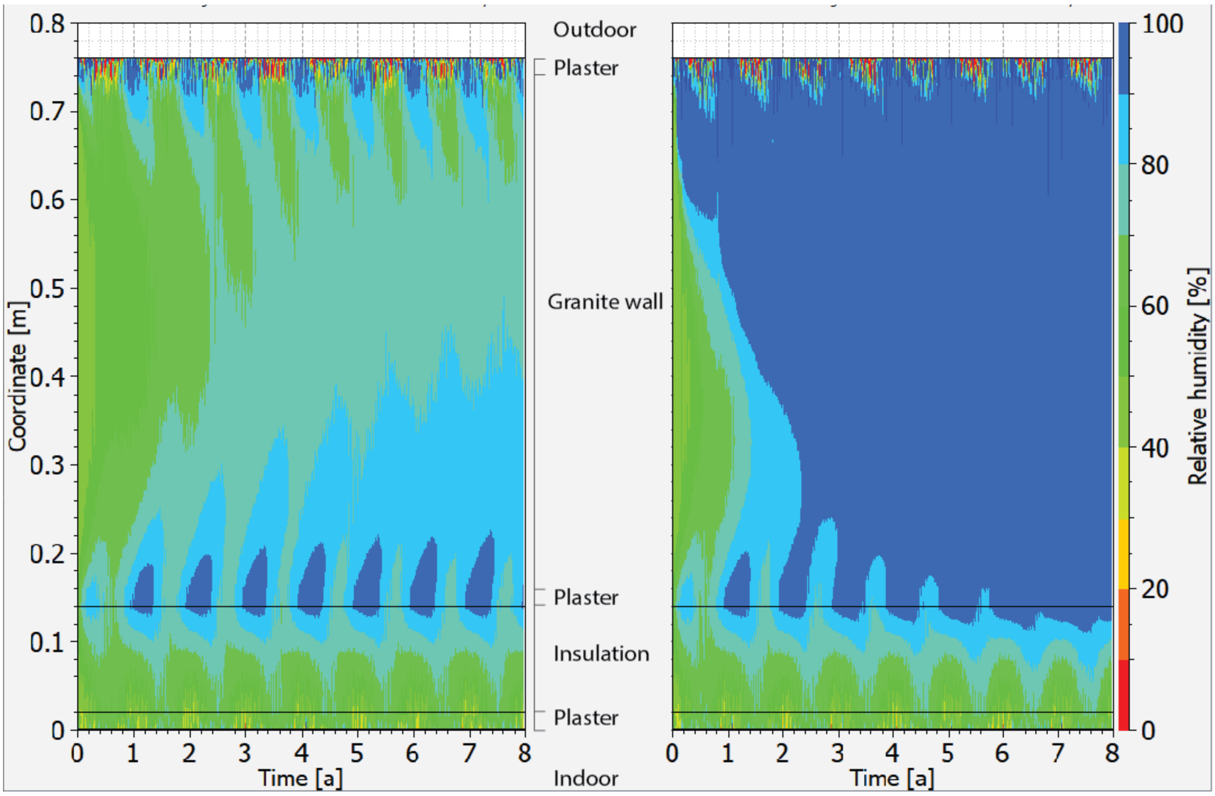


Figure 56 RH profile of granite walls retrofitted with a vapor open insulation system in the climate of Essen (Germany) with/without WDR. Left: present scenario without WDR; Right: present scenario with WDR

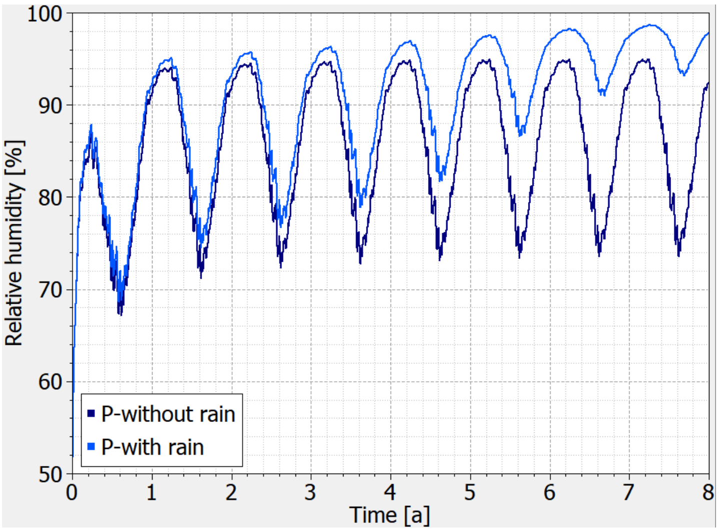


Figure 57 RH (behind insulation) in the granite walls with a vapor open insulation system in the climate of Essen (Germany) with/without WDR at Present scenario

Thus, the most influencing moisture source on RH behind insulation in the studied Climate zones is vapor diffused from the indoor climate. According to WTA 6.2, the driving potential of vapor diffusion is the vapor pressure gradient between indoor and outdoor climate. The density of water vapor flow could be calculated using the following equation:

$$j_v = -\frac{\delta_a}{\mu} \nabla p_v \qquad \textit{Equation 6}$$

j_v [kg/(m^{2}s)] is the density of water vapor diffusion flow rate; δ_a [kg/(m s Pa)] is water vapor permeability of air, and it is a constant; μ [-] is the water vapor diffusion resistance factor of building material; p_v [Pa] is the water vapor partial pressure. Therefore, the water vapor diffusion flow rate is depending on the water vapor partial pressure, which is calculated by the following equation:

$$\nabla p_v = (p_{vi} \cdot RH_i) - (p_{ve} \cdot RH_e) \qquad \textit{Equation 7}$$

p_{vi} [Pa] is the internal saturation vapor pressure; RH_i is the internal relative humidity; p_{ve} [Pa] is the external saturation vapor pressure; RH_e is the external relative humidity. These parameters are calculated by the following equations:

$$p_{vi} = 100 \cdot \left(a_0 + T_i \left(a_1 + T_i \left(a_2 + T_i \left(a_3 + T_i \left(a_4 + T_i (a_5 + T_i (a_6 + T_i)) \right) \right) \right) \right) \right) \textit{Equation 8}$$

$$p_{ve} = 100 \cdot \left(a_0 + T_e \left(a_1 + T_e \left(a_2 + T_e \left(a_3 + T_e \left(a_4 + T_e (a_5 + T_e (a_6 + T_e)) \right) \right) \right) \right) \right) \textit{Equation 9}$$

$$RH_i = \begin{cases} when\ T_e < -10,\ 35 \\ when -10 < T_e < 20,\ \ T_e + 45 \\ when\ 20 < T_e,\ 60 \end{cases} \textit{Equation 10}$$

$$T_i = \begin{cases} when\ T_e < 10,\ 20 \\ when\ 10 < T_e < 20,\ 0.5\,T_e + 15 \\ when\ 20 < T_e,\ 25 \end{cases} \textit{Equation 11}$$

Where a_0 to a_6 are constants. For water, a_0= 6.107799961, a_1= 4.436518521X10^{-1}, a_2= 1.428945805X$10^{-2,}$ a_3= 2.650648471X10^{-4}, a_4= 3.031240396X10^{-6}, a_5= 2.034080948X10^{-8}, a_6= 6.136820929X10^{-11}; For ice, a_0= 6.109177956, a_1= 5.034698970X10^{-1}, a_2= 1.886013408X$10^{-2,}$ a_3= 4.176223716X10^{-4}, a_4= 5.824720280X10^{-6}, a_5= 4.838803174X10^{-8}, a_6= 1.838826904X10^{-11}

According to Equations 8 to 11, water vapor partial pressure is influenced by the external temperature and external RH. When comparing the climate data between P, F1, and F2 in Climate zone II, an increase in external temperature can be seen. This has two contrasting effects on the RH in the wall. On the one hand, according to the adaptive indoor climate model from WTA 6-2, the external outdoor temperature increase leads to the increasing rise of indoor relative humidity (Equation 10), which could increase the moisture content in the wall. On the other hand, the external temperature increase leads to increased external saturation vapor pressure, lowering the water vapor diffusion flow rate (Equation 7).

Since the main moisture source leading to condensation risk is vapor diffused from indoor, there should not be any risks if a vapor-tight insulation is applied (under normal circumstances, e.g. no accidental water ingress or rising damp considered). However, in Climate zone II and III, condensation happens in future scenarios. In the present scenario, the RH in the wall remains under the critical threshold, but it increases over time (Figure 58), and the moisture content accumulates as a consequence of the limited drying potential of the vapor-tight system (Figure 59). Although the accumulated moisture content (MC) slowly dries out in F1 and F2, the RH in the wall regularly exceeds the safe threshold (95%).

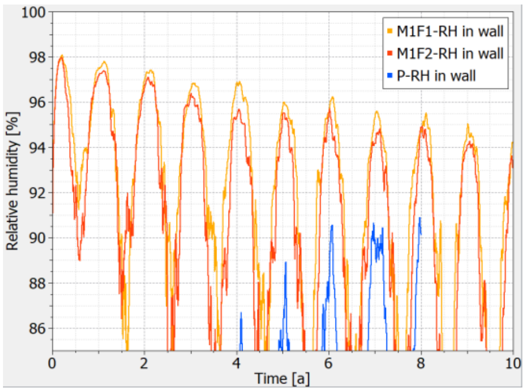


Figure 58 RH in granite wall (VT) in Climate III

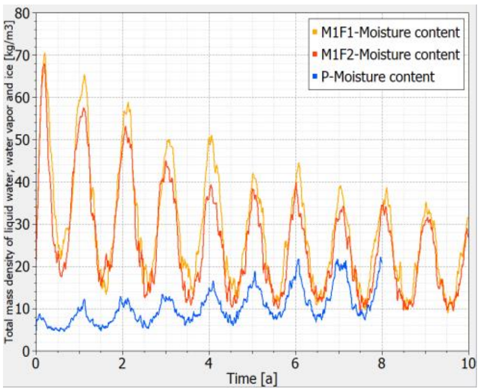


Figure 59 MC in granite wall (VT) in Climate III

7.1.2.2 Mold risk

According to Equations 3 & 4 (Section 3.6.3), the growth rate of the mold depends on the material type, temperature and relative humidity. Since only one insulation material (wood fiberboard) is used in our simulations, the mold growth is influenced by temperature and relative humidity. Moreover, according to equation 4, relative humidity is the most influential factor.

Taking the mold growth in the retrofitted granite wall of Climate zone II with vapor open insulation system of M1F1 and P as an example it can be seen that in the first year (0-1a in Figure 60), when the RH is above the critical RH (80%) (Figure 61), there is an increase in the mold growth index at both P and F1 scenarios. The curve of the mold growth index follows the curve of RH well. At the beginning of the second year (1-2a in Figure 60), mold growth starts again due to the high RH at both scenarios. There is a sharp rise in the mold growth index between 1-1.3a, when the RH is constantly above 90% and the temperature is quite low, showing that RH has a significant impact on the mold growth. From 1.4a, mold growth index drops with RH's fall. In the following simulation years, similar cycles occur.

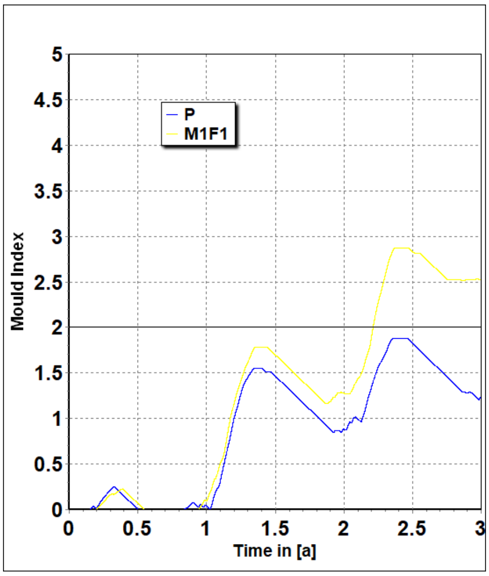


Figure 60 Mold growth index of granite wall with vapor open insulation system in Climate zone II

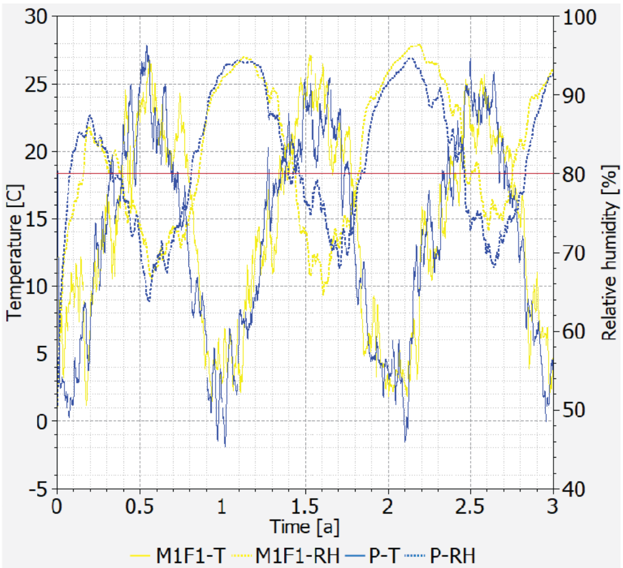


Figure 61 Temperature and Relative humidity in retrofitted granite wall with vapor open insulation system of M1F1 and P

In the case of the wood wall, there is no mold risk in both Climate zone II and III. Since wood walls are retrofitted with a vapor-tight insulation system, the RH behind insulation is under control (Figure 62). Different from the granite wall retrofitted with VT, where the MC accumulates at the present scenario

(Figure 59), the MC in the wood wall does not amass overtime at present (Figure 63). Therefore, the mold risk in the wood wall future is also negligible.

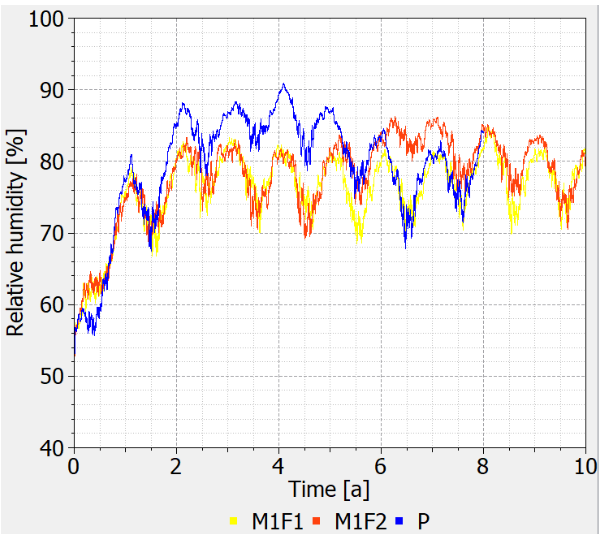


Figure 62 RH in the retrofitted wood wall of Climate zone III

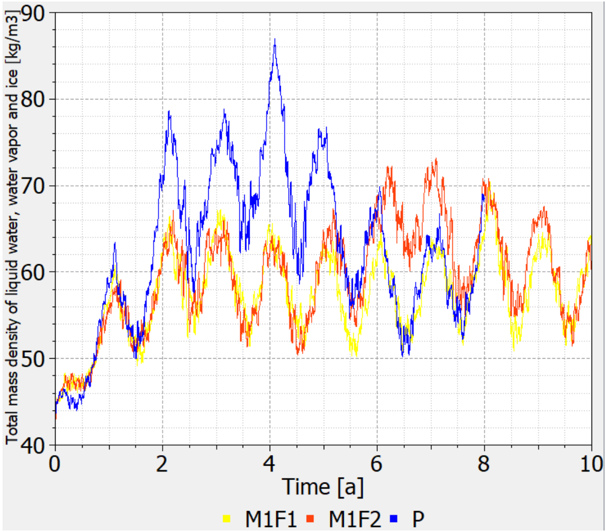


Figure 63 MC in the retrofitted wood wall of Climate zone III

7.1.2.3 Frost-damage risk

According to the results of the assessment, there is no frost-damage related risk in the **masonry** of any Climate zones. Even though the quantity of WDR in some future climate projections rises (e.g., M3 in Climate zone III), the saturation ratio of the wall is still below the S_{crit} (Figure 64).

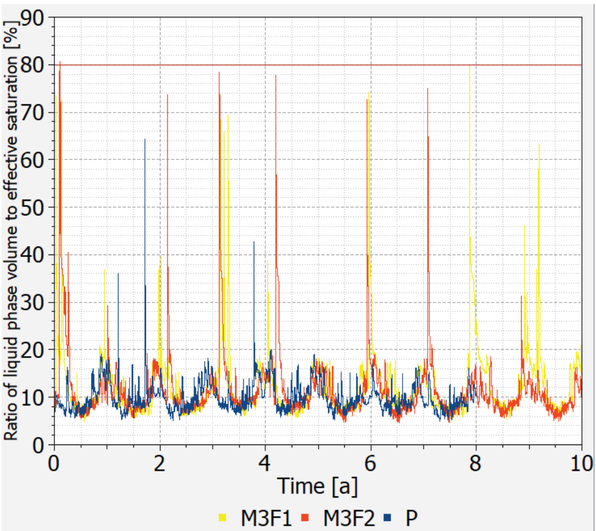


Figure 64 Saturation ratio in retrofitted granite wall of Climate zone III

The S_{crit} of historic external **plaster** is frequently reached in both Climate zones II and III due to the intense precipitation events at present and future (Table 38). The number of hours above S_{crit} is closely related to the quantity of WDR (Figure 36, Figure 38). However, future temperature increase reduces the crossing of the freezing point. Therefore, in some climate projections, there are more freeze-thaw cycles at F1 than F2.

Retrofit actions enlarge the frost-damage risks in the plasters. After the retrofit, there are more hours above S_{crit} (Table 38) because the insulation systems impede the evaporation inwards. Moreover, the addition of insulation makes the temperature lower. Therefore, there are more freeze-thaw cycles.

Table 38 No. of hours above Scrit per year in plasters. (N=without insulation systems, VT=vapor tight insulation system, VO=vapor open and non-capillary active insulation system)

Climate zone	Insulation	No. of hours above S_{crit} per year in plasters								
		P	*F1M1*	*F1M2*	*F1M3*	*F1M4*	*F2M1*	*F2M2*	*F2M3*	*F2M4*
I	N	0	0	0	0	0	0	0	0	0
	VO&VT	0	0	0	0	0	0	0	0	0
II	N	59.25	156.1	87.4	181.2	35.7	180.3	84.4	140.5	51.3
	VO	90.25	241.6	119	280	49.4	274.7	105.9	166.2	78.9
	VT	90.75	243.3	119.3	282.2	49.4	277.5	106.4	166.3	79.1
III	N	239.6	32.4	245.0	85.0	132.3	110.8	294.9	270.7	89.1
	VO	543.8	150.0	481.9	247.0	263.3	364.9	545.4	714.6	179.9
	VT	558.4	152.1	484.0	250.0	266.7	369.1	547.6	720.6	182.4

7.2 Adaptation solutions for overheating

Five adaptation options are tested for each reference building that is at risk of overheating after the retrofit. Table 39 lists a summary of the tested options and details. Measures of insulation, shading, thermal mass, and ventilation are tested to establish the most effective measure to lower the overheating risks in reference buildings.

Among the four climate projections, M2 shows the highest overheating risks for all the reference buildings. Following a worst-case scenario approach, M2 is used to test the adaptation solutions.

Table 39 Tested adaptation options.

No. of options	Adaptive solutions	Details
1	Less insulation	The thickness of insulation for external walls is 6 cm while the insulation for roof and ground floor remain unchanged.
2	Extra shading	The wooden shutter of the window is on when the indoor temperature is higher than 24 °C.
3	Extra thermal mass	3.6 m^3 natural stone is added.
4	New ventilation strategy (a)	The ventilation is active when (i) the room is occupied, (ii) T_i > 24°C, T_e >18°C, (iii) T_i> T_e (**the difference with the original ventilation is that the original ventilation is active when T_i> T_e + 3°C**).
5	New ventilation strategy (b)	The ventilation is active when (i) T_i > 24°C, T_e >18°C and (ii) T_i> T_e + 3°C. **(the room does not have to be occupied)**

Table 40 and Table 41 show a matrix of overheating hours as a result of the implementation of all adaptation options in each reference building for each time period. The color of the table ranges from green (most effective options) to red (least effective options) for each time scenario. Moreover, the overheating hours of un-retrofitted scenarios and retrofitted with current best practice scenarios are presented for comparison.

In the living rooms, to apply less insulation during retrofit is not an effective option to mitigate overheating in most of the scenarios (Table 40). It only performs well at present scenarios in Climate zone II, where the overheating problem is modest. On the contrary, retrofit with less insulation could be effective on the overheating of bedrooms. Since the occupied hours of bedrooms are from 22:00 to 10:00, less insulation could help the night cooling to better perform.

*Table 40 Annual overheating hours of **living rooms** for each adaptation option, for each reference building, under each time period.*

	I-Portici house			I-Rural farmhouse			II-Portici house			II-Rural farmhouse		
	P	F1	F2	P	F1	F2	P	F1	F2	P	F1	F2
Un-retrofitted	3.2	37.2	653.7	1.2	7.2	453.8	0	20.9	318	0	0	64.2
Retrofitted with current best practice	717.9	804.4	1301.5	74.1	246.4	1029.8	90.7	129.6	536.6	15.1	48.3	461.8
1-Less insulation	584.5	730.1	1249.8	49.1	215.5	1002.1	19	64.3	445.1	5.6	36	430.7
2-Extra shading	350.4	481.7	1088	19.5	113.3	871.2	51.2	80.1	425.8	3.3	8	253.2
3-Extra thermal mass	572.7	690.4	1334.5	59.7	197.8	989.3	84.5	108.8	494.8	13.3	33.6	409.2
4- New ventilation strategy-a	660.4	880.5	1445	49.9	113.1	781.5	82.5	81.4	386.2	12.7	16.6	279.3
5-New ventilation strategy-b	346.7	429.5	927.2	31.3	59.8	662.5	46.8	38	160.8	10.5	16.8	158.6
Combination of 2,4,5	78.6	53.3	376.9	2.2	8.1	371.4	11.1	7.1	74.6	0	0	50.4

*Table 41 Annual overheating hours of **bedrooms** for each adaptation option, for each reference building, under each time period.*

	I-Portici house			I-Rural farmhouse			II-Portici house			II-Rural farmhouse		
	P	F1	F2	P	F1	F2	P	F1	F2	P	F1	F2
Un-retrofitted	0	1	163.7	0	1	153.6	0	0	14	0	0	4.9
Retrofitted with current best practice	821.5	556	619.2	71.6	102.5	290.3	113.3	211.4	181.4	3	51.9	108.4
1-Less insulation	636.8	449.5	528.7	30.9	74.9	265.8	14.9	107.3	99.7	2.3	38	86.6
2-Extra shading	477.6	331.1	446.2	13.7	51.3	232.1	81.2	176.8	140.9	1.2	8	53.5
3-Extra thermal mass	684.3	494.9	625	73.7	100.9	286.7	109.6	206.3	174.4	2.8	48.8	101.9
4- New ventilation strategy-a	793.4	538.9	662.4	56.5	89.8	228.4	99.3	201	169.5	2.7	44.4	95.7
5-New ventilation strategy-b	192.9	141.8	292.6	3.8	3.1	167.8	9.1	23.1	31.3	0	1.7	15.4
Combination of 2,4,5	53.2	46.3	155.1	1.1	2.3	78.8	3.5	2.1	10.6	0	0	3.2

To use wooden shutters for the windows could mitigate overheating considerably in both living rooms and bedrooms (Table 40, Table 41). Here the wooden shutter refers to the louver where the wooden slats are contained within a shutter panel (Figure 65). It offers high solar protection while it does not obstruct the ventilation. Many historic buildings used to have hinged shutters, e.g., one of the reference building of this study, Piazza Erbe 11 (Figure 66). However, in the course of the buildings' history, they underwent several interventions, including the removal of these shutters. Considering the significance of shutters on overheating reduction, it is recommended to restore the historic shutters, and close the shutter when the room temperature is high.

Figure 65 Wooden shutters with orientable slats in Bolzano

Figure 66 The hinges of wooden shutter in Piazza Erbe 11

Extra thermal mass has the least effect on overheating control; therefore, this option is not suggested to mitigate overheating. Ventilation strategy could influence the thermal comfort state notably. The effect of new ventilation strategy (a) is limited in the living room of Portici house of Climate zone I and bedrooms of three Climate zones. This is because, in these scenarios, most of the indoor temperature is 3°C higher than the outdoor temperature. Therefore, the new ventilation strategy (a) is not effective.

A new ventilation strategy (b) is the most effective option in all the scenarios. It highlights the importance of ventilation after retrofit. The airtightness is highly enhanced by retrofit, and it is the main reason for overheating risks in this study. However, infiltration could cause great energy uses in winter. To overcome these drawbacks, it is highly encouraged to ventilate more in the retrofitted buildings of South Tyrol.

With the use of wooden shutters and new ventilation strategies, the overheating risks could be minimized, with overheating hours lower than the un-retrofitted cases. At the same time, the buildings' energy efficiency is highly improved.

7.3 Adaptation solutions for moisture risks

The moisture risk categories are summarized in Table 43, according to the proposed criteria of risk assessment (Table 42). In Climate zone I, there is no moisture risks after retrofit. Therefore, both vapor open and vapor-tight insulation systems can be adopted. In Climate zone II and III, both VO and VT applied at the natural stone wall could cause moisture risks both in the present and future scenarios. Therefore, adaptation strategies should be defined.

Table 42 Summary of proposed risk thresholds for the hygrothermal assessment of insulated wall

	No risk	Low risk	High risk
Condensation	Highest RH of all the simulation years is <95%	Highest RH is >95% in less than 50% of the simulation years	Highest RH is >95% in more than 50% of the simulation years
Mold growth	Mold growth index is lower than 3	Mold growth index is higher than 3 but has an obvious decreasing tendency over time	Mold growth index is higher than 3 and the growth increases/persist over time
Frost damage	Saturation ratio is always lower than critical saturation ratio	Saturation ratio is higher than critical saturation ratio, and there are less than 50 freeze-thaw cycles per year	Saturation ratio is higher than critical saturation ratio and there are more than 50 freeze-thaw cycles per year

According to the interpretation of the results, the problem of VO is that water vapor diffused from the internal side leads to high RH behind the insulation. Even though VT could stop the excess vapor diffusion, its obstruction effect makes the moisture content accumulates in the wall. Therefore, a vapor open and capillary active insulation material, calcium silicate board, is suggested for Climate zone II and III. Its water absorption coefficient (A_w) is much higher than wood fibreboard (Table 44), which enables the moisture behind the insulation to dry toward the indoor: The water vapor condensed behind the insulation system will be absorbed and delivered to the indoor surface.

Table 43 Summary of moisture risks in reference constructions. (N=without insulation systems, VT=vapor tight insulation system, VO=vapor open and non-capillary active insulation system)

Risks	Climate zone	Wall construction	Insulation systems	Peak mold growth index								
				P	*F1M1*	*F1M2*	*F1M3*	*F1M4*	*F2M1*	*F2M2*	*F2M3*	*F2M4*
Condensation risk	*I*	Sandstone wall	VO									
			VT									
	II	Granite wall	VO									
			VT									
		Wood wall	VT									
	III	Granite wall	VO									
			VT									
		Wood wall	VT									
Mold risk	*I*	Sandstone wall	VO									
			VT									
	II	Granite wall	VO									
			VT									
		Wood wall	VT									
	III	Granite wall	VO									
			VT									
		Wood wall	VT									
Frost-damage risk	*I*	Plaster	VO,VT&N									
		Sandstone wall	VO,VT&N									
	II	Plaster	N									
			VO &VT									
		Granite wall	VO,VT&N									
	III	Plaster	N									
			VO &VT									
		Granite wall	VO,VT&N									

Table 44 comparison of calcium silicate and wood fiberboard

Materials	λ_{dry} [W/mK]	ρ [kg/m³]	C_p [J/kg·K]	A_w [kg/m²s0.5]	μ_{dry} [-]	θ_{por}[m³/m³]
Calcium silicate board	0.069	270	1158	1.115	3.8	0.910
Wood fiberboard	0.042	150	2000	0.07	3.0	0.981

With calcium silicate board, the RH behind insulation is always below 95% (Figure 67), and MGI is very low (Figure 68). However, the freeze-thaw cycles in plaster sightly increases (Table 45).

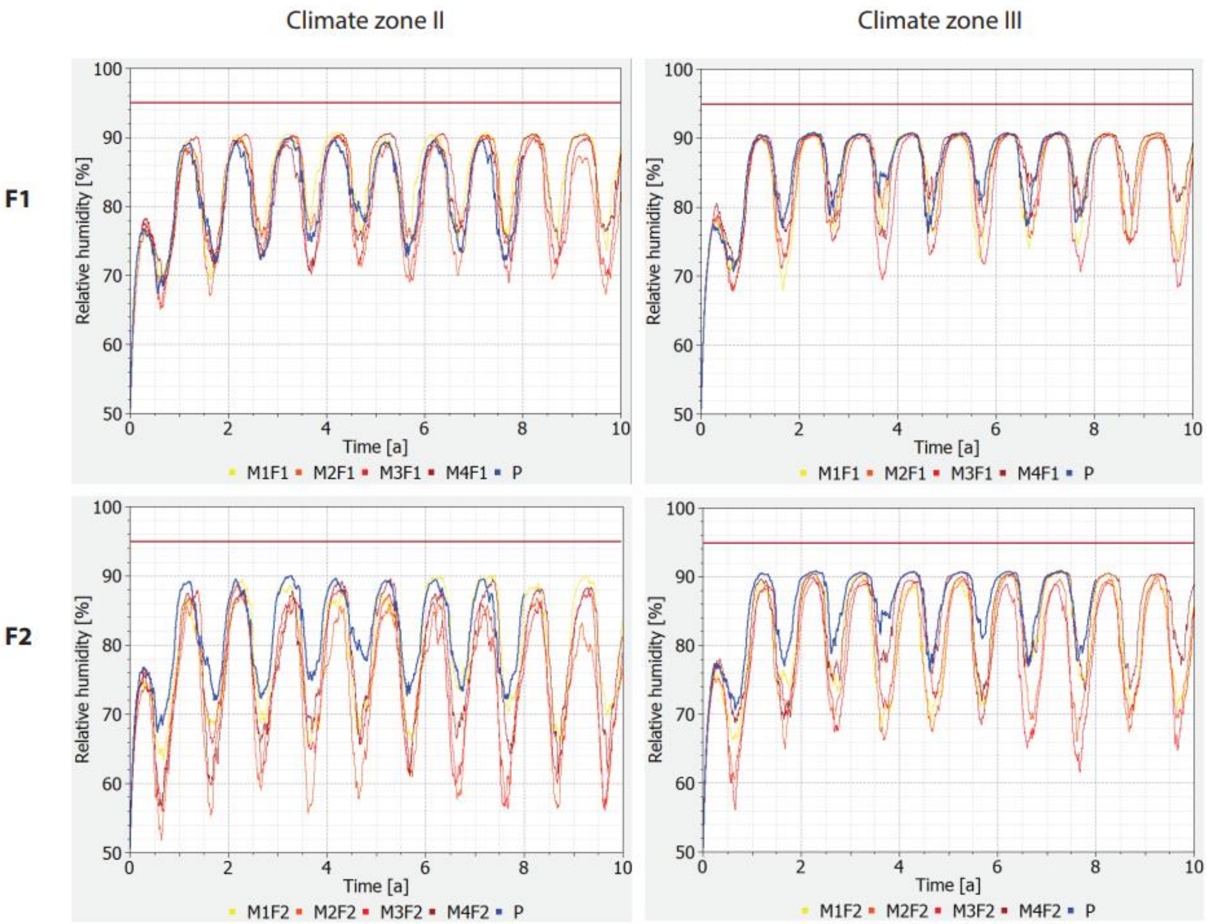


Figure 67 RH in the granite wall retrofitted with calcium silicate board

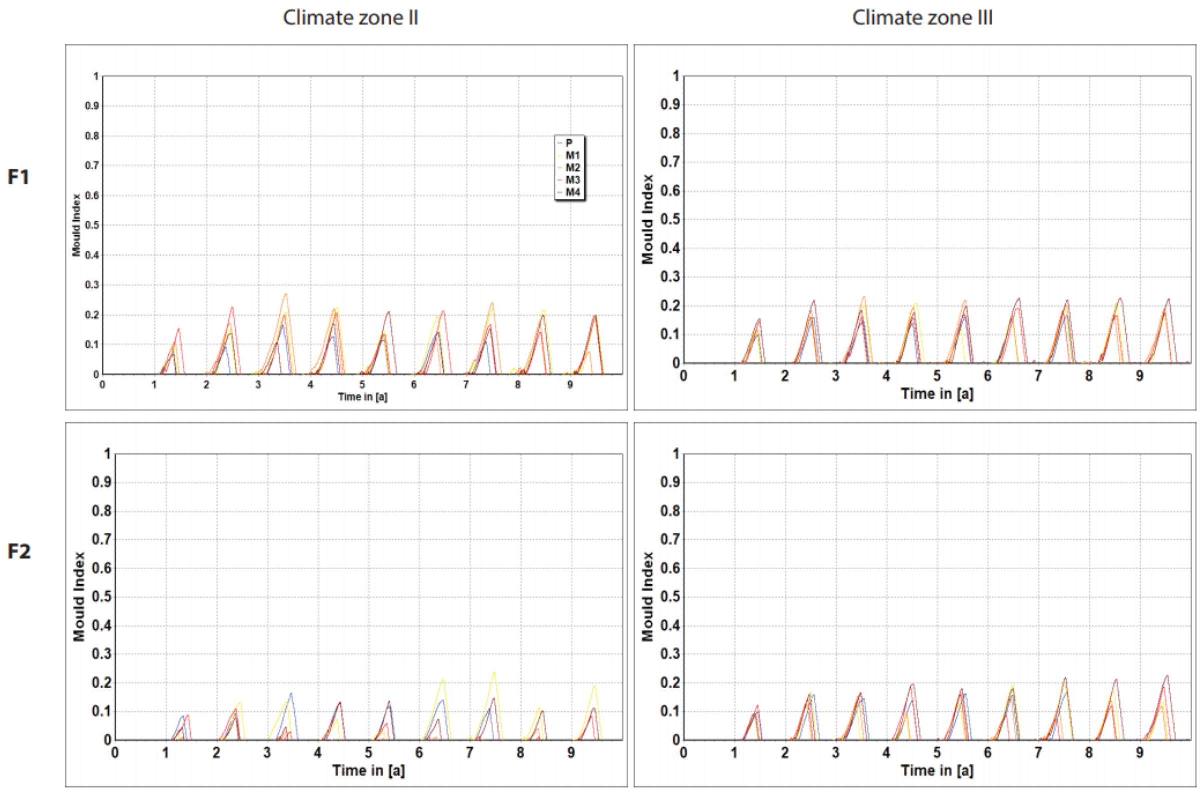


Figure 68 Mold growth index in granite wall retrofitted with calcium silicate board

Table 45 Freeze-thaw cycles per year in reference constructions retrofitted with calcium silicate

Climate zone	Wall construction	Freeze-thaw cycles per year								
		P	*F1M1*	*F1M2*	*F1M3*	*F1M4*	*F2M1*	*F2M2*	*F2M3*	*F2M4*
I	Plaster	0	0	0	0	0	0	0	0	0
	Sandstone wall	0	0	0	0	0	0	0	0	0
II	Plaster	1.6	39	5.7	41.1	6.6	8.5	0	0	2.2
	Granite wall	0	0	0	0	0	0	0	0	0
III	Plaster	195	56	102.3	60	136.2	127.1	57.7	50	37.8
	Granite wall	0	0	0	0	0	0	0	0	0

The crumbling, spalling, and shattering of the plaster due to frost damage must be paid close attention. A neglect of the gradual deterioration may lead to losses of historic fabrics. Therefore, it is suggested to consider the possibility of using a water repellent to protect the plaster against WDR. If a restoration of the plaster is needed, the new plaster should match the original material and, at the same time not cause any damage to the original material.

8. Conclusion

Historic buildings account for more than one-quarter of Europe's existing building stock, and their energy efficiency improvement is going to be crucial in the achievement of future energy targets. In order to ensure their continued use and existence, conservation compatible solutions are needed. Nevertheless, climate change imposes great challenges on the built heritage sector by increasing the risks of energy inefficiency, indoor overheating, and moisture-related damage to the envelope. Therefore, it is urgent to assess these risks and plan adaptation strategies for historic buildings.

This thesis categorizes the historic building stock of South Tyrol and proposes reference buildings on the basis of climate and stock inventory analysis. Then, this research identifies current best retrofit solutions through the analysis of ten case studies of local retrofit practices. This research uses a multidisciplinary approach to the problem incorporating models of future climate projection traditionally used in fields like ecology. Four climate projections are established to represent a range of possible climate change scenarios. With representative reference buildings, current retrofit solutions, and future climate data, this study simulates the performance of historic buildings and calculates the combined impacts of climate change and energy retrofit using several assessment models. Eventually, based on the same performance indicators, different adaptation strategies are proposed, and their performance quantified. Even though this research focuses on the historic building stock in South Tyrol, the methodology proposed could be applied in a wilder context.

The different steps proposed in this research allow checking all the hypotheses anticipated at the beginning of the work. Categorizing the building stock and defining reference buildings (task A), proves that there is a strong relationship between local climate and the characteristics of historic South Tyrolean residential buildings. However, the analysis of how some of these building features developed over time also highlighted the importance of other socio-economical parameters that go beyond the purely climatic factors.

The performance analysis of best practices (with 12 cm wood fibreboard) under current conditions (task B) demonstrated that current retrofit solutions could achieve significant energy savings in winter in all three climate zones. The effect on overheating risk in summer depends on both building categories and climate zones. Except in the case of Portici houses in Climate zone I, the negative impacts of current retrofit interventions are limited. The combination of low S/V ratio increased airtightness, and warm climate leads to more overheating hours in the Portici house of Climate zone I after the renovation. In the case of moisture-related risks, the effect of the retrofit is again closely related to the climate zones. In Climate zone I and II, the application of both VO and VT solutions does not lead to any risk of condensation, mold, or frost in the wall. There is, however, a low risk of frost damage in the plaster of retrofitted walls in Climate zone II. In Climate zone III, VO solutions lead to risks of condensation and mold growth, while VT seems to be a more appropriate solution since no risk is identified. Moreover, the frost damage risk for external plaster in the retrofitted wall rises from low to high level. In sum, current retrofit changes the moisture state of the wall, but in Climate zone I and II, there is no severe moisture risks.

The performance analysis under changing climatic conditions (Task C) highlights that retrofit solutions can still achieve important energy savings in the coming winters in all three climate zones. With future climate change, the overheating hours in retrofitted buildings increase significantly. The impact of climate change on moisture-related risks varies depending on climate zones. In Climate zone I, the retrofitted wall remains in safe conditions in all scenarios. In Climate zone II, climate change increases the condensation and mold growth risks in walls retrofitted with VO and VT solutions, especially in the near future (F1). The risk of frost damage in external plasters remains low. In Climate zone III, the wall retrofitted with VO presents high condensation and mold risks, both in future and present scenarios. In the case of walls retrofitted with VT solutions, moisture risks will increase in the future due to the moisture contents accumulated at the present scenario. The risk of frost damage is still limited to the external plaster but remains considerably high in the future.

In order to develop the adaptive solutions that would ensure future performance of historic buildings (Task D), the thesis firstly investigates the cause of overheating and moisture-related risks found in the previous section of this thesis. It is found that the relationship between indoor operative temperature and outdoor running mean temperature is heavily influenced by the retrofit of the envelope. This analysis also shows when the adaptive solutions are most needed. Direct solar gains, the S/V ratio of the building and ventilation strategy are significant factors in achieving thermal comfort. The adaptive strategies focus on the reintroduction of traditional shading practices and increased air change rates. In terms of moisture-related damage in the walls, the main moisture source leading to moisture accumulation in the wall in South Tyrol is outwards vapor diffusion, rather than WDR, as often reported in current literature. Thus, adaptive solutions are tailored to manage this flux of water vapor from the inside to the outside (e.g. use of capillary active insulation materials). The results of the analysis carried out in this thesis allow defining adaptative solutions that can achieve a balanced performance in terms of energy saving in winter, thermal comfort in summer, and safe moisture conditions under present and future weather conditions.

8.1 Research limitations and further research

The original research question formulated in this study, *"What role will climate play in the performance of retrofitted historic residential buildings of South Tyrol?"* has a broad scope. The multidisciplinary approach proposed in the thesis allows investigating most of the relevant factors simultaneously. However, it still remains some issues that could not be investigated in-depth within this Ph.D. research.

The results suggest that occupants' behavior (e.g., activity schedule, ventilation habit) could significantly influence the thermal comfort in the building. Moreover, the behavior of occupants in rural farmhouses may differ significantly from those in Portici house. However, a generalized occupant profile is adopted in this study.

In this study, indoor temperature and humidity levels are derived from the daily mean of the external air temperature according to EN 15026, while in practice, indoor climate depends more on heating and cooling profiles, humidification, and dehumidification behaviour, etc. With more detailed information, more accurate results on indoor climate could be achieved, as well as adaptation strategies.

Energy use, indoor thermal comfort, and moisture risks in historic envelopes are selected as the indicators of building performance. This multi-criteria performance assessment aims to better prepare the historic buildings for future climate challenges. However, the assessment from economic, environmental aspects could be further implemented.

This thesis is a starting point for further research on the performance of historic buildings in a changing climate. In this study, it is found that energy retrofits can achieve great energy savings both in the present and in the future. This should serve as a reason to advance the research and practices in the energy retrofit of historic buildings and ensure the continued and long-term use of the historic buildings. The results of this thesis clearly illustrate the relation between indoor and outdoor temperature and the effect that retrofit solutions will have on this. However, to predict the indoor thermal comfort state under a specific future climate, the influence of solar radiation, occupancy, HVAC system, adaptation options should be further investigated. Moreover, the moisture risks behind insulation is found to be influenced by the vapor pressure difference between indoor and outdoor climate, but the relationship needs further exploration. Deepening in the investigation of this relationship will allow an effective prediction of moisture risks in future climate, which will contribute to the conservation of historic buildings.

8.2 Research contribution to knowledge

This research proposes a mixed methodology for the categorization of historic buildings, which interpret the building categories with both qualitative and quantitative studies. A deeper understanding of the relationship between historic building design and climate could be achieved during this process.

With considerations of the requirements of building performance simulation, this research develops a methodology for the generation of future climate data. By this methodology, high-resolution hourly climate data, including six climatic variables (temperature, relative humidity, precipitation, wind speed, wind direction, solar radiation), are prepared from representative climate models.

This research contributes to the understanding of the performance of retrofitted historic buildings as a result of several interactions between climate, the existing building, and the retrofit intervention. It develops the provision of practical suggestions on how to propose appropriate retrofit solutions considering the characteristic of local climate and building categories.

This research develops a multi-criteria approach for the selection of retrofit interventions. The interventions are assessed from the perspectives of energy use, indoor thermal comfort, and building conservation.

Through an in-depth analysis of the building performance, this research contributes to improving the understanding of the relationships between indoor and outdoor climate, and moisture content of the wall and outdoor climate, in the field of historic buildings.

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Appendix

A.1 Case studies for best retrofit solutions

Ansitz Kofler

Ansitz Kofler before (2007) and after retrofit

Location	Bozen/Bolzano (South Tyrol, Italy)
Type of (main) use	The area was used to breeding tropical fruits until 1925. From then on, this "Orangery" had been adapted to a housing unit.
Period of construction	The main building was built in 1749, a secondary wing was added later in 1925
Year of last renovation	1925; 2007
Building structure	stone masonry wall with average thickness from 50 to 70cm.
Aim of the retrofit	To get back the historic appearance of the building before 1925, and to adapt space for residential purpose. The provincial office of historical monuments was consulted for the retrofit process. Furthermore, the preservation of the plants should be ensured.
Energy use after retrofit	54.54 kWh/m²a (measured winter 208/2009); 28,00 kWh/m²a (calculated)
Interesting solutions	the building is a listed building so that the eastern façade cannot be altered. Therefore, mineral wool was applied from the internal side on the eastern and northern façade (14cm FLUMROC panel + vapor barrier), while applied from the external side on the western façade (20cm). Wood fiber was applied on

	the southern side to study different behavior of two materials (14cm wood fiberboard + vapor barrier). Roof: 4cm FLUMROC insulation board (mineral fiberboard) on the ceiling, 12cm after the vapor retarder and 14cm in between rafters; floor: the ground was removed and rebuild. On the bottom was 5 cm gravel aggregate bed and 5cm lean concrete sub-base. To prevent rising damp, bituminous sheeting was applied, on which was 2*10cm insulation extruded polystyrene XPS with 2cm impact sound insulation. Other protective and cable layers were on top of it.
Critical issues	Conservation aspects Winter 08/09 measured heating demand 2 times higher than calculated one

Maso Aussergrub

Aussergrubhof/Maso Aussergrub before (1950th) and after retrofit

Location	St. Nikolaus Ultental/San Nicolo Val d´Ultimo (South Tyrol, Italy)
Type of (main) use	Before retrofit, the building has been used as an agricultural residential building. After retrofit, part of the apartments are rent as holiday hotel.
Period of construction	2nd half of 18th century
Year of last renovation	2013
Building structure	Solid stone masonry walls on basement and ground floor, first and top floor in vernacular "Blockbau" (solid wood) technic
Aim of the retrofit	The owner family opted for a retrofit of the not listed farmer house, because they wanted to maintain what their ancestors built: especially the two-wood paneled "Stuben", a smoke kitchen with vaults and an old cellar with perfect climate for food storage seemed to the owner to be of great value. Main wishes for the retrofit: living together for three generations – the son should get his own apartment on first floor; the space on top floor should be gained for three small holiday apartments. Each apartment should have its own entrance. In addition, the farmhouse needed a central heating for space heating and HDW that complies with the current technical standard.
Energy use after retrofit	69 kWh/m²a
Interesting solutions	Insulation of the wooden block construction (after removing the paneling) with 10 cm hemp fiberboard on the inside. A diffusion-open wind paper on the outside of the insulation prevents the penetration of moisture and protects the insulation from cooling out. On the inside of the insulation, an air-tight, diffusion-open vapor barrier was applied to protect the structure from humid room air. Then the original wood paneling or gypsum fiber boards were installed. Only the area of the historical "Stube" from the 18th century remained untouched. Parts of the old stone wall, which were replaced in the 70s with bricks, were rebuilt with a hollow brick and 10cm of EPS exterior insulation. The roof received 16 cm insulation on the rafters over the completely inhabited area; the windows from the 70s were replaced by new larch wood windows with double glazing (Ug value 1.1 W/m²K). The ceiling to the unheated basement was also energetically

	improved thanks to a layer of poly-foam insulation and expanded clay bedding. On the north side of the building, a drainage has been created to prevent moisture from entering the basement walls. The house is heated with renewable energies; the family can use their own wood in the central wood chip heating system.
Critical issues	Execution of the dormer

5.1.3 Maso Huber


Huberhof/Maso Huber before and after retrofit

Location	Rodeneck/Rodegno (South Tyrol, Italy)
Type of (main) use	Rural farmhouse with two apartments
Period of construction	1300-1400, “Stube” from 1730-1750
Year of last renovation	2008
Building structure	Solid stone masonry walls on ground and first floor, top floor in wood structure with vertical wooden cladding
Aim of the retrofit	Before the renovation, the listed farmer house was abandoned and corresponded no longer to the current demands on living quality. The retrofit project was planned from the beginning in strong collaboration with the heritage authority. The aim was to build two residential units while preserving as much as possible of the historic structure and appearance of the building.
Energy use after retrofit	57 kWh/m²a
Interesting solutions	On first floor, the wood paneling and the pavement of the two “Stuben” was removed and reinstalled, insulating the space behind the wooden cladding with 4 cm of wooden fiberboards; Other stone wall was insulated with 12cm wood fiberboard and vapor barrier. On the upper floor, the existing wooden walls were cleaned, fixed and insulated inwards with 16 cm of wooden fiberboards and covered with plasterboard. Roof: the old bearing structure was left visible. The roof was re-covered with larch shingles and insulated from the inside with 20 cm of wood fiberboards. The previously stamped ground was lowered and replaced by a new insulated floor structure (50 cm of insulating glass foam granules as insulation and drainage and 10 cm of PUR). The existing windows with single glazing were replaced by windows with triple glazing.

	A photovoltaic system was installed on the roof of the sheep shelter below the street, it supplies the electric heating system with energy.
Critical issues	Cost-intensive intervention; not quite as sensitive use of “foreign” material indoors: e. g. silver quartzite in the historic “Labe” (entrance area); vanishing of historic “winter windows”; against the rising moisture and cold, an additional wall was constructed in front of the historic stone walls, which might be a critical solution from building physics point of view.

Casa Kohler

Kohlerhaus/Casa Kohler before and after retrofit

Location	Innichen/San Candido (South Tyrol, Italy)
Type of (main) use	After retrofit, part of the apartments are rent as holiday hotel.
Period of construction	Core building was built in 14th century, and the extension to the current size was made in 1784.
Year of last renovation	2012
Building structure	Solid stone masonry walls with wooden roof construction
Aim of the retrofit	The building is listed as “historic ensemble”. After more than 10 year of vacancy, the private building was completely renovated, initially with the aim to give the building its appearance from the early 20th century. In the course of construction works, remains of the old core building were discovered and the history of the building was analyzed. After that, the retrofit interventions were adjusted as far as possible and the exterior of the building received the plastered façade of 1784. To finance the works nine of ten apartment were sold – eight as holiday apartments.
Energy use after retrofit	38,8 kWh/m²a
Interesting solutions	Insulation of exterior stone walls with 12 cm of reed insulation and 3 cm of insulating plaster from outside; 2 cm of reed insulation and 1,5 cm of clay plaster from inside. Insulation of roof with 24 cm wood fiber board below the rafters. Insulation of basement ceiling with 6 cm wood fiber board and 8 cm insulating fill. New wooden box-type windows made from a carpentry with Uw 1,1 W/m²K
Critical issues	Conservation aspects; Cost-intensive insulation system, windows

Piazza Erbe 11

Obstmarkt 11/Piazza Erbe 11 after retrofit

Location	Bozen/Bolzano (South Tyrol, Italy)
Type of (main) use	The ground floor is used as shop, and the upper floors are used as offices and residence.
Period of construction	12th century
Year of last renovation	1950 & 2000
Building structure	Solid natural stone exterior walls with a thickness of 60-80 cm, are plastered with lime plaster (except on basement level). The foundations floor consists of tamped earth. The basement walls were double-layer. Ceilings of the upper floors are built in wooden beams with wooden casing and filling material in between. The floor construction consists of a wooden substructure and wooden boards. Especially on ground and basement floors, the ceilings are vaulted. The construction of the saddle roof is made in timber rafters with wooden casing and roof tiles on it. The glazing were added in the XVII Century. The original window consists of two layers, each with two single-glazed sashes and a skylight.
Aim of the retrofit	The historic authority conducts renovation to improve the general building performance so that to keep the building in service condition. The renovation aims to utilize the attic, which used to be idle space.
Energy use after retrofit	32-52 kWh/m²a
Interesting solutions	The increase of the volume, the modification of the internal layout, the use of the top floors, the closure of the atria, and the construction of dormers. The cellars are used now either for storage, but often also as showrooms. The commercial and residential units often have a decentralized boiler in combination with radiators, while the shops usually use no heating system. The top openings of the atria have been additionally closed, often repeatedly on the level of different stories. For the closure mostly glass canopies were used especially at the roof level, but often also within the court. Insulation of the roof construction and substitution the windows with new double glazing windows.
Critical issues	During the new paving of the Portici Street the ventilation slots were closed with concrete, so that causes several problems of humidity and mold growth in the cellars. Also, cellar and ground floor are not climatically separated by shops and this cause a higher condensation risk of warm and humid air on the cold surfaces of the cellar walls. The top floor is inhabited, losing the original buffer function. The closure cause a

	lower air circulation and overheating during summer. The glass canopies are not easily accessible and often difficult to clean from outside.

Casa Leimegger


Casa Leimegger before and after retrofit

Location	Sand in Taufers / Campo Tures (South Tyrol, Italy)
Type of (main) use	It is a rural farmhouse with stable in the rear
Building structure	Solid stone masonry walls on ground and first floor, top floor in wood structure with vertical wooden cladding
Aim of the retrofit	Before the renovation, the existing building was structurally in a very bad condition. In addition, the hygienic conditions no longer met the modern standard. The space requirements of the residents have changed: only a small part of the barn is still needed. The owner wants to preserve the existing house and rebuild it energy-efficiently. So a gentle renovation was decided.
Interesting solutions	Windows are replaced with new larch windows, as well as wood paneling and balconies. Roof was completely renewed but without any insulation; the ceiling to the attic is insulated with “begehbare”, 20cm. Floor was insulated. The electrical, hydraulic and sanitary charges were renewed. Layout adjustment: In the rear former stable, the garage and the boiler room with the pellet store were accommodated. The wall to the garage and the barn was insulated with a moisture-resistant mineral foam board (16cm). Other external walls are not insulated to avoid damage of external historic plaster.
Critical issues	The retrofit of the stable part is not compatible with historic façade. i.e. it is not good practice in conservation point of view.

Prosenhof


Prosenhof before and after retrofit

Location	Truden/Trodena (South Tyrol, Italy)
Type of (main) use	Residense
Year of last renovation	2016
Building structure	Masonry walls includes stone and brick
Aim of the retrofit	The retrofit aimed at restoring the existing home on the second and third floor, retrofit the attic and use as a dwelling area, without any volumetric increases. In energetic aspect, aimed at improving the airtightness and thermal performance of the envelope.
Energy use after retrofit	174 kWh/m²a
Interesting solutions	Install solar collectors for the production of domestic hot water, embedded in the roof covering of the eastern stratum. Roof: plaster board 1.25cm+ OSB 1.8cm+ wood fiberboard between beams 18cm. New external cladding insulation on the entire north and east facades, made with flexible material so as to respect the existing flatness and finishing it superficially with plaster similar to the existing one. New window with glazing U-value 0.49W/m²K
Critical issues	High energy consumption

Maso Rain

Maso Rain before and after retrofit

Location	Gsies/Valle di Casies (South Tyrol, Italy)
Type of (main) use	Before retrofit, the building has been used as an agricultural-residential building. After retrofit it is used as holiday hotel.
Period of construction	Before 1600
Year of last renovation	2014
Building structure	Solid stone masonry walls on ground floor, first and top floor in vernacular "Blockbau" (solid wood) technic
Aim of the retrofit	The aim of the project was to preserve the overall appearance of the listed building and to enable contemporary living and working. The owner and architect were convinced from the beginning that a general renovation of the building should also include an increase in the energy efficiency and comfort of the building. All characteristic, valuable and typical architectonical elements were to be maintained and restored in consultation with the heritage office.
Energy use after retrofit	60 kWh/m²a
Interesting solutions	Exterior wall in natural stone with interior insulation (4-6 cm of insulating plaster Calcetherm 0,068). The wall of the "Stube" was insulated with 8 cm fiberboard in the space behind the wooden cladding. Insulation of the existing horizontal wood construction (log cabin) with the following building components: windproof seal (wind paper), wood fibreboard (12 cm), air layer/subconstruction, wooden cladding. Windows: Substitution

	of all windows with windows made by a furniture maker. HVAC: The new installed heating system is a combination of a biogas boiler and wood-chip boiler. The typical stove in the "Stube" is not fired with real firewood but it has an integrated wall heating system.
Critical issues	Cost-intensive intervention

Casa Schaller

Casa Schaller before and after retrofit

Location	Glurns/Glorenza (South Tyrol, Italy)
Type of (main) use	Ground floor is used as shop while the upper floors are used as office and residense.
Period of construction	14th century
Year of last renovation	2013
Building structure	The front part is constructed with solid masonry walls and wooden roof, while the behind part (the stable) is constructed with stone masonry corners and wooden fillings, and wooden roof.
Aim of the retrofit	The listed Schallerhaus is part of the Portici Street (Laubengasse) and thus part of an extremely valuable architectural heritage of the city of Glurns, which dates back to the middle ages. The building consists of the dwelling house (towards the street) and the barn house in the rear part of the parcel. The municipality of Glurns acquired the vacant and dilapidated building, in order to renovate it and to make it available to the locals as residential and business space.
Energy use after retrofit	69 kWh/m²a
Interesting solutions	All exterior walls (except on ground floor) were insulated from the inside with 8 cm insulating mineral panel. On first floor, the wood paneling of the two "Stuben" was removed and reinstalled, insulating the space behind the wooden cladding with wooden fiberboards. The existing windows with single glazing were replaced by windows with triple glazing. The vaults on ground floor were filled with expanded perlite. Roof: insulation between rafters 20 cm + 6 cm of wooden fiber board above rafters. Baseplate: The previously stamped ground was lowered and replaced by a new insulated floor structure (12 cm of expanded polystyrene). The building is heated via the district heating system of the neighbor municipality Schluderns. For static reasons, the existing wooden construction of the stable was demolished and a new wood structure inserted into the existing outlines of the stone masonry. The building envelope fulfills the requirements of a new energy efficient construction.

Critical issues	There is no vapor barrier when retrofitting the wood paneling.

Stanglerhof

Stanglerhof before and after retrofit

Location	Völs am Schlern/Fié allo Sciliar (South Tyrol, Italy)
Type of (main) use	Before retrofit it was a stable while after retrofit it is a tavern
Year of last renovation	2012
Building structure	Masonry walls on ground and first floor, top floor in wood structure with vertical wooden cladding
Aim of the retrofit	The house owner asked for a cost-effective and simple retrofit with updated building service system.
Interesting solutions	Straw bale is used as insulation material. A light-weight secondary construction including the wind tunnel was fitted from the inside. Then straw bale was used as insulation (U=0.135W/m2K) on the external wall and roof.
Critical issues	

A.2 Operative temperature distribution of the living room

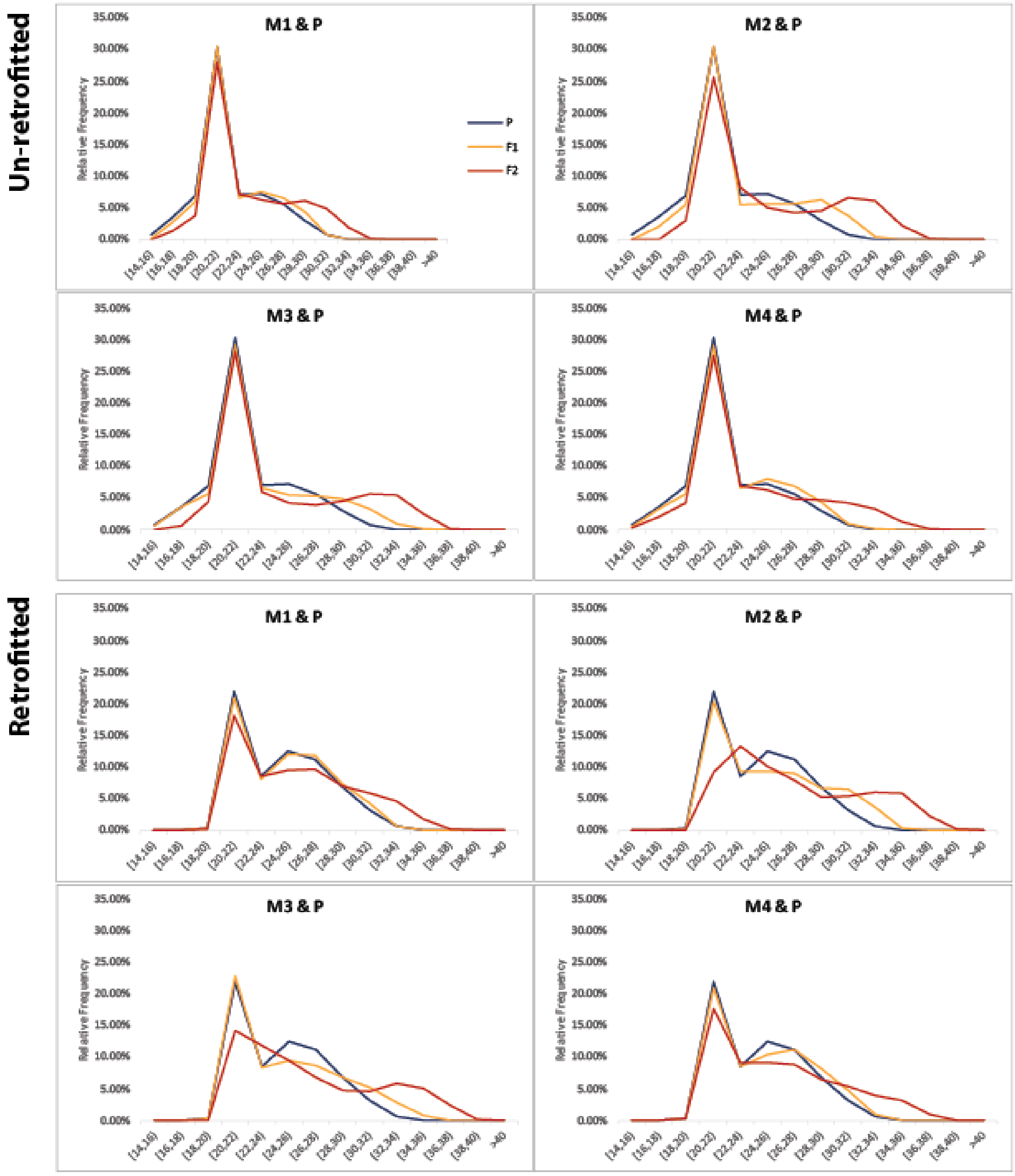

Figure 69 Operative temperature distribution of the living room of Rural farmhouse in Climate zone I

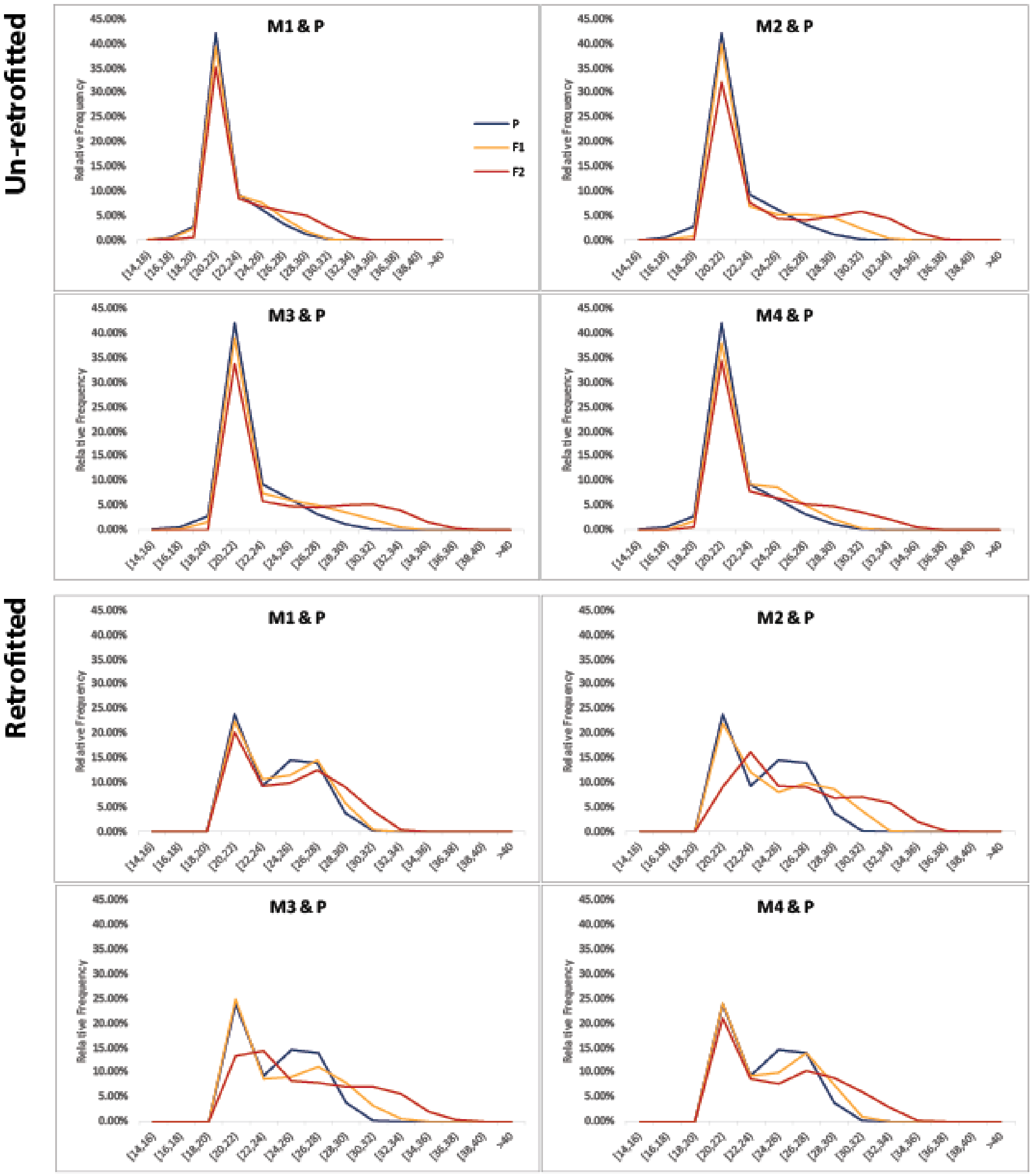

Figure 70 Operative temperature distribution of the living room of Portici house in Climate zone II

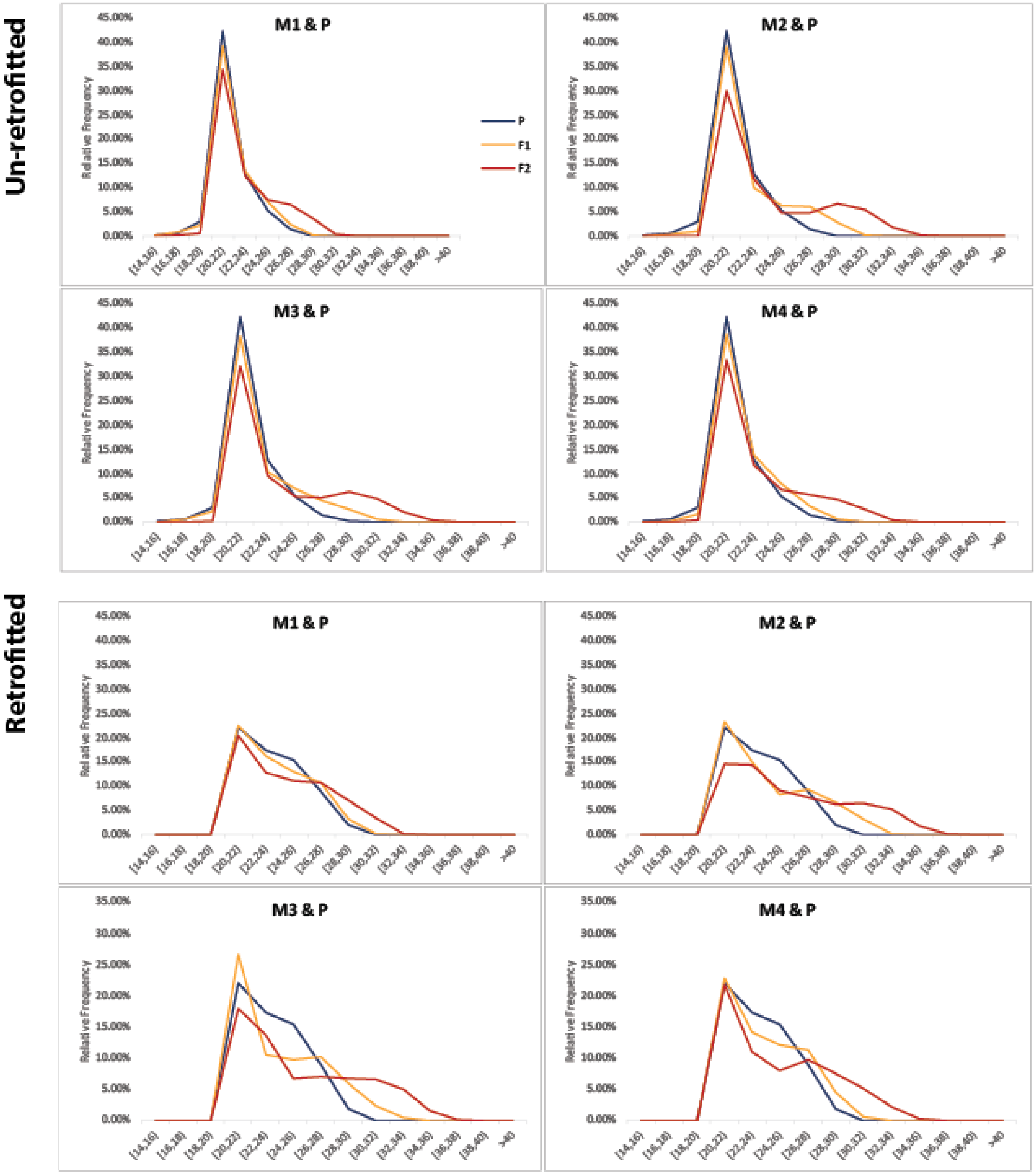

Figure 71 Operative temperature distribution of the living room of Rural farmhouse in Climate zone II

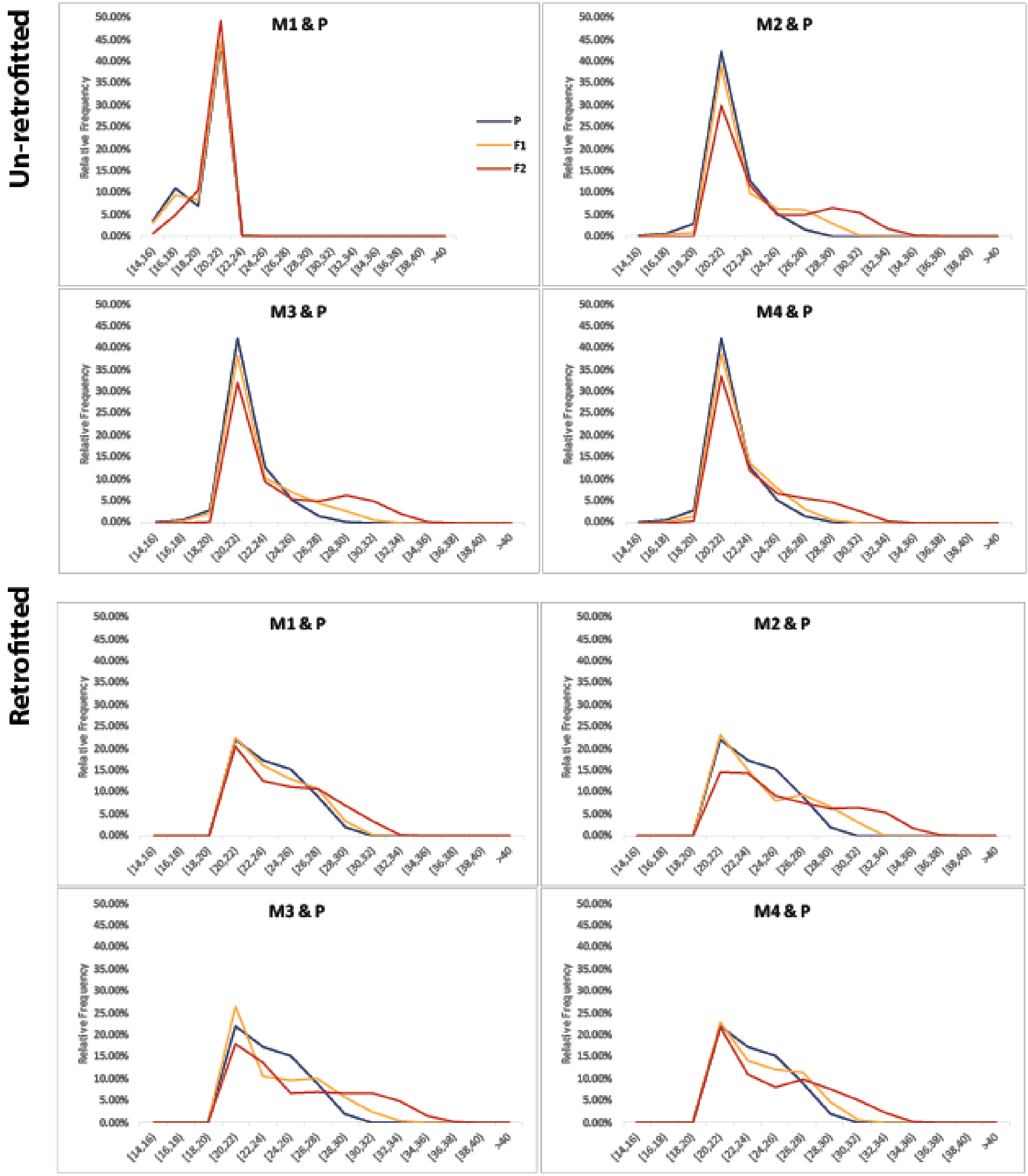

Figure 72 Operative temperature distribution of the living room of Rural farmhouse in Climate zone III

A.3 Average operative temperature as a function of outdoor running mean temperature in the living room

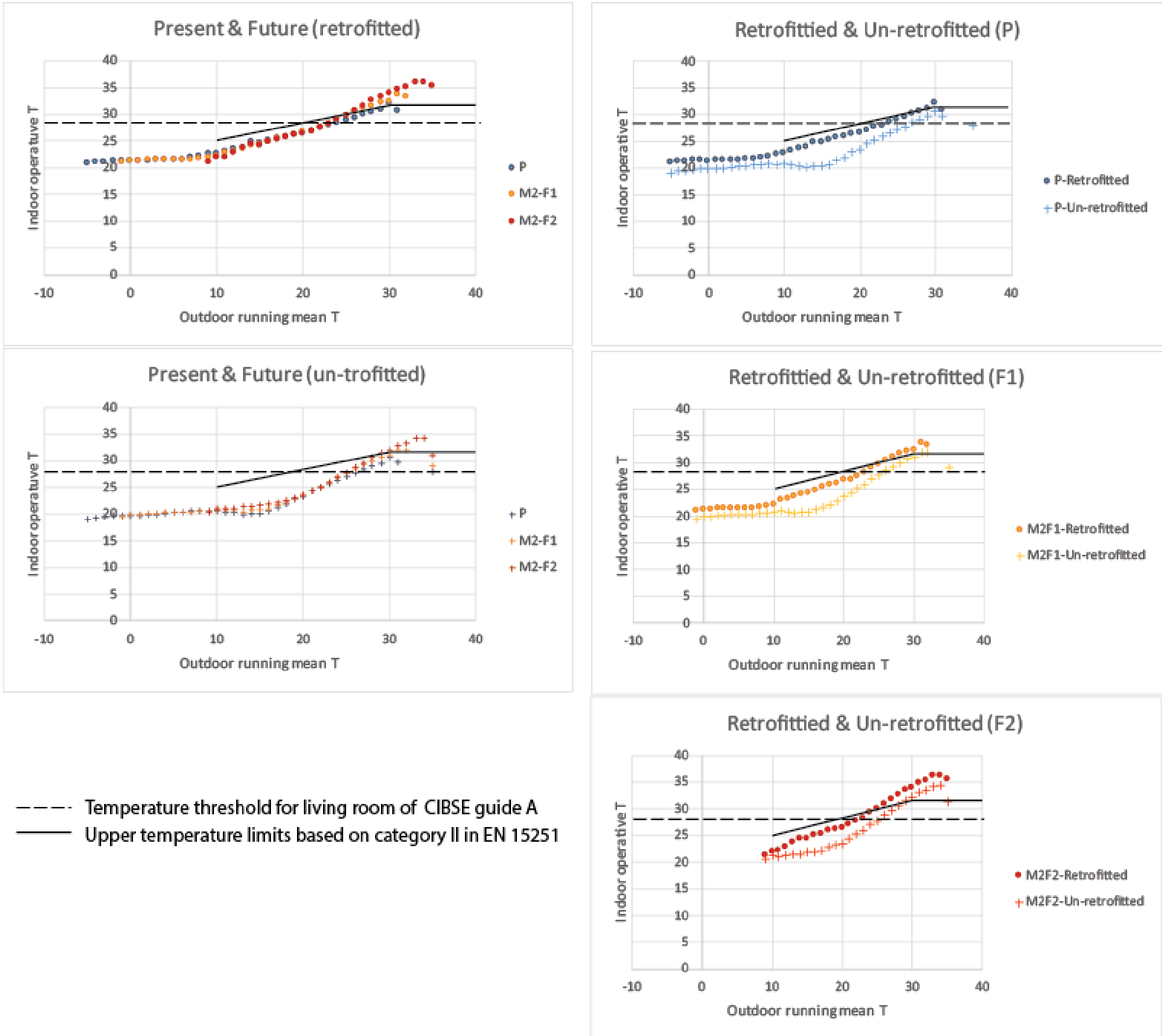

Figure 73 Average operative temperature as a function of outdoor running mean temperature in the living room of Rural farmhouse of Climate zone I

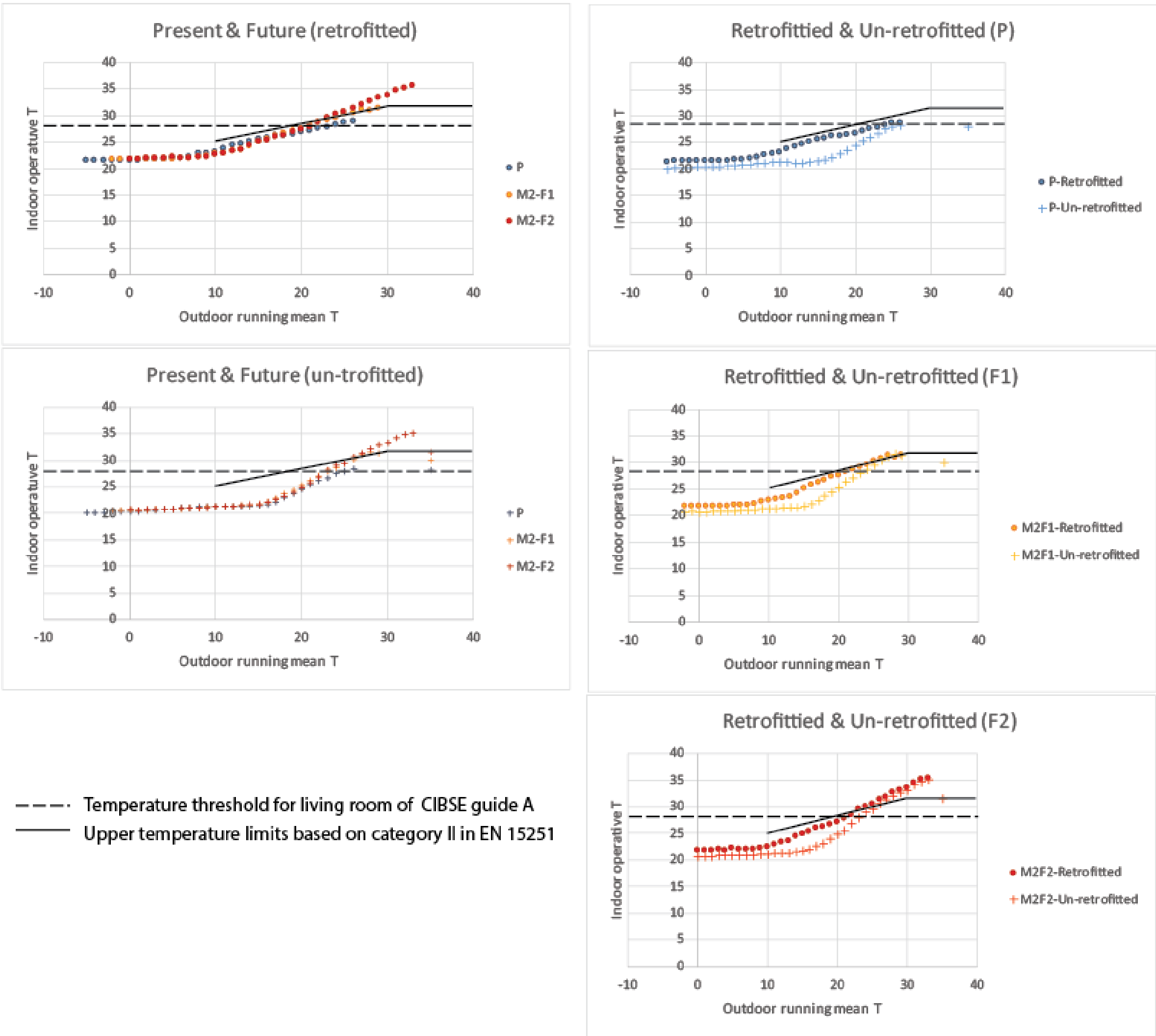

Figure 74 Average operative temperature as a function of outdoor running mean temperature in the living room of Portici house of Climate zone II

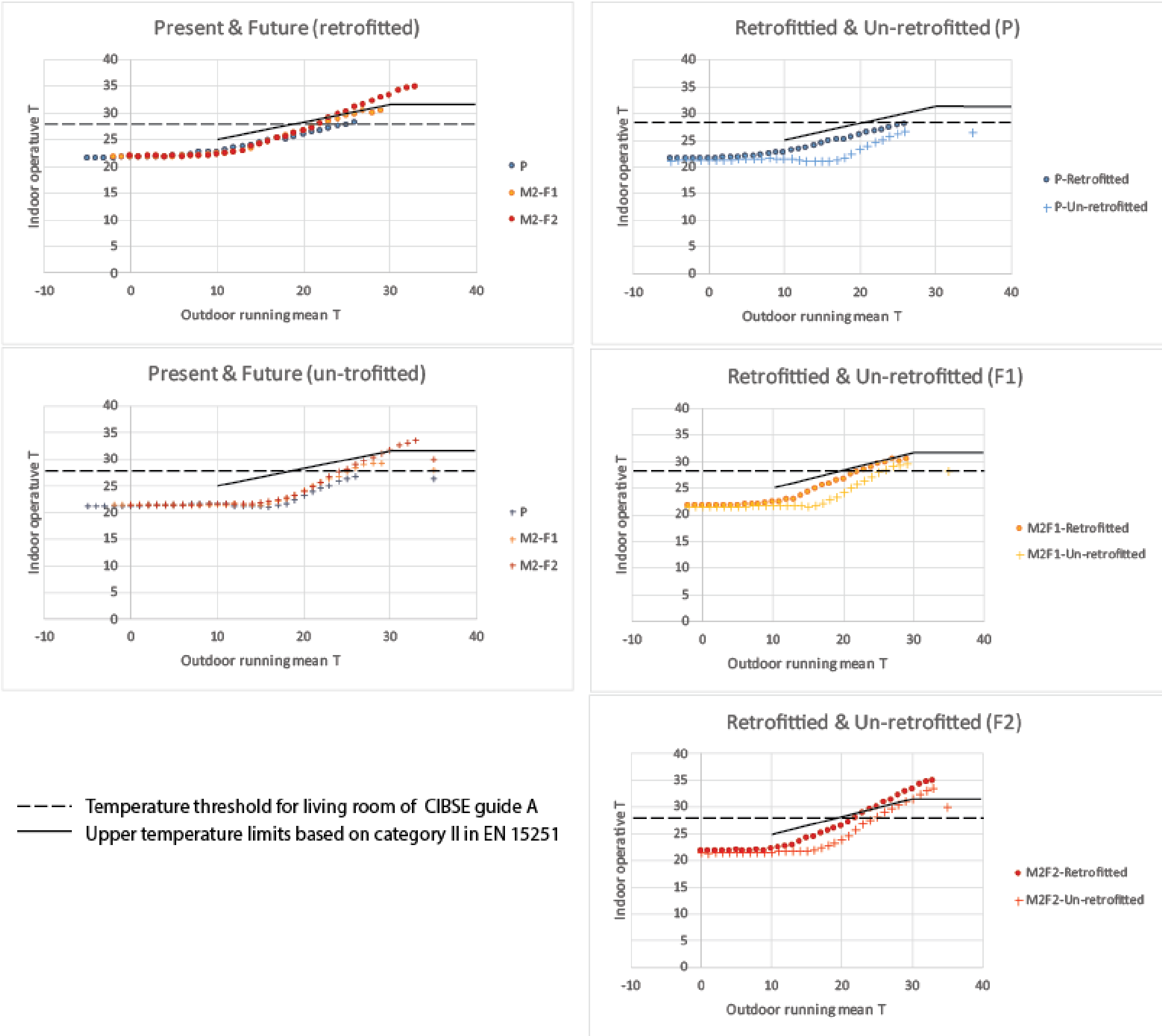

Figure 75 Average operative temperature as a function of outdoor running mean temperature in the living room of Rural farmhouse of Climate zone II

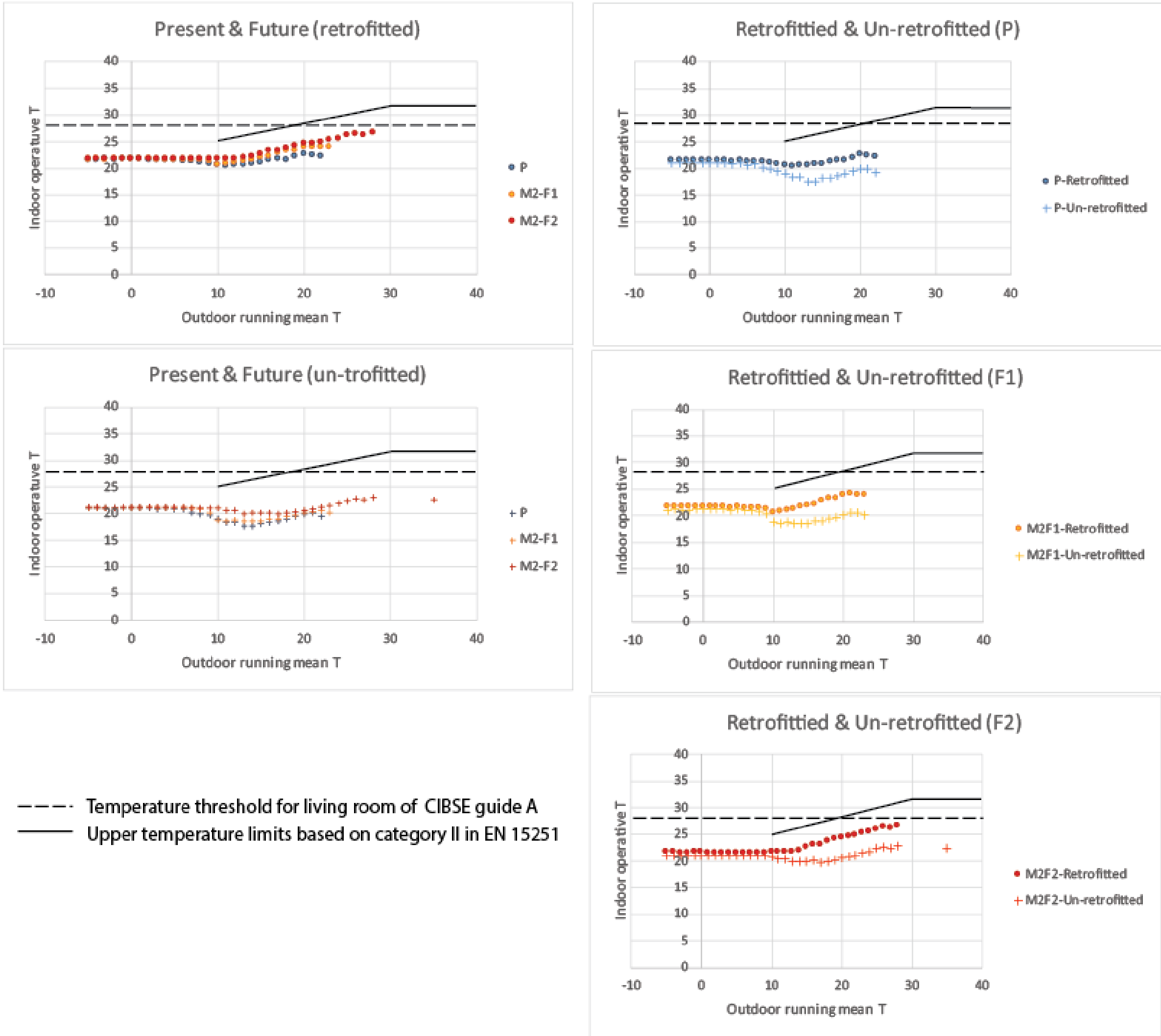

Figure 76 Average operative temperature as a function of outdoor running mean temperature in the living room of Rural farmhouse of Climate zone III