HeriTACE

Ventilative cooling guide

Deliverable D3.6

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Executive Summary

Deliverable D3.6 is produced within Work Package 3 of the HeriTACE project (Task T3.3.3) and presents a decision-making guide for the application of ventilative cooling in heritage townhouses. Ventilative cooling – the use of outdoor air as the sole cooling medium, by means of controlled ventilation and airing – responds directly to two converging pressures on Europe's historic residential stock: the rising overheating risk driven by a warming climate and by energy-renovation measures that reduce the passive dissipation of heat, and the regulatory imperative introduced by the recast Energy Performance of Buildings Directive, which establishes indoor environmental quality as a core performance metric. For protected buildings, where intrusive mechanical cooling is frequently incompatible with conservation requirements, ventilative cooling offers a low-impact, heritage-compatible pathway to thermal comfort that exploits the building's own architectural features.

The guide is built on the Ventilative Cooling Potential Method (VCPM), originally developed within IEA EBC Annex 62 and subsequently formalised within the European technical specification FprCEN/TS 18335 "Ventilative Cooling Systems – Design". The method provides a simplified, single-zone dynamic thermal balance, based on EN ISO 52016-1, that estimates free-floating indoor temperatures and the corresponding cooling potential of outdoor air. The deliverable adapts the nine-step design workflow of the technical specification to the specific context of heritage townhouses, following the "cooling ladder" principle in which mechanical cooling is treated as a last resort. For each step, heritage-specific guidance is provided, including lookup tables – derived from the HeriTACE envelope characterisation work – for thermal mass classes, glazing solar transmittance, urban-obstruction shading factors and envelope airtightness of common heritage constructions across four European climates.

The VCPM was applied to 57 parametric configurations across four heritage townhouse locations – Trondheim, Tallinn, Ghent and Mantova – under both contemporary and future (RCP8.5, 2050) climates, for a total of 114 annual assessments. The results show a strong dependence on climate and construction. In the Nordic and Baltic cases, cooling needs are low and ventilative cooling can fully offset the cooling penalty introduced by deep energy renovation, with peak airflow requirements within the reach of natural stack ventilation. In the maritime climate of Ghent, ventilative cooling is highly effective, removing of the order of 54–71% of the cooling need. In the Mediterranean continental climate of Mantova, the cooling need is the highest of all locations and is increasingly constrained by hot, humid hours during which outdoor air cannot provide cooling, so that ventilative cooling, while valuable, must rely on ventilation strategies that allow for airflow rates well beyond the reach of single-sided or conventional window ventilation – typically stack ventilation exploiting the full building height, supported by mechanical assistance during the calm, humid evenings when the natural buoyancy drive alone is insufficient.

The full workflow was validated on a seventeenth-century Palazzetto in Mantova, one of the most demanding cases for natural ventilative cooling. A stack-driven strategy was developed that exploits the building's existing central staircase and tower as a vertical airflow path, and was evaluated through a coupled multi-zone thermal and airflow-network model in EnergyPlus. The detailed simulation confirmed the VCPM-based design: the intended airflow direction (inflow at the occupied rooms, exhaust at the wind tower) was maintained for more than 99.8% of ventilative cooling hours, the achievable airflow

exceeded the design requirement during 99.6% of night-ventilation hours and 97.0% of daytime hours, and the strategy delivered a substantial reduction in occupied degree-hours above the comfort limit – demonstrating that a heritage feature originally conceived for passive environmental control can be re-activated as an effective, low-impact cooling system.

For practitioners, the deliverable provides a reproducible, early-stage method and ready-to-use parameter tables that make a credible feasibility assessment of ventilative cooling possible before detailed survey data are available, together with guidance on when the simplified method must give way to detailed simulation. For conservation authorities, it reframes heritage features – thermal mass, deep window reveals, courtyards, stairwells and chimneys – as cooling assets whose preservation is aligned with, rather than opposed to, climate adaptation. For policymakers, it provides evidence that passive, heritage-compatible cooling can meet a meaningful share of the cooling demand and should be prioritised over mechanical cooling, while also identifying the regulatory gap concerning passive cooling devices in protected urban centres that remains to be addressed.

Abbreviations and acronyms

Acronym	Description
ACH	Air changes per hour
AFN	AirflowNetwork (multi-zone airflow model in EnergyPlus)
AIVC	Air Infiltration and Ventilation Centre
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BS	Baseline scenario (PB: pre-renovation baseline; RB: renovation baseline)
CEN	European Committee for Standardization (CEN/TC: Technical Committee; WG: Working Group)
CIBSE	Chartered Institution of Building Services Engineers (AM10: Applications Manual 10)
CINEA	European Climate, Infrastructure and Environment Executive Agency
DDH	Discomfort degree hours
DF	Decrement factor
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EACEA	European Education and Culture Executive Agency
EC	European Commission
ELA	Effective leakage area
EN	European Standard (European Norm)
EPBD	Energy Performance of Buildings Directive
EPW	EnergyPlus Weather (file format)
EU	European Union
Fc	Solar radiation reduction factor of a shading device
g-value	Total solar energy transmittance (solar heat gain coefficient) of a glazing system
GA	Grant Agreement
GlobalABC	Global Alliance for Buildings and Construction
HR	Heat recovery
HV	Heritage value class (HV_I to HV_III)
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor air quality
IDF	Input Data File (EnergyPlus input file)
IEA EBC	International Energy Agency – Energy in Buildings and Communities Programme
IEQ	Indoor environmental quality
IGU	Insulated glass unit

Acronym	**Description**
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KPI	Key performance indicator
MVHR	Mechanical ventilation with heat recovery
n50	Air change rate at 50 Pa reference pressure (envelope airtightness)
NPL	Neutral pressure level
NV	Natural ventilation
NZEB	Nearly zero-energy building
PCM	Phase change material
RCP	Representative Concentration Pathway (e.g. RCP8.5)
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
RH	Relative humidity
SERI	Swiss State Secretariat for Education, Research and Innovation
TDR	Temperature Difference Ratio (also reported as Temperature Drop Ratio)
TMP	Thermal mass parameter
TMY	Typical Meteorological Year
TS	Technical Specification (FprCEN/TS: final draft CEN Technical Specification)
U-value	Thermal transmittance (W/m^2K)
Uf	Thermal transmittance of the window frame
Ug	Thermal transmittance of the glazing
UHI	Urban heat island
UNEP	United Nations Environment Programme
VC	Ventilative cooling
VCPM	Ventilative Cooling Potential Method
WP	Work Package
WWR	Window-to-wall ratio

Introduction

1.1. Scope and motivation

Historical buildings across Europe face a growing tension between heritage conservation and the need to provide adequate indoor environmental conditions for their occupants. These buildings were originally conceived within a fundamentally different paradigm of comfort and energy use: spaces were naturally ventilated and cooled through operable windows, permeable envelopes and architectural features such as courtyards, high ceilings, chimneys and thick masonry walls. Heating was provided locally, typically by fireplaces or stoves, conditioned to the patterns of occupancy in individual rooms. This approach, while energy-intensive in absolute terms, was inherently demand-responsive: energy was supplied only where and when occupants required it.

During the twentieth century, the gradual installation of central heating systems in historical buildings brought more uniform indoor temperatures, but also a significant increase in energy demand, as spaces were heated regardless of whether they were occupied. These fossil fuel-based systems typically operate at high supply temperatures. The transition to clean energy sources, which operate most efficiently at lower temperatures, thus presents a considerable challenge: emission systems designed for high-temperature fossil fuel boilers must be adapted or replaced to function with heat pumps or other low-carbon alternatives, a process that is particularly constrained in protected buildings where invasive interventions may not be permissible.

In parallel, envelope renovation measures undertaken to reduce heating energy demand, such as internal insulation, draught-stripping and replacement of windows, often reduce the air infiltration. While this is beneficial for heating energy performance, it can significantly degrade Indoor Air Quality (IAQ) unless compensatory ventilation is introduced. Today's mechanical ventilation systems, however, are typically not optimised for the architectural and physical specificities of historic buildings, where duct routing is constrained, visible external components may be prohibited, and room geometries differ substantially from those assumed in standard design methods.

Moreover, as a result of improved thermal insulation and a warming climate, cooling demands are increasing and historic buildings are facing growing thermal comfort challenges. These structures were often designed with inherent passive cooling logic adapted to their local climate, but their heritage status restricts the installation of intrusive mechanical systems.

According to the HeriTACE project, these converging challenges call for a fundamental rethinking of how heritage buildings are conditioned. The way forward lies in **dynamic and energy-efficient conditioning of historical building spaces, optimised to the occupants' indoor environmental quality needs that vary in space and time**. The ingredients for this approach are provided by recent innovations and research in several complementary fields: smart control of Heating, Ventilation and Air Conditioning (HVAC) systems; IEQ research on user behaviour, comfort sufficiency and health; hybrid heat emission systems and local comfort systems; demand-controlled and performance-based ventilation systems; and natural and ventilative cooling technology.

1.2. Ventilative cooling for heritage townhouses

Ventilative cooling is defined as the application of the cooling potential of outdoor air by means of ventilation and airing, relying on outdoor air as the sole cooling medium without the use of vapour-compression or absorption cycles (FprCEN/TS 18335). It encompasses strategies ranging from controlled natural ventilation through window openings to mechanically assisted airflow, and includes both daytime ventilation for direct occupant cooling and night ventilation for discharging thermal mass accumulated during the day.

The relevance of ventilative cooling is now explicitly recognised at the European policy level: the EPBD Guidance Annex on Technical Building Systems (European Commission, 2025) identifies ventilative cooling – particularly nocturnal operation in combination with thermal mass – as a primary passive strategy for climate adaptation, alongside solar shading and natural ventilation. The 2025–2026 UNEP Global Status Report for Buildings Construction (United Nations Environment Programme, 2026) reinforces this framing at the global scale, introducing a "passive cooling deficit" – defined as the share of buildings lacking shading, ventilation, or cool roofs – as a new resilience monitoring indicator, and explicitly calling on governments to promote passive thermal comfort strategies to reduce cooling energy demand.

Heritage townhouses have several characteristics that make them, in principle, well-suited to ventilative cooling. Their solid masonry walls provide high thermal capacity that can buffer heat gains during the day and be discharged by cooler night air. Tall floor-to-ceiling heights and multi-storey stairwells create natural stack-driven airflow paths. Existing chimneys and shafts, originally designed for combustion exhaust, can potentially be repurposed as ventilation exhaust routes. At the same time, heritage constraints create specific limitations: original windows may have restricted operability, external louvres or mechanical components on listed façades may be prohibited, and dense urban surroundings typical of historic centres may limit cross-ventilation potential and introduce noise and air quality concerns.

Through ventilative cooling, this work responds directly to one of the central challenges identified by the HeriTACE project – the low indoor environmental quality (IEQ) in heritage buildings – and to the broader regulatory imperative now established by the EPBD recast, which introduces IEQ as a core performance metric and requires Member States to set national IEQ standards for thermal comfort and ventilation in both new construction and major renovation. By leveraging the cooling capacity of outdoor air, ventilative cooling can simultaneously improve thermal comfort and indoor air quality, reduce or eliminate the need for energy-intensive mechanical cooling, and exploit the inherent thermal mass of heritage masonry construction as a passive energy storage mechanism – offering a technically and heritage-compatible pathway toward the optimal IEQ conditions that European building regulation now mandates.

1.3. Scope of this work

This deliverable presents a **decision-making guide for the specific use of ventilative cooling in heritage townhouses**. The guide is designed to support practitioners and building professionals in assessing the potential of ventilative cooling for a given heritage building and in selecting appropriate ventilative cooling strategies that are compatible with the building’s architectural, physical and heritage constraints.

The work builds on the Ventilative Cooling Potential Method (VCPM) originally developed within IEA EBC Annex 62 "Ventilative Cooling" (Annamaria Belleri et al., 2023) and subsequently updated and formalised within the European standardisation framework of CEN/TC 156/WG 21, as part of the technical specification FprCEN/TS 18335 "Ventilative Cooling Systems – Design". The VCPM provides a simplified, single-zone thermal balance calculation based on EN ISO 52016-1:2017 to estimate free-floating indoor temperatures, from which the cooling potential of outdoor air and the required ventilation rates can be derived. A key advancement in the method is the consideration of lumped thermal capacity in the thermal balance, which makes it particularly relevant for heavyweight heritage construction.

The guide adapts the nine-step design workflow defined in the CEN/TS to the specific context of heritage townhouses. For each step, heritage-specific guidance is provided, including lookup tables for the key building parameters that practitioners must estimate in the early design stages: thermal mass categories for common heritage wall constructions, solar heat gain coefficients for typical heritage glazing systems, shading factors accounting for urban obstructions from surrounding buildings, and infiltration ranges for heritage envelopes at various states of repair.

The VCPM is applied to HeriTACE case studies across four European climates, representing a range from Nordic (Trondheim, Norway), through Baltic (Tallinn, Estonia) and maritime (Ghent, Belgium), to Mediterranean (Mantua, Italy) conditions. Both contemporary and future (RCP8.5) weather scenarios are considered to assess the climate resilience of ventilative cooling strategies. The complete workflow is then tested on the Italian case studies by developing, designing and modelling a ventilative cooling strategy.

1.4. Structure of the report

The deliverable is organised to guide the reader from the conceptual framing of ventilative cooling in heritage buildings to the practical application and validation of design strategies. The report opens with a literature review of the potential of ventilative cooling and the constraints specific to historic contexts. It then presents a structured ventilative cooling design workflow, including performance criteria definition, assessment of cooling potential, decision support workflow of ventilation principles and development of control strategies, supported by heritage-specific guidance and parameterisation. The methodology is subsequently applied to a set of European case studies to analyse climatic and typological variability, and validated through detailed modelling in a representative Italian case study. The report concludes with synthesis, recommendations for practice, and supporting annexes and references, providing both methodological guidance and evidence-based insights for implementation

2. Potential of ventilative cooling in historic townhouses

Reliance on mechanical cooling raises concerns across multiple dimensions: resilience, as systems are vulnerable to power outages and component failure precisely during the extreme heat events when cooling is most needed; affordability, as the capital and operational costs of mechanical systems can be substantial, particularly in residential heritage buildings where economies of scale are limited; carbon emissions, as both the energy consumption and the refrigerant leakage of vapour-compression systems contribute to greenhouse gas emissions; and environmental quality, as external condensing units release waste heat, generate noise and create visual clutter that degrades the surrounding streetscape.

2.1. Ventilative cooling strategies in historic townhouses

A systematic review was conducted to identify main ventilative cooling strategies and link them to specific geographical area. This provides a setting where the challenges of cooling buildings before the introduction of mechanical refrigeration and air conditioning can be studied.

The literature search was conducted in Scopus over the literature published in the latest 10 years (between 2016 and 2026) using a structured keyword query combining terms related to ventilative cooling strategies, heritage building types, and European geographical contexts. The ventilative cooling terms included night ventilation, night cooling, night purge, courtyard ventilation, courtyard cooling, stack effect, chimney ventilation, wind tower, windcatcher, earth tubes, earth-air heat exchangers, hypogeal and subterranean cooling, cellar cooling, and thermal mass and ventilation, free cooling, passive cooling and ventilation, overheating and ventilation, summer ventilation, and cross-ventilation. These were combined with heritage qualifiers (historic, heritage, vernacular, traditional, listed, conservation area, protected) and residential typology terms (dwellings, houses, residential, townhouses, terraced, row houses, courtyard houses, timber frame, half-timbered, log house, brick house, masonry building, apartment building, multi-family). The geographical scope covered Europe broadly, with explicit terms for Mediterranean, Alpine, Nordic, and Central European countries. The search returned 21 documents. Following abstract screening, 10 papers were excluded as not relevant to historic buildings or the target geographical area; 2 additional papers identified through complementary literature search were integrated. 12 papers were reviewed in total.

The reviewed literature is geographically uneven. The large majority of studies concerns hot-dry Mediterranean climates (Cyprus, southern Italy, Portugal, Spain), with a smaller body of evidence from temperate continental climates (Poland, Slovakia, Denmark). No study in English-language peer-reviewed literature was identified that directly addresses ventilative cooling strategies in cold-temperate oceanic or Nordic historic townhouses in the recent literature. This absence may partly reflect the scope of the search, which was limited to English-language indexed literature of the latest 10 years; relevant knowledge may exist in older publications, grey literature, technical guidance documents, or publications in local languages that were not captured by the Scopus query. It may also reflect a genuine historical condition: in these climates, summer overheating of traditional masonry buildings was not historically a primary design concern, and passive cooling strategies were not systematically embedded in vernacular building culture to the same degree as in Mediterranean Europe. Both factors are likely to contribute to the gap.

The reviewed literature covers several distinct historic residential building typologies that differ in their thermal mass regime, ventilation potential, and heritage constraints. Compact two-storey urban townhouses with massive masonry load-bearing walls – the typology most directly comparable to the HeriTACE case studies – are the most studied: they appear in Cyprus (Michael et al., 2017; Stavroula et al., 2016), southern Italy (Fiorito et al., 2022; Gagliano et al., 2016; Maria Patane et al., 2024), and Portugal (Cortiços, 2026). They share window-to-wall ratios typically between 5–15% on the street façade and larger openings on the courtyard side. Night cross-ventilation and courtyard-driven airflow are the dominant effective strategies. Single-storey rural vernacular dwellings represent the extreme thermal-mass, minimal-opening end of the spectrum, documented in Alentejo (Costa-CarrapiçO et al., 2022).

In historic townhouses of oceanic and continental climates (Denmark (Bugenings et al., 2025), UK (Kumar et al., 2024), Poland (Kuczyński et al., 2021; Staszczuk, 2025)), massive masonry construction also provides passive thermal resilience but within a winter-dominated energy balance; the summer performance of these buildings has not been systematically studied in the heritage context.

Table 1. Summary of reviewed papers on ventilative cooling strategies in EU heritage townhouses.

References	**Region**	**Building typology**	**Ventilative cooling strategy identified**	**Effectiveness**	**Thermal mass**	**Window to Wall Ratio / orientation**	**Note**
(Michael et al., 2017)	Cyprus (semi-mountainous)	Two-storey listed vernacular dwelling	Night cross-ventilation	71.5–74.5% Temperature Difference Ratio (TDR)[1];Thermal mass discharged	Stone + adobe, 40–50 cm walls; time lag 4 h 40 min – 6 h 10 min	WWR <10%; openings ~80×110 cm	Dense urban fabric limits wind speed to ~0.01 m/s indoors; cooling is mass-dominated
(Stavroula et al., 2016)	Cyprus (Nicosia – urban historic core; Bsh/Csa)	two-storey urban vernacular dwelling in the historic centre of Nicosia	Combination of cross ventilation from street (via sachnisi windows[2] at first floor) to courtyard + stack ventilation through the staircase connecting the portico (lower, cooler) to the sachnisi (upper, warmer) + nighttime ventilation (19:00–07:00)	99% of comfort hours in the ground floor and 71%of comfort hours in the first floor	Load-bearing mud brick, 50 cm walls; heavyweight; diurnal indoor swing <2 °C vs 8.7 °C outdoor	Small street-façade openings; larger courtyard + sachnisi windows (30% effective opening modelled)	8.7 °C outdoor diurnal swing is sufficient to drive night mass discharge; the sachnisi projection is the cross-ventilation enabler
(Cortiços, 2026)	Mediterranean Portugal (Santarém, inland Csa)	Traditional construction archetypes of dwellings in santarem	Cross-ventilation (primary summer cooling, no AC; indoor 22–28 °C); night ventilation (indoor >26 °C & outdoor <22 °C); free cooling; stack effect via courtyard	Cooling demand is near zero due to reliance on natural ventilation, with indoor summer temperatures floating at 26–28 °C; stronger climate resilience compared to modern buildings, remaining habitable during outages	Traditional heavy construction; night ventilation discharges stored heat through mass	South orientation, operable shutters, fixed eaves; courtyard geometry	Simulation comparison of three typologies (traditional / hybrid / contemporary NZEB); traditional form needs no AC
(Costa-CarrapiçO et al., 2022)	Rural Alentejo, Portugal (São Vicente e Ventosa – Csa)	Single-storey rural vernacular limestone/earth dwellings, 1800s (22 case studies)	Nighttime natural cross ventilation performed via built in wickets and chimney (no windows) and mechanical daytime ventilation	Nighttime NV combined with daytime mechanical ventilation was the best-performing occupied strategy, achieving a mean decrement factor of 0.19 over the full	Limestone + earth masonry, 0.60 m walls; 18-h decrement delay; DF 0.11 unoccupied; ~14 °C indoor–outdoor jump at 45 °C peak	WWR <1% – no windows; only 0.15 m² door wickets; lime-washed reflective walls; rear courtyard as ventilation buffer	Uninsulated roof (U = 3.13) is the thermal weak point; behavioural shift away from night NV (due to security reasons) erodes performance

[1] It expresses how much a ventilation strategy suppresses the indoor peak relative to the outdoor temperature swing – essentially (outdoor peak − indoor peak) as a fraction of the outdoor diurnal range. Higher = better passive cooling.

[2] A traditional architectural element found in Greece, the Balkans, Turkey, Cyprus, and parts of the Middle East. It is essentially an enclosed projecting bay window or wooden balcony that extends outward from the upper floor of a building.

References	Region	Building typology	Ventilative cooling strategy identified	Effectiveness	Thermal mass	Window to Wall Ratio / orientation	Note
				summer monitoring period (compared to 0.30 for combined daytime NV + mechanical, and 0.29 for mechanical ventilation alone).			
(Laurini et al., 2017)	Central Apennine Italy (L'Aquila – inland mountainous Med)	15th-century noble courtyard palace	Basement-to-upper-floor stack ventilation via an inserted duct exploiting cool basement air (underground water tanks); revival of the vernacular air-well / cave strategy	Improved comfort conditions demonstrated via monitored temperatures	High – thick mixed stone + brick historic masonry, uninsulated (not quantified)	Not reported; significant air leakage at duct penetrations and windows	Comfort driven by humidity reduction (RH 51% vs 58%) more than temperature; small passive gains achieve EN 15251 adaptive comfort without mechanical cooling
(Fiorito et al., 2022)	Southern Italy (Molfetta, Apulia – coastal Csa)	Historic masonry townhouse, medieval centre	Natural ventilation only (HVAC off)	Stochastic window operation cuts discomfort (DDH) 30–50% vs rule-based; days-with-discomfort rise 32% (TMY) → 89% (2080); comfort 'unacceptable' from 2050	Historic masonry, medieval centre (measured in situ 2012)	Window opening modelled rule-based vs stochastic (Jones et al.)	
(Gagliano et al., 2016; Maria Patane et al., 2024)	Sicily (Catania – coastal Csa)	Traditional heavyweight basalt/lava-stone dwellings (pre-1960s)	Daytime + night window ventilation governed by occupant behaviour	High mass retains an advantage even under full ventilation; night ventilation 1–3 ACH (00:00–06:00) cuts cooling demand 14–31%	TM2 traditional heavyweight basalt/lava stone (pre-1960s) vs TM1 mediumweight concrete/clay brick; TM2 ~4 °C cooler when closed; lava-stone masonry 80 cm, 1813 kg/m^2, time lag 10 h, decrement factor 0.05	~8% WWR, single→selective double glazing	Survey-based window operation (68 questionnaires, 13 months); night ventilation threatened by rising nocturnal temperatures; adding insulation to massive walls raises summer loads by blocking night mass discharge;
(Kumar et al., 2024)	South-east England (Kent + London – Cfb)	Three historic homes: 1662 timber farmhouse, 1828 Georgian maisonette, 1776 tidal mill	Cross-ventilation	Cross-ventilation scored strongest mitigation effect; House Mill 29.2 °C indoor vs 39.4 °C outdoor (~10 °C below peak) in 2022 heatwave	Low-Medium (timber-frame farmhouse) to High (solid masonry mill); House Mill ~10 °C below outdoor peak in 2022 heatwave	Double glazing; high ceilings noted as buffering; internal curtains for shading	night ventilation constrained by security, noise, listed status; natural infiltration
(Kuczyński et al., 2021;	Poland (temperate continental)	Full-scale laboratory test buildings; lightweight→very-heavy	Combined: thermal mass + external blinds + night ventilation	10ach night ventilation leads to 7.4 K indoor temperature peak	TMP 152–922 kJ/m^{2}K tested	South-facing windows with external blinds	PCM (<1 °C benefit) far inferior to traditional heavy masonry; ground coupling

References	Region	Building typology	Ventilative cooling strategy identified	Effectiveness	Thermal mass	Window to Wall Ratio / orientation	Note
Staszczuk, 2025)		experimental rooms (top floor, south façade)		reduction; isolated mass alone 3.6–4.3 K; ground coupling +~2.5 K; PCM <1 K (inferior)			via uninsulated slab adds ~2.5 °C reduction over masonry alone
(Bugenings et al., 2025)	Denmark (Aarhus + Aalborg, Jutland – Cfb)	Pre-1973 residential – single-family (1968) + multi-family (1972), masonry/concrete, not listed	Louvred openings (fixed lamellae + operable hatch) replacing windows; enables night-purge during absence, rain and noise	Multi-room louvre cross-ventilation brings overheating near/below Danish limits (≤100 h >27 °C, ≤25 h >28 °C)	Masonry cavity walls (single-family) / transverse load-bearing concrete (multi-family); pre-1973 stock, not heritage-listed	Louvred opening retrofit into existing window openings; preventive 24 °C setpoint near-eliminates overheating	Ability to ventilate during sleep and absence is essential; living rooms most overheating-prone; discharge coefficient and opening width least influential

The literature identifies a limited but coherent set of ventilative cooling strategies recurrently applied in historic townhouse contexts:

Night ventilation and night purge. Night ventilation — the practice of opening windows during the cooler night hours to discharge heat accumulated in the building fabric and reduce indoor air temperatures — is the dominant and most consistently effective ventilative cooling strategy documented across all European climates studied. Its effectiveness rests on the interaction between two physical conditions: the availability of a sufficient indoor–outdoor temperature differential at night, and the presence of sufficient thermal mass in the building fabric to store daytime heat and release it when exposed to cooler air. In historic masonry townhouses both conditions are typically well met, making night ventilation the strategy with the highest leverage.

Empirical evidence from Cyprus (Michael et al., 2017) provides the clearest quantification. Field monitoring of a stone and adobe vernacular townhouse in the semi-mountainous region of Kapedes demonstrated that night cross-ventilation (21:00–07:00) reduces peak indoor temperatures by up to 6.5 °C relative to outdoor peak and achieves a Temperature Drop Ratio of 59–74.5%, depending on the number of openings engaged. Daytime ventilation of the same building yielded a TDR of only 4.5–9.5%, confirming that the outdoor temperature conditions is the critical operational variable. Simulation studies in Catania (Gagliano et al., 2016) corroborate this: nighttime air change rates of 1–3 ACH applied between midnight and 06:00 reduce seasonal cooling energy demand by 14–31% in an 18th-century lava-stone palazzo. Without night ventilation, the same building's free-running indoor temperature stabilises above 29 °C after approximately two weeks, as heat accumulates in the massive walls faster than it dissipates. In Nicosia (Stavroula et al., 2016), simulation and monitoring of a traditional two-storey urban dwelling showed that the best-performing ventilation scenario — cross-ventilation across both floors at night — extended thermal comfort time on the thermally critical first floor from 38.8% to 71.6% of summer hours, with a mean operative temperature reduction of 1.5 °C. In Alentejo (Costa-CarrapiçO et al., 2022), long-term monitoring of single-storey limestone vernacular dwellings confirmed that traditional nighttime natural cross-ventilation through door wickets achieves a mean seasonal decrement factor of 0.19 — significantly better than daytime mechanical ventilation (0.29–0.30) — by convectively discharging the 18-hour thermal lag of the walls and resetting their absorption capacity for the following day.

Experimental data from temperate continental Poland (Kuczyński et al., 2021; Staszczuk, 2025) provide the most controlled quantification of the relationship between thermal mass and night ventilation across the widest range of mass levels (thermal capacity of walls 152–922 kJ/m²K). Thermal mass alone reduces peak indoor temperatures by 3.6–4.3 K relative to lightweight construction. The addition of external solar shading raises this to approximately 5–6 K. The further addition of night-purge ventilation at 10 ACH achieves a combined peak temperature reduction of 7.4 °C daytime and 6.3 °C night — a magnitude that no single strategy and no alternative technology, including phase-change materials (which contribute less than 1 °C under identical conditions), can approach. This finding is directly applicable to historic European townhouses, whose thermal capacity typically fall in the 400–900 kJ/m²K range by virtue of their stone or brick masonry construction.

An important constraint specific to massive heritage buildings concerns the interaction between insulation and night ventilation. (Gagliano et al., 2016) demonstrate quantitatively that adding internal insulation to already-massive lava-stone walls in a Mediterranean climate can increase summer heat loads rather than reduce them, because the insulation layer impedes the discharge of stored heat to the cooler outdoor environment during night ventilation.

Cross-ventilation – airflow driven through the building from one facade or opening to another on the opposite side – consistently amplifies night ventilation performance by increasing the air change rate achievable through passive means. In dense historic urban fabric, where surrounding buildings limit wind exposure and indoor air velocities are very low, cross-ventilation through the full depth of the building from courtyard to street, or from one facade to another, is the single most important architectural enabler of effective ventilative cooling.

(Michael et al., 2017) provide the most precise quantification: opening three or more windows on opposing walls reduces the mean nocturnal indoor–outdoor temperature differential to 0.1 °C, compared to 3.0 °C for single-opening ventilation and 1.0 °C for two openings on the same wall – demonstrating a step change in performance that is disproportionate to the increase in opening area. (Stavroula et al., 2016) confirm this for the Nicosia sachnisi typology: opening the projecting bay's street-facing windows to create through-building cross-flow yields the highest air change rates of all scenarios tested, particularly on the thermally critical first floor where roof-transmitted solar gains concentrate. In both cases, the architectural layout of the traditional townhouse – with a rear courtyard or transitional space on one side and a street-facing facade on the other – is the primary determinant of cross-ventilation potential, and its preservation is therefore directly relevant to passive cooling performance. In temperate oceanic climates, the dual-aspect configuration of the UK case study buildings (Kumar et al., 2024) was similarly identified as a strong mitigating factor against overheating risk, contributing −5 to −6 points in the risk assessment scoring, while the Danish study (Bugenings et al., 2025) demonstrated that cross-ventilation through louvred openings on multiple facades substantially outperforms single-sided ventilation even in a cool climate where overheating would historically have been considered a marginal concern.

Courtyard ventilation. The internal or semi-internal courtyard is documented across the corpus as the primary ventilation inlet for historic townhouses in dense urban fabric, where street-facing facades have limited openings and are shielded from wind by adjacent buildings. In the Nicosia case study (Stavroula et al., 2016), the courtyard provides the main airflow path for both floors, with the portico opening directly onto it and the first-floor sachnisi drawing air through it when courtyard-facing windows are opened. In Alentejo (Costa-CarrapiçO et al., 2022), the rear courtyard provides the secondary airflow path for traditional nighttime cross-ventilation through the building's front and rear door wickets and also serves as a microclimate buffer and shaded outdoor space. (Cortiços, 2026) similarly describes the courtyard as a core element of the passive cooling system of the Santarém vernacular dwelling, providing shading from vegetation and buffering the airflow path between indoor and outdoor. The courtyard's contribution to ventilative cooling is in all cases architectural rather than technological: it is the spatial organisation of the building that creates and preserves this asset, and heritage conservation of the historic townhouse plan is therefore directly aligned with the retention of its passive cooling potential.

Stack-effect ventilation – buoyancy-driven airflow arising from temperature differences between lower and upper parts of a building, or between a cool underground reservoir and warmer upper floors – is documented as both a vernacular strategy and a retrofit application in the Italian context. (Laurini et al., 2017) monitored a passive cooling duct installed in a 15th-century courtyard palace in L'Aquila, exploiting the temperature differential between a cool basement fed by underground water tanks and the upper living floors. The dominant measured benefit was hygrometric rather than thermal: relative humidity in the stack-ventilated room dropped to 50.94% against 57.93% in the reference room, a difference sufficient to shift the adaptive comfort assessment from outside to within the EN 15251 (now EN 16798:2019) comfort zone, at air velocities of approximately 0.1 m/s. The temperature reduction was modest (~0.5 °C at peak), but in the temperate Mediterranean inland climate of L'Aquila – a context relevant to the humid summer conditions of Mantua – this hygrometric benefit alone proved decisive for occupant comfort. The paper also documents that the L'Aquila historic building stock historically encoded stack-effect logic natively: underground caves, air wells, double-height atria, and attic ducts oriented to summer breezes were all observed vernacular features. (Stavroula et al., 2016) describe a comparable arrangement in the Nicosia townhouse, where the staircase connecting the ground-floor portico to the first-floor sachnisi generates buoyancy-driven vertical airflow that partially supplements wind-driven cross-ventilation, though the two effects can also partially counteract each other depending on wind direction and the relative magnitude of the temperature differential.

2.2. Heritage constraints as design drivers

The following considerations reinforce why passive and ventilative cooling strategies should be pursued as far as possible before resorting to mechanical systems in heritage buildings:

Preservation of architectural integrity. Heritage townhouses derive their cultural significance from the authenticity of their materials, construction techniques and spatial character. Mechanical cooling installations – external condensing units on façades, rooftop plant, visible ductwork, suspended ceilings concealing fan coil units – can compromise this significance through direct physical alteration and visual intrusion. Ventilative cooling, by contrast, works with the existing building fabric: it exploits operable windows, internal doors, stairwells and chimneys that are already part of the building's architectural vocabulary. The building's architectural vocabulary already encodes its cooling logic. Where new components are required (trickle vents, automated window actuators, heritage-compatible louvre panels, fan for assisted ventilation), they can often be designed to be reversible and minimally invasive, in keeping with conservation principles of minimum intervention and reversibility.

Reversibility and minimum intervention. Mechanical cooling systems typically require extensive and partly irreversible installation works: penetrations through historic walls for refrigerant piping, structural modifications for plant rooms, and permanent alteration of ceiling voids. Field evidence demonstrates that substantial cooling performance is achievable without any substantial physical modification to the building. Even mechanically assisted ventilation systems can be integrated through existing shafts or with minimal new penetrations, and the components can be removed without lasting damage to the historic fabric. The heritage integration challenge for stack ventilation is noted explicitly by (Laurini et al., 2017). Regulatory frameworks lack specific provisions for passive cooling devices in historic centres, creating a legal gap that is distinct from the building-physics and conservation challenges and that would need to be addressed for systematic application at scale.

Compatibility with thermal mass. Solar shading and high thermal mass are not ventilative cooling strategies in themselves, but they are the enabling physical preconditions without which night ventilation cannot function effectively, and they are consistently documented across the literature as inseparable from ventilative cooling performance in historic buildings. Solar shading protects the thermal mass from daytime charging, preserving its capacity to act as a heat sink during the following night ventilation cycle. High thermal mass stores the heat that does enter the building, attenuates the indoor temperature swing, and provides the thermal storage that night ventilation can discharge. Thermal mass values documented across the corpus are consistently very high relative to modern construction: decrement factors of 0.03–0.30, time lags of 10–18 hours, and wall surface densities up to 1813 kg/m² (lava stone, Catania; limestone, Alentejo; mud brick, Nicosia). Heritage-compatible forms of solar shading documented include fixed eaves and operable shutters on south-facing openings (Cortiços, 2026), external venetian blinds (used by 83% of surveyed occupants in Nicosia (Stavroula et al., 2016)) and minimal window-to-wall ratio inherent to the typology rather than added as a retrofit measure.

Urban context and streetscape. Heritage townhouses are typically located in protected urban centres where the visual integrity of the streetscape is a conservation objective in its own right. External mechanical cooling equipment – condensing units, cooling towers, ventilation grilles – is often prohibited or severely restricted by local planning and heritage authorities. Beyond visual impact, mechanical cooling in dense historic centres contributes to urban heat island intensification through waste heat rejection: field evidence from Catania documents that rising nocturnal temperatures, partly attributable to urban heat island effects, are already reducing the diurnal temperature swing that makes night ventilation effective (Maria Patane et al., 2024), while projections for Mediterranean cities suggest that the background warming combined with local UHI effects will make passive-only approaches insufficient for the majority of summer hours by mid-century (Fiorito et al., 2022). Mass adoption of mechanical cooling systems that reject waste heat to already-overheated urban canyons would accelerate this trajectory, creating a feedback loop that undermines the passive cooling potential of surrounding buildings. Ventilative cooling, which relies on airflow through the building envelope rather than on external mechanical plant, avoids these impacts entirely. Where mechanical assistance is needed (fans, small air-handling units), the equipment can typically be accommodated internally, out of sight from the public realm.

Long-term climate resilience. Under projected climate change scenarios, the passive cooling potential of the Mediterranean historic building stock is under increasing pressure. (Fiorito et al., 2022) project that passive natural ventilation alone will be insufficient to maintain thermal comfort for the majority of summer hours in Mediterranean historic urban buildings by mid-century (2050), with the proportion of days with discomfort rising from approximately 32% under the 1951–1970 TMY to 89% by 2080. (Maria Patane et al., 2024) observe that rising nocturnal temperatures are already reducing the diurnal temperature swing that makes night ventilation effective, particularly in urban locations subject to the heat island effect. These findings point toward the need for hybrid strategies that preserve heritage integrity while providing supplementary cooling capacity – whether through low-impact mechanical assist, earth-to-air heat exchange, or other means – as purely passive approaches become progressively less sufficient. For the northern climates the relevant trajectory is different but equally significant. Buildings dimensioned for winter heat retention and with no historical provision for cooling may face increasing summer overheating risk precisely because their envelope and spatial logic offer fewer of the passive resources – deep thermal mass combined with ventilative cooling design, cross-ventilation depth, courtyard geometry – that give Mediterranean heritage buildings their latent adaptive capacity. The Danish evidence (Bugenings et al., 2025) suggests that even modest overheating mitigation in temperate climates requires ventilation strategies that go beyond conventional occupant-operated windows, yet the building typologies and heritage constraints of the northern sites make retrofit more complex than in post-1960 non-listed stock.

It is clear from United Nations Environment Programme (UNEP) and the Global Alliance for Buildings and Construction (GlobalABC) (United Nations Environment Programme, 2026) that the response to this challenge should not default to mechanical cooling. Buildings that rely entirely on mechanical systems become critically dependent on continuous energy supply and functioning equipment, with no passive fallback during system outages or extreme events. A heritage building renovation strategy should maintain a degree of passive resilience even when outdoor conditions exceed the ventilative cooling envelope.

Occupant engagement and adaptive opportunity. Heritage buildings are occupied by users who have direct control over window operation and shading and might have a certain level of freedom to choose in which room to stay. Across multiple studies and climate contexts, occupant behaviour emerges as a decisive modifier of ventilative cooling performance. Three behavioural patterns are particularly well documented. First, the progressive abandonment of traditional nighttime ventilation practices: in Alentejo (Costa-CarrapiçO et al., 2022), nighttime cross-ventilation through door wickets – the most effective cooling strategy available – has been largely discontinued due to security concerns, with occupants shifting to early morning and evening ventilation when outdoor temperatures are still too high for effective convective mass discharge. In Nicosia (Stavroula et al., 2016), only 42% of occupants with purpose-designed stack exhaust openings (arseres) on their street facades actually use them, attributing non-use to lack of awareness of their function or inaccessibility. Second, the adoption of all-day summer window opening: in Catania (Maria Patane et al., 2024), occupants of traditional stone apartments maintain windows open from 08:00 to 23:00 in summer – a behaviour that provides air movement comfort but effectively equalises indoor temperatures between heavyweight traditional and mediumweight modern construction in living spaces, neutralising the thermal mass advantage. These findings collectively confirm that the design and communication of ventilative cooling strategies for historic buildings must address occupant behaviour as explicitly as building physics. Ventilative cooling strategies that rely on occupant interaction – opening windows for cross-ventilation, closing shutters during peak solar hours, using fans to enhance air movement – should be consistent with the use pattern and the level of adaptive opportunity available to occupants. This aligns with the adaptive comfort approach (EN 16798-1) adopted for the case studies in HeriTACE project, which recognises that occupants in naturally ventilated buildings accept and adapt to a wider range of indoor temperatures than those in mechanically conditioned spaces.

3. Ventilative cooling design workflow

The ventilative cooling design workflow described in the following sections follows the cooling ladder ethos embedded in FprCEN/TS 18335. The cooling ladder establishes a hierarchy of design actions in which mechanical cooling is treated as a last resort to address overheating risk, to be considered only after passive and low-energy measures have been systematically explored and exhausted. The sequence proceeds from prevention (reducing heat gains at source through solar control, modulation of internal loads and optimisation of the envelope), through passive dissipation (ventilative cooling using outdoor air as the sole cooling medium), to supplementary free cooling (night ventilation, ground cooling, evaporative strategies), and finally, only where residual overheating persists, to active mechanical cooling.

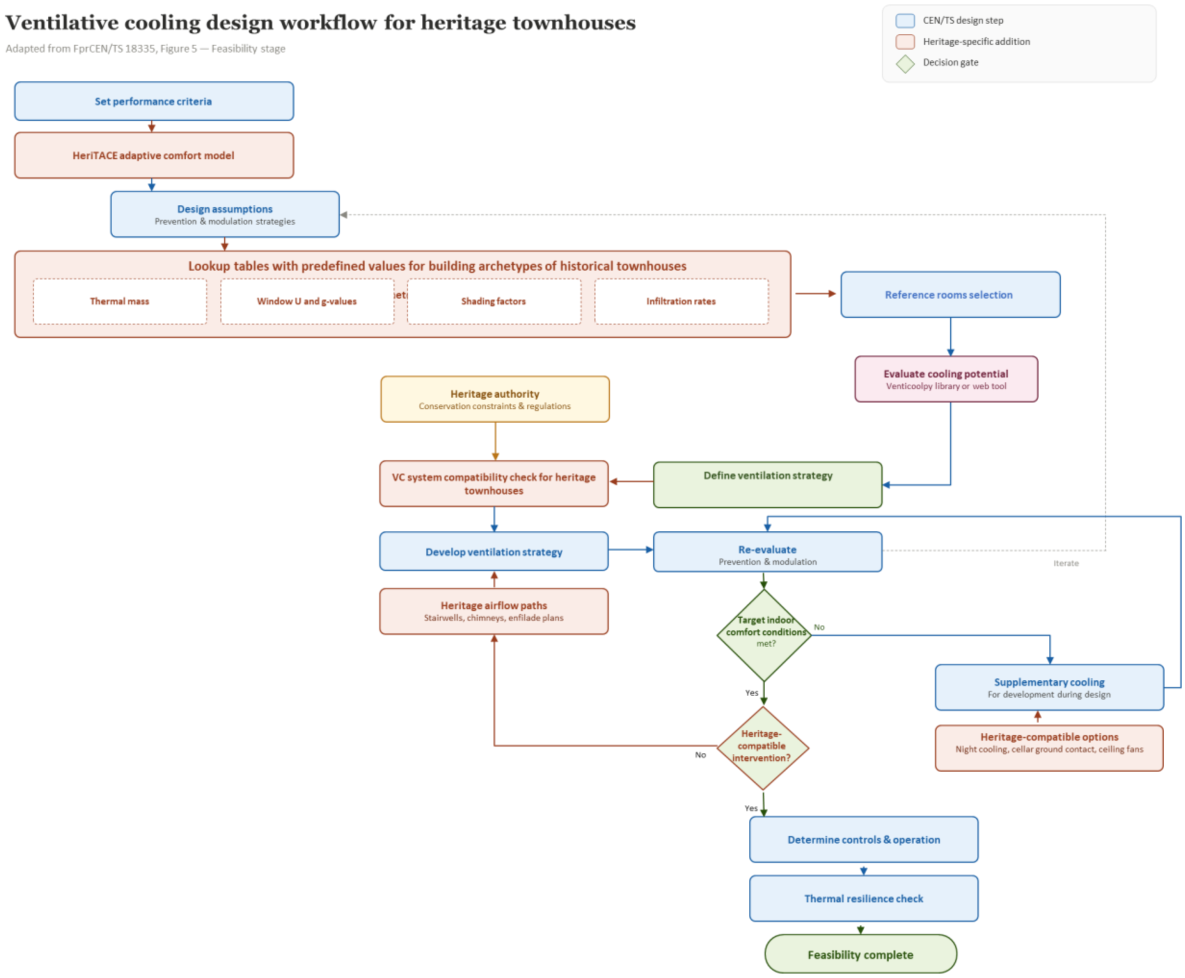

Figure 1. Ventilative cooling design decision flow chart.

3.1 Step 1 — Set performance criteria and requirements

The first step in the workflow requires the designer to define the **target comfort category** according to EN 16798-1. The target comfort category determines two critical parameters that affect the ventilative cooling potential assessment:

- the minimum ventilation airflow rates required for indoor air quality

- the adaptive comfort temperature range against which ventilative cooling performance is evaluated

EN 16798-1 defines four comfort categories:

- Category I (high level of expectation) applies to spaces occupied by very sensitive or fragile persons;
- Category II (normal level of expectation) is the default for new buildings and renovations;
- Category III (moderate level of expectation) is acceptable for existing buildings;
- Category IV (low level of expectation) should only be accepted for limited periods.

Each category sets progressively wider comfort temperature bands and lower minimum ventilation rates.

For heritage residential townhouses, the designer should select the comfort category in consultation with the building owner and, where relevant, the heritage authority. Category II is recommended as the starting point for heritage dwellings undergoing renovation, as it represents the standard expectation for renovated buildings and aligns with the adaptive comfort model's recognition that occupants in naturally ventilated buildings actively manage their thermal environment. Category III may be appropriate for heritage buildings where conservation constraints severely limit the scope of intervention – for instance, where original single-glazed windows must be retained on all façades and no shading devices can be added – and where the building owner accepts a wider range of indoor conditions as the price of preserving the building's authenticity.

The minimum airflow rates for indoor air quality derived from the chosen comfort category determine the direct ventilative cooling effectiveness. In heritage buildings with high infiltration rates, the uncontrolled air leakage through the permeable envelope may already meet or exceed the indoor air quality airflow requirement. Conversely, in renovated heritage buildings where airtightness has been improved through draught-stripping and window replacement (n_{50} reduced from 8–10 to 3–4 1/h), the infiltration contribution to ventilation losses drops and a larger share of the ventilation losses must be provided on purpose, increasing the ventilative cooling capacity.

3.2 Step 2 — Specify design assumptions on prevention and modulation strategies

The second step requires the designer to specify the design assumptions related to cooling prevention and modulation strategies, which are related to: envelope thermal capacity and transmittance, solar shadings, fenestration area and air tightness of the envelope.

For heritage townhouses, a fundamental distinction applies: most of these parameters are not freely chosen by the designer but are fixed by the existing building fabric and its conservation status. The designer's task is to characterise the building as it stands (or as it will be after a defined renovation scenario) rather than to specify new design values.

Solar control is typically provided by existing shading devices – exterior wooden shutters with adjustable slats in Italian townhouses, interior shutters or curtains in Belgian and Nordic buildings – and by the self-shading effect of deep window reveals and urban obstructions from surrounding buildings. Thermal mass modulation is provided by the heavy masonry fabric itself, activated through direct contact between the room air and the exposed interior surfaces.

To support this characterisation at the early feasibility stage, when detailed measurements or survey data may not yet be available, the HeriTACE project has derived a set of lookup tables with predefined parameter values for common heritage townhouse constructions across the four case study climates. These tables draw on the envelope characterisation work reported in Deliverable D2.1 (Klõšeiko et al., 2025), on in-situ measurements performed on the case study buildings (blower door airtightness tests, window thermal transmittance assessments, wall thickness surveys), and on the parametric renovation scenarios defined for each building archetype and heritage value classification.

Table 2 reports the estimated wall characteristics of HeriTACE case studies and the corresponding thermal mass class as reported in Table B.14 of EN ISO 52016-1 standard. Construction classes were assigned based on the thermal mass characteristics of the exterior walls, following the classification defined in EN ISO 52016-1 Table B.14. While these classes are intended to represent the aggregate effective heat capacity of all building constructions within the thermal zone, exterior wall mass was considered the most representative and consistently available parameter across the building typologies analysed.

Table 2. Opaque envelope characteristics for historic townhouses in Mantua, Ghent, Trondheim and Talinn. Source: deliverable 2.1 (Klõšeiko et al., 2025)

City	Archetype	Wall type	Construction	Application	Wall thickness [m]	U-value [W/m²K]	Density [kg/m³]	CEN/TS mass class
Mantua	Gothic lotto / Palazzetto	Solid brick masonry + lime plaster (front façade)			0.44-0.46	0.8-0.9	1200-1800	Heavy
Mantua	Gothic lotto / Palazzetto	Solid brick masonry + lime plaster (backyard façade)			0.32-0.34	1.0-1.2	1200-1800	Heavy
Mantua	Extended building	Solid brick masonry + lime plaster			0.32-0.40	0.9-1.1	1200-1800	Heavy
Mantua	Courtyard building	Solid brick masonry + lime plaster			0.60-0.80	0.7-0.9	1200-1800	Heavy
Ghent	All archetypes	Massive masonry (uninsulated)	Solid brick masonry in lime mortar with interior and exterior lime plaster	Front façade – ground floor	0.4	1.20	1670	Medium-heavy
Ghent	All archetypes			Front façade – upper floor /Back facade	0.3	1.52	1670	Medium-heavy
Ghent	All archetypes			Annex facade	0.2	2.05	1670	Medium-heavy
Ghent	All archetypes	Top boundary	Traditional wooden purlin supported roof with ceramic tiles + 6cm mineral wool insulation between the rafters	Pitched roof		0.71		Light
Ghent	All archetypes		Wooden beam structure finished with lime plaster ceiling and bituminous roofing + 6cm mineral wool insulation	Flat roof		0.56		Light
Ghent	All archetypes	Floor	Wooden floor structure	Basement ceiling		1.22		Light

Ghent	All archetypes		Vaulted hallway floor (cement tiles)	Basement ceiling		1.22		Medium
Trondheim	Townhouse with courtyard	Wall	Timber log with interior and exterior wooden cladding	Front facade	0.10-0.25	0.54-1.2	400-600	Light
Trondheim	Townhouse with courtyard	Wall	Vertical plank framing with interior and exterior wooden cladding	Back facade	0.15	0.80	450-500	Light
Trondheim	Townhouse with courtyard	Floor/ceiling	Wooden beam structure insulated with clay	Ceiling and intermediate floors	0.25	0.95-1.0	700-1000	Medium
Tallinn	Wooden apartment	Horizontal log or double plank			0.15-0.20	0.7-1.0	400-600	Light
Tallinn	Stalinist brick apartment	Brick masonry (with/without cavity)			0.40-0.60	1.0-1.5	1400-1800	Medium-heavy
Tallinn	Both types	Limestone masonry plinth			0.60-0.70	2.0-2.3	1950	Heavy

Table 3 reports the thermal transmittance and g-values for the window systems estimated for the pre-renovation and renovation baselines of the HeriTACE case studies in deliverable 2.1 (Klõšeiko et al., 2025).

Table 3. Thermal transmittance and g-value for the window systems found in HeriTACE case studies. Source: deliverable 2.1 (Klõšeiko et al., 2025)

Country	**City**	**Application**	**Window type**	**Ug [W/m²K]**	**Uf [W/m²K]**	**g-value [-]**
Belgium	Ghent	Front facade	Original single glazed (wooden frame)	5.8	2.0	0.8
Belgium	Ghent	Front facade	Double glazing (contemporary replacement) wood-PVC-alu frame	2.8	2.0-2.5	0.8
Belgium	Ghent	Back facade	Original single glazed (wooden frame)	5.8	2.0	0.8
Belgium	Ghent	Back facade	Double glazing (contemporary replacement) wood-PVC-alu frame	2.8	1.8-2.5	0.8
Belgium	Ghent	Front facade	Original wooden frames with thin double glazing	1.8	2.0	0.6

Belgium	Ghent	Front façade	New harmonizing windows with high performance glazing	1.0	1.8	0.6
Belgium	Ghent	Back facade	Contemporary windows (wood-PVC-alu) with high performance double glazing	1.0	1.8-2.5	0.6
Norway	Trondheim	Townhouse with courtyard	Old wooden frame with single glazing + single casement	1.5		n.a
Norway	Trondheim	Townhouse with courtyard	Standard double glazed window	1.0		n.a
Norway	Trondheim	Townhouse with courtyard	New wooden windows – high performance glazing	0.85		n.a
Estonia	Tallinn	Wooden apartment / Stalinist brick	Original double wooden frame (2× single glass)	5.8	~4.5	0.8
Estonia	Tallinn	Wooden apartment / Stalinist brick	Modernized (single frame, 2-pane IGU)	1.5	~1.8	0.6
Estonia	Tallinn	Wooden apartment	Modern replacement	1	~1.4	0.5
Italy	Mantua	All archetypes	Original single glazed (wooden frame)	5.8	4.8	0.87
Italy	Mantua	Courtyard building	Replica with double glazing	1.2-1.5	1.6-1.8	0.65
Italy	Mantua	All archetypes	Replacement double glazing (early, pre-1990)	2.8	2.6	0.77
Italy	Mantua	All archetypes	Replacement double glazing (post-1990)	1.2-1.5	1.5-1.8	0.65
Italy	Mantua	All archetypes	New harmonized window (renovation)	1	1.4-1.6	0.6

Table 4 reports the shading devices found in HeriTACE case studies and estimated reduction factors of solar radiation.

Table 4. Shading devices found in HeriTACE case studies and estimated reduction factor of solar radiation. Source: deliverable 2.1 (Klõšeiko et al., 2025)

Country	City	Shading device	Position	Fc-value (reduction factor)	Notes
Italy	Mantua	Exterior wooden shutters with slats (closed fins)	Exterior	0.15	Most effective; traditional, found on all buildings
Italy	Mantua	Exterior wooden shutters with slats (open fins, 45°)	Exterior	0.25	Allows some daylight and ventilation
Italy	Mantua	Exterior plain wooden shutters (closed)	Exterior	0.15	Simpler construction, limited light control

Italy	Mantua	Interior wooden shutters (foldable)	Interior	0.65-0.85	Found in 3 of 4 case studies; much less effective than exterior
Belgium	Ghent	Roller blinds (exterior, in casement)	Exterior	0.15-0.25	NOT FROM D2.1. Generic value from EN 13363-1 Table 1 / EN ISO 52022-3.
Belgium	Ghent	Interior curtains/blinds	Interior	0.50-0.75	NOT FROM D2.1. Generic value from EN 13363-1 / DIN 4108-2 Table 7 for interior textile blinds.
Norway	Trondheim	Interior curtains/blinds	Interior	0.50-0.75	Generic value from EN 13363-1 / DIN 4108-2 Table 7 for interior textile blinds. No shading devices described in D2.1 for Norwegian archetype.
Estonia	Tallinn	Interior curtains/blinds	Interior	0.50-0.75	Generic value from EN 13363-1 / DIN 4108-2 Table 7 for interior textile blinds. No shading devices described in D2.1 for Estonian archetypes.

Table 5 reports the airtightness values measured in HeriTACE case studies. The airtightness of the HeriTACE case study buildings was measured according to EN ISO 9972 using the fan pressurisation method (blower door test) at a reference pressure of 50 Pa. Under natural conditions, the pressure differences driving infiltration through a building envelope are generated by wind and stack effects and are typically in the range of 1–4 Pa. The airflow rate measured at the test reference pressure (Δp_r,1 = 50 Pa) is converted to the natural operating pressure (Δp_r,2 ≈ 1 Pa) using the power law pressure scaling equation.

Table 5. Airtightness of the envelope measured in HeriTACE case studies. Source: deliverable 2.1 (Klõšeiko et al., 2025)

Country	**City**	**Archetype**	**Baseline scenario**	**Description**	**n50 [1/h]**	**v@50 Pa[m³/hm²]**	**v@1Pa**	**Source**
Belgium	Ghent	All archetypes	BS1_PB	All original windows, uninsulated roof		16	1.25 m³/hm²	Assumed from measurements + SENVIVV
Belgium	Ghent	All archetypes	BS2_PB	Original front windows, replaced back		14	1.10 m³/hm²	Assumed based on measured cases
Belgium	Ghent	All archetypes	BS3_PB	All windows replaced, no airtightness measures		12	0.94 m³/hm²	Default Flemish EPBD (pre-regulation)

Belgium	Ghent	All archetypes	BS1_RB	Roof renovated + vapour barrier, front glazing upgraded		8	0.63 m^3/hm^2	Based on best measured cases
Belgium	Ghent	All archetypes	BS2_RB, BS3_RB	Comprehensive renovation, all windows replaced, roof insulated		6	0.47 m^3/hm^2	Decorte (2024), deep energy renovation
Norway	Trondheim	Townhouse with courtyard	BS1_PB, BS2_PB	Pre-renovation, original or replaced windows	~10		0.78 m^3/h-m^3	Literature (Brunsell et al. 1980)
Norway	Trondheim	Townhouse with courtyard	BS1_RB	Restricted intervention, preserved windows	~5		0.39 m^3/h-m^3	Estimated
Norway	Trondheim	Townhouse with courtyard	BS2_RB, BS3_RB	Interior/exterior insulation + new windows	~3		0.23 m^3/h-m^3	Estimated
Estonia	Tallinn	Wooden apartment	BS1_PB	Original condition, double wooden frames		10	0.78 m^3/hm^2	Measured (3 buildings)
Estonia	Tallinn	Stalinist brick	BS2_PB	Plastered brick, better inherent airtightness		5.5	0.43 m^3/hm^2	Measured (1 building)
Estonia	Tallinn	Wooden apartment	BS1_RB	Partial interior insulation, mixed windows		9	0.70 m^3/hm^2	Estimated from intervention level
Estonia	Tallinn	Stalinist brick	BS3_RB, BS4_RB	Window replacement, partial insulation		4	0.31 m^3/hm^2	Estimated
Italy	Mantua	All archetypes	BS1_PB	All original windows	7.5		0.59 m^3/h-m^3	Literature + measurements (D'Ambrosio et al.)
Italy	Mantua	All archetypes	BS2.1_PB	Some windows replaced	6		0.47 m^3/h-m^3	Blower door at Montanara (step tests)
Italy	Mantua	All archetypes	BS2.2_PB, BS3_PB	All windows replaced	4.5		0.35 m^3/h-m^3	Based on Leonardo measurement (n50=4.7)
Italy	Mantua	All archetypes	BS0_RB to BS3_RB	Business-as-usual renovation	3		0.24 m^3/h-m^3	Proposed for renovation modelling

3.3 Step 3 — Evaluate the ventilative cooling potential

The ventilative cooling potential is evaluated using the Venticoolpy Python library (Annamaria Belleri, 2026). The Ventilative Cooling Potential Method (VCPM) implements an hourly dynamic thermal balance based on EN ISO 52016-1, using a single-node resistance-capacity model that accounts for envelope transmission, ventilation losses, solar gains, internal gains and the thermal storage effect of the building mass. The method is described and validated in (Annamaria Belleri et al., 2023) and integrated into the FprCEN/TS 18335:2026 "Ventilative cooling systems – Design"[3].

For each hour of the annual climate record, the algorithm classifies the building's thermal state into one of four ventilative cooling modes:

VC Mode 0 – Ventilative cooling is not required. The indoor free-floating temperature is below the lower comfort zone limit or heating is needed.

VC Mode 1 – The indoor temperature is within the comfort zone. Maintaining the minimum ventilation rate for indoor air quality is sufficient to keep the zone comfortable.

VC Mode 2 – Ventilative cooling with increased airflow can potentially restore comfort. The indoor free-floating temperature exceeds the comfort temperature, but the outdoor air is cool enough (with at least 3°C below the indoor temperature) and dry enough (relative humidity below the accepted limit) to provide effective cooling.

VC Mode 3 – Ventilative cooling cannot provide benefit. The outdoor air is too warm (less than 3°C below indoor temperature) or too humid.

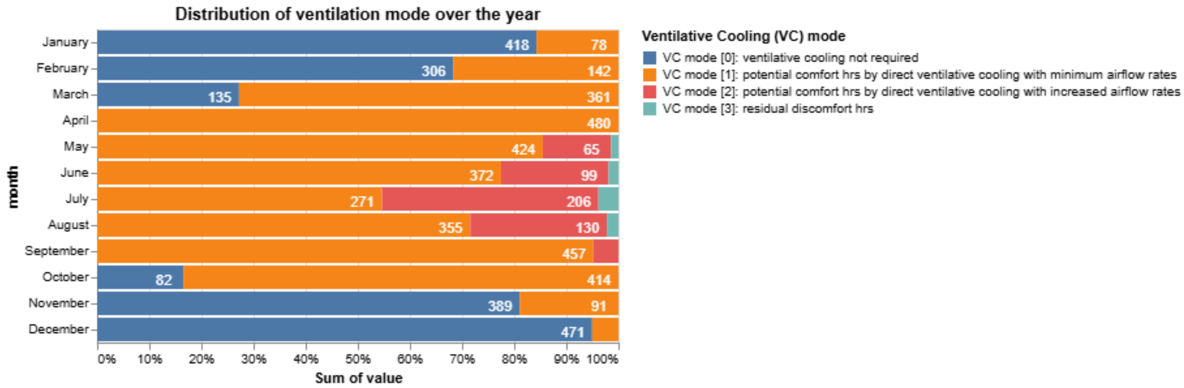

Figure 2. Example of ventilative cooling potential evaluation outcome generated using the venticoolpy library that shows the distribution of VC mode over the total simulated hours per each month.

[3] At the moment of the preparation of this deliverable the document FprCEN/TS 18335:2026 on "Ventilative cooling systems" was out for Formal Vote.

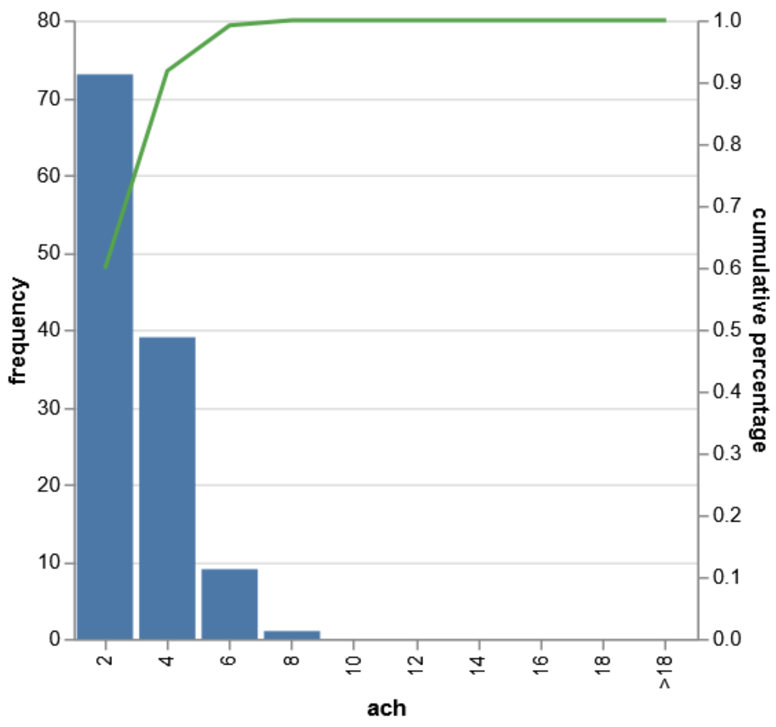

Figure 3. Example of frequency analysis of required ventilation rate for ventilative cooling system to meet comfort requirements. generated using the venticoolpy library that shows the distribution of VC mode over the total simulated hours per each month.

The 3°C critical temperature difference ($\Delta\ \theta$ crit) ensures that ventilative cooling is only classified as effective when there is a meaningful driving force between indoor and outdoor conditions. This threshold filters out marginal hours where the theoretical cooling effect would be negligible in practice.

The key outputs of the VCPM assessment are: the distribution of occupied hours across the four VC modes (monthly and annual); the required ventilation airflow rates at the 80th and 95th percentiles for VC Mode 2 hours; the annual sensible cooling need with and without ventilative cooling (in kWh); and the number of discomfort hours when outdoor conditions are too hot or humid for VC.

These outputs directly inform the subsequent design steps: the VC mode distribution indicates whether ventilative cooling is a viable strategy for the building and climate; the required airflow rates determine which ventilation principle (single-sided, cross, stack, mechanical) is needed; and the residual cooling need after VC quantifies the gap that supplementary measures must fill.

The ventilative cooling potential method assesses a single representative thermal zone. In heritage townhouses, which are typically multi-storey buildings with varying conditions across floors and orientations, the selection of the reference room is a critical step that determines whether the VCPM results are representative of the building's worst-case conditions.

The reference room selected for the evaluation should be the most likely to experience overheating based on designer judgement. Solar exposure (typically a south- or west-facing room on the upper floors), internal gains, glazing-to-wall ratio, presence of shadings are the factors that should be taken into account when selecting the reference room.

In practice, this is often a top-floor street-facing room under the roof, which combines high solar exposure, reduced thermal mass (lighter roof construction compared to masonry walls), and proximity to the roof surface with high thermal transmittance. If the building has multiple distinct conditions (e.g. a ground-floor commercial space and upper-floor residential use), separate VCPM assessments should be conducted for each use zone.

When the VCPM assumptions hold and when they break down for heritage buildings

The Ventilative Cooling Potential Method rests on a set of simplifying assumptions inherited from the EN ISO 52016-1 single-zone resistance-capacity model. These assumptions were developed for conventional modern buildings and their applicability to heritage townhouses is not automatic. Understanding where they hold and where they fail is essential for interpreting the VCPM results correctly and for knowing when a practitioner should move beyond the simplified tool to detailed simulation:

Uniform air temperature within the zone. The VCPM represents the reference room as a single node with a single air temperature. This assumption holds reasonably well for individual rooms in heritage townhouses during the occupied daytime period, when internal doors are open and occupant activity promotes air mixing. It breaks down in two situations common to heritage buildings. First, tall rooms with high ceilings (3.5–4.5m) develop significant thermal stratification, with temperatures near the ceiling 3–5°C above the occupied zone — the VCPM calculates a single average that neither reflects the occupant's thermal experience nor the temperature driving stack ventilation at ceiling level. Second, the single-zone assumption cannot capture the thermal coupling between floors that occurs through the multi-storey stairwell, which acts simultaneously as an airflow path and a thermal buffer connecting zones at different temperatures.

One-dimensional heat conduction through envelope elements. The VCPM models heat transfer through walls as a one-dimensional process using a lumped thermal capacity. This is a reasonable approximation for the large, planar wall surfaces of heritage masonry construction, where the wall thickness (0.3–0.8 m) is much smaller than the wall dimensions in the other two directions. However, heritage buildings contain substantial thermal bridges at window reveals, lintels, cornices and wall-to-floor junctions that create localised two- and three-dimensional heat flow paths. These thermal bridges are calculated in stationary conditions without considering their heat storage contribution. In practice, the deep window reveals typical of heritage construction (15–25 cm depth in solid masonry) function as localised thermal mass elements that absorb solar radiation falling on the reveal surface and re-radiate it into the room over subsequent hours — an effect the VCPM does not capture. The net impact is modest for the annual energy balance but may affect peak temperature predictions during heat wave events.

Lumped thermal capacity. The VCPM uses a single-zone lumped thermal balance model to represent the thermal mass of the entire zone. Italian and Belgian heritage townhouses typically have heavy masonry walls and are well-suited to the lumped-capacity approach because their thermal diffusivity is relatively uniform and their response time aligns with the diurnal cycle. The effectiveness of the wall thermal mass depends on the accessible depth. In heritage buildings, the accessible depth depends on interior surface finishes: exposed brick or lime plaster provides direct thermal coupling to the room air, while renovation interventions such as interior insulation or plasterboard dry-lining can dramatically reduce the accessible mass. Another limitation of this approach is that the single-zone lumped thermal balance model represents the building thermal mass through an equivalent lumped heat capacity and does not explicitly resolve heat storage and delayed transfer within massive envelope components. Consequently, the influence of the distribution and exterior exposure of thermal mass, which is particularly relevant in historic buildings with exposed masonry walls, is only approximated.

Solar radiation distribution assumed uniform. The VCPM distributes solar gains uniformly across the zone floor area. In modern buildings with moderate glazing ratios and light-coloured interiors this is acceptable. In heritage townhouses, solar penetration is often highly non-uniform: deep rooms (5–7 m from window to back wall) with tall narrow windows receive concentrated solar patches on the floor and near-wall surfaces during specific hours, while the back of the room remains in shade. The thermal mass near the window absorbs solar radiation directly, while distant mass does not participate. The VCPM averages this effect, which tends to underestimate peak air temperatures near the window (where the occupant may be seated) and overestimate temperatures at the back of the room.

Shading from surrounding buildings. Heritage townhouses are typically located in dense urban centres where neighbouring buildings create significant shading on lower floors. The VCPM allows the user to specify a shading factor and a solar irradiance threshold for its activation, but it does not model the time-varying geometry of urban obstructions – the shadows cast by a building across a narrow street vary hour by hour and season by season. The current approach applies the shading factor as a binary switch (on/off at the irradiance threshold), which is a crude approximation for the graduated shadow patterns in a street canyon. For upper floors that are fully exposed above the surrounding roofline, the VCPM shading model is adequate. For ground-floor and first-floor rooms in tight medieval streets, a more detailed solar access analysis (e.g. using sunlight hour diagrams or ray-tracing tools) may be warranted. For the case study analysis reported in chapter 4 a simplified method to consider shading from surrounding buildings have been implemented and applied (section 4.3).

Infiltration and ventilation rate. The VCPM adopts the minimum ventilation rate required for indoor air quality purposes, as determined using the perceived air quality method (Method 1) in EN 16798-1:2019. These ventilation rates vary hourly according to the predefined occupancy schedules associated with each building category. Infiltration is not modelled explicitly; instead, it is assumed to be implicitly included within the minimum ventilation rates required to maintain adequate indoor air quality. For the purpose of a simplified ventilative cooling assessment, this assumption is considered acceptable, as the prescribed ventilation rates represent the overall baseline air exchange, regardless of the specific air supply mechanism. However, in building types where infiltration may significantly deviate from typical conditions—such as historic townhouses with particularly high airtightness—neglecting infiltration can influence the accuracy of the estimated cooling potential. To address this, the method allows the minimum ventilation rate to be replaced by a user-defined constant infiltration rate. In such cases, this constant value is applied throughout the year and fully substitutes the minimum ventilation rate derived from the standard.

The 3°C critical temperature difference for ventilative cooling to be effective. The VCPM requires at least a 3°C difference between the indoor free-floating temperature and outdoor air before classifying an hour as VC Mode 2 (ventilative cooling effective). This threshold prevents the calculation to return too high and unrealistic required airflow rates for ventilative cooling. In heritage townhouses with high thermal mass, the indoor temperature swing is dampened by the masonry fabric: the mass absorbs heat during warm hours and releases it during cool hours, maintaining relatively stable indoor conditions. As a result, the indoor-outdoor temperature difference during potential VC hours tends to be larger and more sustained than in lightweight buildings, where indoor temperatures track outdoor conditions more closely. A 3°C driving force applied to a heavy masonry room with large exposed wall surfaces can deliver substantial cooling, because the airflow is simultaneously cooling the air and discharging heat stored in the mass – a dual effect that the threshold does not account for. The 3°C requirement therefore filters out hours that could, in practice, still deliver meaningful cooling benefit in heavyweight heritage construction.

The ventilative cooling potential method provides a practical approach for application during the early stages of renovation design, such as the feasibility stage. It enables preliminary evaluation in the absence of detailed system specifications and leverages the adaptive comfort model to account for occupants' ability to adapt to varying indoor conditions, offering a realistic assessment of comfort levels. the use of more comprehensive dynamic simulation tools is strongly recommended. As building design progresses and more detailed information becomes available, transitioning to advanced modelling platforms ensures greater accuracy, more reliable predictions, and the development of an optimized ventilative cooling strategy.

3.4 Step 4 — Determine ventilative cooling principles and dissipation techniques

The VCPM assessment (Step 3) produces two outputs that can guide the choice of ventilative cooling principle: the required airflow rates for ventilative cooling and the number of hours during which ventilative cooling is effective. These outputs must be matched against the heritage constraints identified through the authority consultation (Step 1) to determine which ventilative cooling principle is both physically capable of delivering the required airflow and practically implementable within the conservation needs of the building.

FprCEN/TS 18335 describes nine ventilative cooling system types – three natural (single-sided, cross and stack ventilation), three mechanical (unidirectional exhaust, unidirectional supply, bidirectional with heat recovery) and three hybrid (fan-assisted natural, stack-plus-wind assisted, dual-mode seasonal switching). Each system relies on a different driving force (buoyancy, wind, mechanical pressure, or a combination) and implies different building fabric requirements. The matrix reported in **Error! Reference source not found.** assesses all nine principles against six heritage constraint categories that recur across the HeriTACE case studies:

- Restrictions on façade intervention
- Availability of roof access for ventilation components
- Usability of the stairwell as a stack path
- Limitations from party walls on cross-ventilation potential
- Level of noise exposure from the street

- Ground-floor security concerns

Each cell provides a traffic-light suitability rating (green = generally compatible, amber = conditionally compatible on a case-by-case basis, red = generally incompatible or impractical) with a brief justification.

The matrix reported in **Error! Reference source not found.** covers the 9 VC strategies (3 natural, 3 mechanical, 3 hybrid) reported in the FprCEN/TS 18335:2026 on ventilative cooling design and assesses them against 6 heritage constraint categories.

Table 6. VC compatibility matrix. Traffic light: ■ Green = generally compatible | ■ yellow = conditionally compatible (case-by-case) | ■ Red = generally incompatible or impractical

VC System Type	Façade intervention restricted	Roof access available	Stairwell usable as stack path	Party walls limit cross-ventilation	High noise exposure (street)	Ground-floor security concerns	Overall Heritage Suitability	Key Heritage Opportunities & Constraints
Single-sided natural VC (one façade, buoyancy/wind)	Works with existing operable windows; no façade modification needed	Not required; ground-level openings sufficient	Not utilised; single-room strategy	Not affected; operates on one façade only	Street-facing windows admit traffic noise when open	Ground-floor windows may need restrictor stays or top-hung opening only	**Limited**	Lowest intervention. Effective only for shallow rooms (depth ≤ 2× ceiling height) and moderate ACH ≤5. Heritage-friendly but capacity-limited.
Cross natural VC (openings on opposite façades)	May require new/enlarged openings on rear façade if only street façade has operable windows and openings in party walls	Not required	Not utilised directly; air path through rooms	Party walls block lateral cross-ventilation in terraced houses; only front-to-back axis available	Street-side windows exposed to noise; rear windows in courtyard typically quieter	Ground-floor front openings need security; rear openings usually less exposed	**Moderate**	High airflow potential (10+ ACH) but requires front-to-back airflow path. Enfilade room layouts and internal doors provide the path in many heritage townhouses. Party walls are the main constraint in terraced configurations.
Stack natural VC (buoyancy-driven, height difference)	Supply through existing windows; extract via roof or chimney requires minimal visible intervention	Roof-level extract point needed (existing chimney, roof hatch or discrete terminal)	Multi-storey stairwell is the primary asset; 8–12 m height gives strong buoyancy drive	Stack operates vertically; party walls can block airflow to the staircase	Street-level supply can use restricted openings; noise path is short	Supply at upper floors; ground floor can be isolated from the stack path	**High**	Best natural match for heritage townhouses. Exploits existing stairwells and chimneys. Independent of wind. Effective for night cooling to discharge masonry thermal mass. Requires clear vertical path from

								lower supply to upper extract.
Unidirectional exhaust mechanical VC	Exhaust fan in roof space or chimney; supply through existing windows/vents. Minimal façade impact.	Ideal: fan mounted in roof space or existing chimney flue, invisible from street	Stairwell/chimney as extract duct; fan boosts natural stack effect	Exhaust operates vertically; not affected by party walls	Controlled exhaust reduces need for large street-facing openings	Mechanical extract creates negative pressure drawing air inward; ground-floor openings can be small/secure	**High**	Heritage-optimal mechanical option. Fan in roof space enhances natural stack through stairwell/chimney. Supply through existing window openings or trickle vents. Low visual impact. Moderate energy use.
Unidirectional supply mechanical VC	Supply duct penetration through façade or roof; visible grilles on façade likely needed	Supply unit can be in roof space but duct distribution through heritage interiors is invasive	Stairwell can distribute supply air downward but against natural buoyancy	Supply operates independently of party walls	Supply air can be filtered and intake located on quiet façade or roof	Positive pressure keeps ground floor secure; air pushed out, not drawn in	**Low**	Problematic for heritage: requires duct distribution through protected interiors and visible intake grilles. Supply against natural stack direction in stairwell is energy-inefficient. Only justified where air filtration (pollution, pollen) is essential.

Bidirectional mechanical VC (supply + exhaust with HR)	Extensive ductwork for both supply and extract; multiple façade/roof penetrations	Central unit in roof space possible but duct runs through all floors	Ductwork partially follows stairwell but concealment in protected interiors is difficult	Independent of party walls	Full control of air path; intake can be on quietest façade; acoustic attenuation possible	Balanced pressure; no security issue from openings	**Low**	Most invasive option. Extensive ductwork incompatible with protected interiors. Suspended ceilings to conceal ducts destroy original ceiling proportions. Only for deep renovation where heritage interiors are already lost.
Fan-assisted natural VC (natural base + fan boost)	Natural openings as base; small fan in chimney/roof as boost. No façade intervention.	Small fan in existing chimney or roof hatch; invisible from street	Fan assists the natural stack in stairwell when buoyancy alone is insufficient	Stack-based; not affected by party walls	Fan boost reduces need for large street openings during high-noise periods	Same as stack: ground floor can use restricted openings	**Very high**	Optimal heritage solution in most cases. Combines the low-intervention advantage of natural stack with the reliability of mechanical assistance. Fan operates only when natural driving forces are insufficient (low wind, small ΔT). Low energy use.
Stack + wind assisted hybrid VC	Cross-ventilation openings on both façades needed for wind component	Roof extract for stack component	Stairwell stack provides the buoyancy component	Wind component requires openings on opposite façades; party walls limit lateral wind capture	Wind-driven component requires street-facing openings; stack component does not	Ground-floor openings needed for wind-driven supply	**Moderate**	Combines stack and wind driving forces. More complex control but higher total driving pressure. Wind component limited by same party-wall constraints as cross-ventilation. Best for detached or end-of-terrace heritage buildings.

Dual-mode hybrid VC (alternating natural/mechanical)	Natural mode uses existing openings; mechanical mode requires ductwork or extract fan	Mechanical extract fan in roof for winter mode; natural openings for summer mode	Stairwell serves natural mode; mechanical mode independent	Each mode operates independently; party walls only limit natural cross-vent mode	Mechanical mode in winter provides filtered air without opening windows; natural mode in summer	Mechanical mode in winter keeps building sealed; natural mode in summer with upper-floor openings	**Moderate-High**	Seasonal switching: mechanical ventilation with heat recovery in winter, natural VC in summer. Good heritage fit if mechanical components are contained in roof space. Higher capital cost but addresses both heating-season IAQ and summer cooling.

3.5 Step 5 — Define and Develop Ventilation Strategy

Having established which VC system types are compatible with the building's heritage constraints, a specific ventilation strategy should be developed. The ventilation strategy is meant here as a detailed plan that defines the path of air within a building, usually based on a distinction between habitable rooms, circulation rooms and service rooms.

In heritage townhouses, the airflow strategy must work with the existing building layout. Common heritage airflow paths include: front-to-back cross-ventilation through rooms connected by internal airflow components (doors, interior openings), stairwell stack ventilation exploiting the full building height from ground-floor entry to roof-level extract, chimney-assisted extract using existing flues that are no longer in active use, and courtyard ventilation in buildings with internal courtyards that provide a sheltered, cooler air source.

The estimated airflow rates achieved by the chosen strategy should be calculated according to EN16798-7 or using an airflow network model when multizone airflows are involved and compared with the required airflow rates from the VCPM assessment (Step 3). If the achievable rates fall short of the 80th percentile requirements, the designer should consider whether additional openings, mechanical assistance, or a hybrid approach can bridge the gap within heritage constraints or move towards step 6 which invites to re-consider other overheating prevention and modulation interventions.

3.6 Step 6 — Re-evaluate prevention and modulation interventions (iterative loop)

If the VCPM results from Step 3 show insufficient ventilative cooling potential – the residual cooling need after VC remains unacceptably high, or VC Mode 3 hours (outdoor air too hot or humid) dominate the cooling season – or the achievable ventilation rates estimated in Step 5 based on the selected ventilation strategy fall short of the 80th percentile requirements the workflow returns to prevention and modulation before resorting to supplementary or active cooling. The question at this stage is not "what cooling system should be added?" but rather "what heritage-compatible interventions can reduce the cooling load so that ventilative cooling, combined with passive measures, comes closer to meeting the comfort target?"

The following interventions are ordered from least to most invasive in terms of heritage impact. The designer should work down the list sequentially, re-running the VCPM after each intervention to assess whether the improvement is sufficient before proceeding to a more invasive measure.

Adjusting internal shading operation. Many heritage buildings in central Europe does not have shading devices. Ensuring that shutters are closed when solar radiation hits the fenestration surface (solar radiation on the vertical surface > 150 W/m²) can substantially reduce solar gains. The effect can be tested directly in Venticoolpy by lowering the shading factor (more radiation blocked) and reducing the shading control setpoint (shading activates at lower irradiance levels).

Improving solar control at secondary glazing level. Where original single-glazed windows are retained for heritage reasons and secondary glazing is added on the interior, the secondary glazing unit offers an opportunity to incorporate solar control coatings or integral blinds without affecting the original window. A low-emissivity coating on the secondary glazing can reduce the solar heat gain coefficient from 0.80 (clear single glass plus clear secondary) to 0.45–0.55, cutting solar gains by 30–40%. This intervention modifies the secondary glazing only – a modern addition that is itself reversible – and leaves the heritage window untouched. However, solar control coatings simultaneously reduce visible light transmittance, and this trade-off must be assessed carefully in the context of heritage rooms. Heritage townhouses typically have deep plans (5–7 m from window to back wall) with moderate window-to-wall ratios (15–30%), meaning that daylight levels at the back of the room may already be marginal. A solar control coating that reduces the g-value from 0.80 to 0.50 will also reduce visible light transmittance by a comparable proportion, causing lighting discomfort. The designer should verify the daylighting impact before specifying a solar control coating, ideally through a simple daylight factor calculation for the room.

Activating exposed thermal mass by removing modern coverings. Modern interventions in heritage interiors sometimes conceal the original thermal mass: suspended plasterboard ceilings hide massive timber-and-masonry floor structures, wall-to-wall carpet insulates solid stone or tile floors, and vinyl wallcovering seals plaster surfaces. Removing these modern additions restores the thermal coupling between the room air and the building mass, increasing the effective thermal capacity available for diurnal heat storage. In VCPM terms, this shifts the construction mass class from "light" or "medium" toward "heavy," reducing peak indoor temperatures and increasing the hours during which ventilative cooling alone can maintain comfort. This intervention is not only thermally beneficial but often desirable from a conservation perspective, as it reveals and restores original heritage finishes.

Improving roof insulation. The roof is typically the weakest element in the heritage envelope from a summer overheating perspective. Original roof constructions – timber rafters with tiles or slates, with no insulation or only minimal loft-floor insulation – have U-values of 2–4 W/m²K and transmit large quantities of solar heat into the top-floor rooms during summer. The HeriTACE case study results consistently show that top-floor street-facing rooms are the most overheating-prone zones in heritage townhouses, and roof insulation is the single most effective intervention for reducing their cooling load. Insulation can be added at the rafter level (between or above the rafters), at the loft floor level where an unoccupied roof void exists, or as a reflective membrane under the tiles to reduce radiant heat transfer. The choice of method depends on the heritage status of the roof structure: where original roof timbers, ceiling decorations or visible rafters are protected, loft-floor insulation or a reflective membrane may be the only permissible options. Roof insulation reduces both the heating demand in winter and the cooling load in summer, making it one of the highest-value interventions in the renovation sequence.

Improving wall insulation – with caution regarding thermal mass. Internal insulation of external walls can reduce transmission heat gains during hot periods and is often part of a broader energy renovation strategy. However, in the context of ventilative cooling, wall insulation presents a critical trade-off: insulation applied on the interior face of a masonry wall (the most common heritage-compatible configuration, since external insulation is generally prohibited on listed façades) decouples the thermal mass from the room air. The insulation layer prevents the room air from "seeing" the massive masonry behind it, eliminating the thermal buffering effect that is one of the principal assets of heritage construction for passive cooling. A 44 cm solid brick wall with original lime plaster functions as heavy thermal mass, absorbing and releasing heat over the diurnal cycle. The same wall with 8 cm of internal insulation and plasterboard becomes thermally invisible to the room – the indoor temperature responds to gains almost as quickly as in a lightweight building, peak temperatures rise, and the effectiveness of night ventilation for mass discharge drops substantially. The designer must therefore assess wall insulation on a case-by-case basis, weighing the winter heating energy saving against the summer cooling penalty. The VCPM assessment should be re-run with the post-insulation construction mass class to verify that the cooling benefit of ventilative cooling has not been undermined by the insulation intervention.

Adding internal thermal mass. Where the existing exposed mass is insufficient – for example in timber-framed buildings classified as "light" mass – additional thermal storage can be introduced through heritage-compatible surface finishes. Lime plaster applied directly to masonry walls (replacing modern gypsum board), clay plaster finishes, and exposed clay tile or stone flooring all add accessible thermal mass without altering the building's character.

Heritage-compatible intervention check. Before implementing any intervention identified in the re-evaluation loop, the designer must verify that it is compatible with the building's heritage value classification and the constraints established by the heritage authority.

If the proposed intervention is heritage-compatible, the workflow proceeds to controls and operation. If it is not, the designer must go to step 7 to determine supplementary cooling strategy or accept the residual overheating risk.

3.7 Step 7 — Determine supplementary free cooling

When the target comfort conditions cannot be met through ventilative cooling and the heritage-compatible passive measures described in step 6, the designer should assess supplementary free cooling options before considering the implementation of active mechanical cooling. A range of supplementary strategies could be evaluated; their compatibility with heritage townhouses varies substantially.

Night cooling – high compatibility. Night cooling extends ventilative cooling into the unoccupied nighttime hours to discharge the heat stored in the building mass during the day, so that the thermal mass starts each morning at a lower temperature and can absorb more heat before indoor conditions become uncomfortable. This is the most effective supplementary strategy for heritage townhouses and the one most naturally aligned with their construction. Heavy masonry walls (44–80 cm solid brick in the Italian archetypes, 28–33 cm in the Belgian) provide a large thermal storage reservoir, and the exposed interior surfaces (lime plaster, exposed brick, stone or tile floors) offer direct thermal coupling between the cool night airflow and the stored heat. Night cooling requires secure ventilation openings that can remain open while occupants sleep – top-hung windows with restrictors, stairwell extract with a locked ground-floor door, or a low-power extract fan in the roof space operating on a timer. These are all heritage-compatible measures with minimal or no visible impact on the building fabric. The designer should verify that the night ventilation path does not create noise transmission issues between dwellings in multi-family heritage buildings, and that security concerns at ground level are addressed through restricted opening sizes or upper-floor-only ventilation paths.

Evaporative cooling. FprCEN/TS 18335 Annex G identifies two evaporative cooling approaches: supply air cooling (directly adiabatic, where outdoor air passes through a wetted medium before entering the building) and exhaust air cooling (indirectly adiabatic, where the exhaust air stream is humidified to cool the supply air through a heat exchanger without adding moisture to it). Both approaches exploit the temperature reduction achievable through the latent heat of water evaporation, and their effectiveness depends directly on the wet-bulb depression – the difference between the dry-bulb and wet-bulb temperatures of the outdoor air. In hot-dry climates with large wet-bulb depressions, evaporative cooling can reduce supply air temperature by 8–12°C; in humid climates the achievable reduction is much smaller. Among the HeriTACE case study locations, Mantova has the highest cooling demand but also high summer humidity (mean July relative humidity around 65%), which limits the achievable temperature reduction to approximately 3–5°C.

Ground cooling via existing cellars or earth contact. Many heritage townhouses have cellars or semi-basement levels with substantial ground contact area. The undisturbed ground temperature at 2–3 m depth approximates the mean annual outdoor air temperature of the location (Kusuda T., Achenbach P.R., 1965). For the HeriTACE case study cities, this corresponds to approximately 8°C in Trondheim, 9°C in Tallinn, 13°C in Ghent and 17°C in Mantova – all significantly below summer outdoor air peak temperatures, providing a useful cool source during the cooling season. Ground cooling can be exploited passively by drawing supply air through the cellar before it enters the occupied floors – the air is pre-cooled by contact with the earth-coupled cellar walls and floor. This strategy requires an airflow path from the cellar to the upper floors (through the stairwell, or through existing service penetrations) and integrates naturally with the stack ventilation principle: cool cellar air is drawn upward through the building by the buoyancy-driven extract at the roof, providing both pre-cooling and the driving airflow in a single passive system. However, not all heritage cellars are suitable: those with standing water, poor drainage, high humidity (above 80% RH sustained), radon risk, or contaminated ground should be excluded or treated with caution.

Ceiling fans and personal comfort devices. Ceiling fans are personalized comfort systems that increase air speed when and where is actually needed. While the heat generated from a human body does not vary, the forced convection accelerates the heat transfer between the parts of the body skin hit by the airflow and the surrounding thermal environment. The generated air movement can provide comfort cooling comparable with a more energy-intensive cooling system source in specific range of temperatures (approximately from 26°C to 32°C). If fans are available, research has shown that the same level of comfort can be achieved also at higher operating temperatures (Edward Arens, Stephen Turner, Hui Zhang, 2009). Based on this, both ASHARE 55 and EN16798-1 state that an operative temperature correction can be applied for buildings equipped with fans or personal systems providing building occupants with personal control over air speed at occupant level. This means that a higher cooling set-point can be used depending on the assumed average air speed, namely 1.2 °C higher for 0.6 m/s, 1.8 °C for 0.9 m/s, and 2.2 °C for 1.2 m/s.

Decision criteria for supplementary or active cooling. After applying the applicable supplementary strategies, the designer should re-run the detailed simulation to quantify the remaining residual cooling need. Active mechanical cooling falls outside the scope of this guide, but the following criteria indicate when it becomes necessary: the residual cooling need after all passive and ventilative measures exceeds 15 kWh/m²·yr; more than 150 occupied hours per year remain in VC Mode 3 with indoor temperatures above the upper comfort limit by more than 3°C; or the building function requires strict temperature control that adaptive comfort cannot accommodate (e.g. archive storage in a heritage building, or a ground-floor commercial use with specific regulatory requirements).

3.8 Step 8 — Determine controls and operation

The control of a ventilative cooling system enables the ventilation airflow rate within the building to be varied in response to changing conditions. Several drivers should be considered in the control of a ventilative cooling system:

- to meet indoor air quality requirements;
- to mitigate high temperatures during the cooling season;
- to achieve low energy use;
- to prevent the ingress of pollutants during outdoor pollution peaks, and
- to protect against weather conditions such as rain or temperature peaks during heat waves.

A key system control decision is whether the operation shall be manual, automated, or a combination of both. For heritage townhouses, where the recommended ventilative cooling principles are stack ventilation through the stairwell and fan-assisted natural ventilation, the control strategy should be **a combination of manual and automated operation** – with a clear division between what occupants manage and what the building should manage autonomously.

Room-level manual controls. At the individual room level, occupants are the natural operators. They open and close windows based on perceived thermal comfort, noise, privacy and security preferences. They operate interior or exterior shutters to manage solar gains and daylight. This adaptive behaviour is the foundation of the adaptive comfort model adopted in the VCPM. Room-level interventions should be intuitive and manual: window handles, shutter latches and ceiling fan switches that occupants can operate according to their preferences.

Building-level automated controls. Ventilation strategies such as stack ventilation through staircases or fan assisted ventilation rely on components that are physically inaccessible to occupants (i.e. window or louvre at the top of a three-storey stairwell, low-power extract fan in the roof space) and must therefore be automated. These components should be operated according to context-specific designed control logics that combine multiple controlling interventions: daytime ventilation (D), night-time ventilation (N), dynamic solar shading (S), interior temperature setpoints (A), and external humidity limits (R).

Daytime mode (D). The automated stairwell extract (motorised window or louvre at the top of the stairwell, or extract fan) activates when the indoor temperature in the reference zone exceeds the cooling setpoint and the indoor-outdoor temperature difference is at least 1°C..

If the outdoor temperature exceeds the indoor temperature, the extract closes to prevent warm air inlet.

Night cooling mode (N). The stairwell extract activates on a time schedule (typically 22:00–07:00) when the indoor temperature at the end of the occupied period exceeds a threshold (e.g. 24°C) and the outdoor temperature is at least 1°C below indoor. The extract runs at maximum capacity during night mode to discharge the masonry thermal mass before the next day. Night ventilation should target a nightly air change rate of at least 2 ACH and ideally 5 ACH. Night mode is disabled when outdoor temperature drops below a minimum threshold (e.g. 16°C) to prevent overcooling the mass.

Dynamic solar shading (S). Automated dynamic solar shading is not commonly applicable to heritage townhouses. Many heritage buildings in Central and Northern Europe have no dedicated exterior shading devices at all, and where traditional shutters exist – as on mediterranean townhouses – they are typically operated manually and cannot be retrofitted with actuators. The shading control strategy for heritage townhouses should therefore primarily rely on occupant operation guided by simple rules: during hot summer periods close shutters or blinds when direct sun hits the window, and reopen them when the façade returns to shade.

Where automated shading is feasible – for instance on non-listed rear façades, on secondary glazing with integral motorised blinds, or on new heritage-compatible shutter systems designed to accept concealed actuators – the following control logic should be applied: shading activates when solar irradiance on the vertical surface of the façade exceeds 150 W/m² and the indoor room temperature exceeds 23°C. The dual condition prevents unnecessary shading on cool sunny days (bright but comfortable) and on hot overcast days (warm but no direct solar gain to block).

External humidity limit (R). External relative humidity is a potential constraint on ventilative cooling. In humid climates. the control strategy should have a humidity override that closes ventilation openings when outdoor relative humidity exceeds 70%. The humidity limit reduces the available ventilative cooling hours but prevents the introduction of moisture that could cause thermal discomfort but also potential damages to heritage buildings interior finishes.

Rain protection override. For heritage townhouses, rain ingress through an open rooflight or stairwell window during an unoccupied period can cause serious damage to protected interiors. A rain sensor connected to the actuator controller should override all other control signals: when rain is detected, all automated openings close immediately and remain closed until the sensor confirms dry conditions for a minimum dwell period (15–30 minutes) to avoid rapid cycling during intermittent rain. Louvre designs that shed rain while maintaining partial airflow (downward-angled blades with drainage channels) can reduce the frequency of full closure events but add visual complexity that may conflict with heritage requirements at visible roof edges.

Extreme heat protection override. During heat wave events, when outdoor air temperatures exceed indoor temperatures for sustained periods, opening windows or activating ventilation components during daytime would introduce hot air into the building and accelerate overheating rather than mitigate it. The control system should include a thermal protection mode that keeps all automated ventilation openings and fan-assisted components closed during daytime hours when outdoor air temperature exceeds the comfort temperature by more than 3°C. In this mode, the building relies entirely on its thermal mass to buffer indoor conditions: the heavy masonry walls absorb internal and transmitted heat gains during the day, maintaining indoor temperatures several degrees below the outdoor peak for 24–48 hours depending on the building's thermal time constant.

3.9 Step 9 — Evaluate thermal resilience

Thermal resilience is defined as "the ability of a building to prepare and plan for, absorb, recover from, and more successfully adapt to disruptive events like heat waves, power outages, etc." (*Resilient Cooling Design Guidelines*, 2024) established four criteria for assessing a building's level of thermal resilience: **vulnerability** (the long-term and short-term thermal performance under historical and projected conditions) represents the overheating exposure risk, **resistance** (the building's ability to react to thermal shocks such as heat waves and foreseeable future weather), **robustness** (the capacity to survive otherwise critical thermal events by adapting performance), and **recoverability** (the extent to which building services and occupants can recover from thermal failure). Ventilative cooling enables renovated buildings to adapt to climate change in terms of resilience, such as recoverability and this is integrated into the 9 key design steps for ventilative cooling system design.

For heritage townhouses – buildings that have already stood for one to three centuries and are expected to remain in use for at least as long again – the resilient design perspective is not theoretical but existential. The ventilative cooling strategy designed today must function under climate conditions that will progressively diverge from the contemporary weather file over the remaining service life of the building.

The thermal resilience of the chosen ventilative cooling strategy should be evaluated at the feasibility stage, before advancing to detailed design. The pre-detailed design check is performed by repeating the VCPM assessment with a future weather scenario. The recommended scenario is RCP8.5, which represents a high-emission pathway and provides a conservative bound on the climate conditions the building may experience. For heritage buildings, where the planning horizon extends well beyond the typical 50-year building service life, using the most severe available scenario is justified – underestimating future warming creates a risk of locking in a ventilative cooling strategy that becomes inadequate within decades.

The resilience check compares the following metrics between the contemporary and future VCPM runs: the change in VC mode distributions (and particularly in VC mode 3 distribution), the **increase in sensible cooling need** both with and without ventilative cooling, the **change in required ventilation airflow rates** at the 80th and 95th percentiles.

Deliverable 5.5 reports recommended indicators to evaluate overheating under present and future climate conditions from multi-zone building energy model results and suggest related risk thresholds. This KPIs can be used at later design stages for the final resilience check.

4. Ventilative cooling potential method application to HeriTACE case studies

This chapter presents a cross-case application of the ventilative cooling potential evaluation across the selected heritage townhouse case studies. The analysis is structured to explicitly highlight how variations in climatic conditions, building fabric characteristics, and heritage-related constraints influence both the achievable cooling potential and the suitability of different ventilation strategies. Input data used for the ventilative cooling potential assessment are synthesised in summary tables. This comparative perspective supports a more robust understanding of the transferability of ventilative cooling solutions and provides an evidence-based foundation for guiding system selection in heritage buildings under varying boundary conditions.

4.1 Case studies

The ventilative cooling (VC) potential assessment method was applied to a set of heritage residential townhouses identified as case studies within the HeriTACE project (Maton et al., 2024). These buildings represent recurrent townhouse archetypes across four European cities – Ghent, Trondheim, Tallinn and Mantova – selected to span different climate and cultural contexts. This range allows the method to be tested under markedly different cooling demands and ventilative cooling opportunities, while keeping the focus on the constraints that are typical of protected historic townhouses. In total, 57 case configurations were assessed.

Error! Reference source not found. summarises the case studies and their renovation scenarios, with the underlying information retrieved from deliverables D2.1 (Klõšeiko et al., 2025) and D5.4 (Himpe et al., 2025a). For each case it reports the building archetype, its heritage value class (HV_I to HV_III) (Buda et al., 2025), the building function, the assumed comfort requirements (heating and, where relevant, cooling setpoints, including night setbacks), the envelope renovation scenario, and the associated technical system. The scenarios are organised into pre-renovation (PB) and renovation baseline (RB) types: the pre-renovation scenario describe the buildings in their present state, while the renovation baseline scenario corresponds to a renovation according to the common practice today.

Error! Reference source not found. reports the input parameters used to compute the ventilative cooling potential for each case. These comprise the climate, the building typology, the fenestration area and orientation, the comfort category, the thermal transmittance of the opaque (u_value_opaque) and transparent (u_value_fen) envelope components, the construction (thermal) mass class, the solar energy transmittance of the glazing system (g_value_glazing_sys), the shading control setpoint and shading factor, the minimum required ventilation rate (my_min_req_vent_rate), and the heating balance temperature (ti_hsb). Together with the qualitative descriptions in **Error! Reference source not found.**, these parameters define the boundary conditions of the VC potential calculation and make the assessment reproducible for each configuration.

Table 7. HeriTACE case studies and renovation scenario. Data are retrieved from D2.1 and D5.1.

City	Archetype	Heritage value	building function	comfort	Building envelope renovation scenario	Technical system
Ghent	middle-class townhouse	HV_I	single-family house	20 °C during the day, with a night setback to 15 °C	BS1_PB	heating only - no mechanical ventilation - no cooling
Ghent	middle-class townhouse	HV_II-III	single-family house	20 °C during the day, with a night setback to 15 °C	BS2_PB	heating only - no mechanical ventilation - no cooling
Ghent	middle-class townhouse	HV_II-III	single-family house	20 °C during the day, with a night setback to 15 °C	BS3_PB	heating only - no mechanical ventilation - no cooling
Ghent	middle-class townhouse	HV_I	single-family house	20 °C during the day, with a night setback to 15 °C	BS1_RB	heating + MVHR
Ghent	middle-class townhouse	HV_II-III	single-family house	20 °C during the day, with a night setback to 15 °C	BS2_RB	heating + MVHR
Ghent	middle-class townhouse	HV_III	single-family house	20 °C during the day, with a night setback to 15 °C	BS3_RB	heating + MVHR
Ghent	middle-class townhouse	HV_III	multi-family house	20 °C during the day, with a night setback to 15 °C	BS3_RB	heating + MVHR
Ghent	modest house	HV_I	single-family house	20 °C during the day, with a night setback to 15 °C	BS1_PB	heating only - no mechanical ventilation - no cooling
Ghent	modest house	HV_II-III	single-family house	20 °C during the day, with a night setback to 15 °C	BS2_PB	heating only - no mechanical ventilation - no cooling
Ghent	modest house	HV_II-III	single-family house	20 °C during the day, with a night setback to 15 °C	BS3_PB	heating only - no mechanical ventilation - no cooling
Ghent	modest house	HV_I	single-family house	20 °C during the day, with a night setback to 15 °C	BS1_RB	heating + MVHR
Ghent	modest house	HV_II-III	single-family house	20 °C during the day, with a night setback to 15 °C	BS2_RB	heating + MVHR
Ghent	modest house	HV_II-III	single-family house	20 °C during the day, with a night setback to 15 °C	BS3_RB	heating + MVHR
Ghent	private mansion	HV_I	single-family house	20 °C during the day, with a night setback to 15 °C	BS1_PB	heating only - no mechanical ventilation - no cooling
Ghent	private mansion	HV_II	single-family house	20 °C during the day, with a night setback to 15 °C	BS2_PB	heating only - no mechanical ventilation - no cooling
Ghent	private mansion	HV_I	single-family house	20 °C during the day, with a night setback to 15 °C	BS1_RB	heating + MVHR
Ghent	private mansion	HV_II	single-family house	20 °C during the day, with a night setback to 15 °C	BS2_RB	heating + MVHR
Ghent	private mansion	HV_I	multi-family house	20 °C during the day, with a night setback to 15 °C	BS1_RB	heating + MVHR

Ghent	private mansion	HV_II	multi-family house	20 °C during the day, with a night setback to 15 °C	BS2_RB	heating + MVHR
Ghent	private mansion	HV_I	office	20 °C during the day, with a night setback to 15 °C	BS1_RB	heating + MVHR
Ghent	private mansion	HV_II	office	20 °C during the day, with a night setback to 15 °C	BS2_RB	heating + MVHR
Ghent	multi-family townhouse	HV_II	multi-family house	20 °C during the day, with a night setback to 15 °C	BS2_PB	heating only - no mechanical ventilation - no cooling
Ghent	multi-family townhouse	HV_II	multi-family house	20 °C during the day, with a night setback to 15 °C	BS2_RB	heating + MVHR
Trond heim	townhouse with courtyard	HV_II	multi-family house	living room 21°C - setback 17°C /bedroom 16°C -setback 8°C	BS1_PB	nat. ventilation - extraction in bathrooms
Trond heim	townhouse with courtyard	HV_III	multi-family house	living room 21°C - setback 17°C /bedroom 16°C -setback 8°C	BS2_PB	nat. ventilation - extraction in bathrooms
Trond heim	townhouse with courtyard	HV_II	multi-family house	living room 21°C - setback 17°C /bedroom 16°C -setback 8°C	BS1_RB	nat. ventilation - extraction in bathrooms
Trond heim	townhouse with courtyard	HV_III	multi-family house	living room 21°C - setback 17°C /bedroom 16°C -setback 8°C	BS2_RB	nat. ventilation - extraction in bathrooms
Trond heim	townhouse with courtyard	HV_III	multi-family house	living room 21°C - setback 17°C /bedroom 16°C -setback 8°C	BS3_RB	nat. ventilation - extraction in bathrooms
Talinn	wooden apartment building	HV_II-III	apartment building	21°C in all rooms	BS1_PB	nat. ventilation - no cooling
Talinn	stalinist style brick apartment building	HV_II-III	apartment building	21°C in all rooms	BS2_PB	nat. ventilation - no cooling
Talinn	wooden apartment building	HV_I	apartment building	21°C in all rooms	BS1_RB	mechanical exhaust ventilation
Talinn	wooden apartment building	HV_II	apartment building	21°C in all rooms	BS2_RB	mechanical exhaust ventilation
Talinn	stalinist style brick apartment building	HV_I	apartment building	21°C in all rooms	BS3_RB	mechanical exhaust ventilation
Talinn	stalinist style brick apartment building	HV_II	apartment building	21°C in all rooms	BS4_RB	mechanical exhaust ventilation
Manto va	Gothic lotto	HV_I	multi-family house	heating 20°C for 14 hours/day - cooling 26°C	BS1_PB	no mechanical ventilation - window opening - no cooling
Manto va	Gothic lotto	HV_II	multi-family house	heating 20°C for 14 hours/day - cooling 26°C	BS2.1_PB	no mechanical ventilation - window opening - no cooling
Manto va	Gothic lotto	HV_II	multi-family house	heating 20°C for 14 hours/day - cooling 26°C	BS2.2_PB	no mechanical ventilation - window opening - no cooling
Manto va	Gothic lotto	HV_III	multi-family house	heating 20°C for 14 hours/day - cooling 26°C	BS3_PB	no mechanical ventilation - window opening - no cooling

Mantova	Gothic lotto	HV_I	multi-family house	heating 20°C for 14 hours/day - cooling 26°C	BS0_RB	no mechanical ventilation - window opening - active cooling
Mantova	Gothic lotto	HV_II	multi-family house	heating 20°C for 14 hours/day - cooling 26°C	BS1_RB	no mechanical ventilation - window opening - active cooling
Mantova	Gothic lotto	HV_II	multi-family house	heating 20°C for 14 hours/day - cooling 26°C	BS2_RB	no mechanical ventilation - window opening - active cooling
Mantova	Gothic lotto	HV_III	multi-family house	heating 20°C for 14 hours/day - cooling 26°C	BS3_RB	staircase exploited as a wind tower - active cooling
Mantova	extended building	HV_I	multi-family house/youth center	heating 20°C for 14 hours/day - cooling 26°C	BS1_PB	no mechanical ventilation - window opening - no cooling
Mantova	extended building	HV_II	multi-family house/youth center	heating 20°C for 14 hours/day - cooling 26°C	BS2.1_PB	no mechanical ventilation - window opening - no cooling
Mantova	extended building	HV_III	multi-family house/youth center	heating 20°C for 14 hours/day - cooling 26°C	BS3_PB	no mechanical ventilation - window opening - no cooling
Mantova	extended building	HV_I	multi-family house/youth center	heating 20°C for 14 hours/day - cooling 26°C	BS0_RB	no mechanical ventilation - window opening - active cooling
Mantova	extended building	HV_I-II	multi-family house/youth center	heating 20°C for 14 hours/day - cooling 26°C	BS1_RB	no mechanical ventilation - window opening - active cooling
Mantova	extended building	HV_II-III	multi-family house/youth center	heating 20°C for 14 hours/day - cooling 26°C	BS2_RB	no mechanical ventilation - window opening - active cooling
Mantova	extended building	HV_III	multi-family house/youth center	heating 20°C for 14 hours/day - cooling 26°C	BS3_RB	staircase exploited as a wind tower - active cooling
Mantova	courtyard building	HV_I	housing/offices/archives	heating 20°C for 14 hours/day - cooling 26°C	BS1_PB	no mechanical ventilation - window opening - no cooling
Mantova	courtyard building	HV_I_II	housing/offices/archives	heating 20°C for 14 hours/day - cooling 26°C	BS2.1_PB	no mechanical ventilation - window opening - no cooling
Mantova	courtyard building	HV_II_III	housing/offices/archives	heating 20°C for 14 hours/day - cooling 26°C	BS2.2_PB	no mechanical ventilation - window opening - no cooling
Mantova	courtyard building	HV_III	housing/offices/archives	heating 20°C for 14 hours/day - cooling 26°C	BS3_PB	no mechanical ventilation - window opening - no cooling
Mantova	courtyard building	HV_I	housing/offices/archives	heating 20°C for 14 hours/day - cooling 26°C	BS0_RB	no mechanical ventilation - window opening - active cooling

Mantova	courtyard building	HV_I_II	housing/offices/archives	heating 20°C for 14 hours/day - cooling 26°C	BS1_RB	no mechanical ventilation - window opening - active cooling
Mantova	courtyard building	HV_II_III	housing/offices/archives	heating 20°C for 14 hours/day - cooling 26°C	BS2_RB	no mechanical ventilation - window opening - active cooling
Mantova	courtyard building	HV_III	housing/offices/archives	heating 20°C for 14 hours/day - cooling 26°C	BS3_RB	staircase exploited as a wind tower - active cooling

Table 8. Parameters considered for the calculation of the ventilative cooling potential

Climate	**Building typology**	**fenestration_area**	**fenestration_orientation**	**comfort_requirements**	**u_value_opaque**	**u_value_fen**	**construction_mass**	**g_value_glazing_sys**	**shading_control_setpoint**	**shading_factor**	**my_min_req_vent_rate**	**ti_hsb**
Gent	Detached house	6.84	SW	category II	1.52	5.8	light	0.8	Na	0	22.65	15
Gent	Detached house	6.84	SW	category II	1.52	5.8	light	0.8	Na	0	19.82	15
Gent	Detached house	6.84	SW	category II	1.52	2.8	light	0.6	Na	0	16.99	15
Gent	Detached house	6.84	SW	category II	1.2	2	light	0.6	Na	0	21.6	15
Gent	Detached house	6.84	SW	category II	1.2	1.8	light	0.6	Na	0	21.6	15
Gent	Detached house	6.84	SW	category II	0.35	1.8	light	0.6	Na	0	21.6	15
Gent	Apartment building	6.84	SW	category II	0.35	1.8	light	0.6	Na	0	21.6	15
Gent	Detached house	6.84	SW	category II	1.52	5.8	light	0.8	Na	0	22.65	15
Gent	Detached house	6.84	SW	category II	1.52	5.8	light	0.8	Na	0	19.82	15
Gent	Detached house	6.84	SW	category II	1.52	2.8	light	0.6	Na	0	16.99	15
Gent	Detached house	6.84	SW	category II	1.2	2	light	0.6	Na	0	21.6	15
Gent	Detached house	6.84	SW	category II	1.2	1.8	light	0.6	Na	0	21.6	15
Gent	Detached house	6.84	SW	category II	0.35	1.8	light	0.6	Na	0	21.6	15

Gent	Detached house	6.84	SW	category II	1.52	5.8	light	0.8	Na	0	22.65	15
Gent	Detached house	6.84	SW	category II	1.52	5.8	light	0.8	Na	0	19.82	15
Gent	Detached house	6.84	SW	category II	1.2	2	light	0.6	Na	0	21.6	15
Gent	Detached house	6.84	SW	category II	1.2	1.8	light	0.6	Na	0	21.6	15
Gent	Apartment building	6.84	SW	category II	1.2	2	light	0.6	Na	0	21.6	15
Gent	Apartment building	6.84	SW	category II	1.2	1.8	light	0.6	Na	0	21.6	15
Gent	Office	6.84	SW	category II	1.2	2	light	0.6	Na	0	21.6	15
Gent	Office	6.84	SW	category II	1.2	1.8	light	0.6	Na	0	21.6	15
Gent	Apartment building	6.84	SW	category II	1.52	5.8	light	0.8	Na	0	19.82	15
Gent	Apartment building	6.84	SW	category II	1.2	5.8	light	0.6	Na	0	21.6	15
Trondheim	Apartment building	1.26	SW	category I	1.2	1.5	light	0.8	Na	0	113.25	17
Trondheim	Apartment building	1.26	SW	category I	1.2	1	light	0.6	Na	0	113.25	17
Trondheim	Apartment building	1.26	SW	category I	0.54	1	light	0.8	Na	0	56.62	17
Trondheim	Apartment building	1.26	SW	category I	0.3	1	light	0.6	Na	0	33.97	17
Trondheim	Apartment building	1.26	SW	category I	0.3	0.65	light	0.6	Na	0	16.99	17
Tallin	Apartment building	1.44	SW	category I	0.75	2.9	medium	0.6	Na	0	14.16	17
Tallin	Apartment building	1.44	SW	category I	1.5	2.9	medium	0.6	Na	0	7.79	17
Tallin	Apartment building	1.44	SW	category I	0.4	1.2	medium	0.6	Na	0	86.4	17
Tallin	Apartment building	1.44	SW	category I	0.3	0.9	medium	0.6	Na	0	86.4	17
Tallin	Apartment building	1.44	SW	category I	1.5	0.9	medium	0.6	Na	0	86.4	17

Tallin	Apartment building	1.44	SW	category I	0.45	0.9	medium	0.6	Na	0	86.4	17
Mantua	Apartment building	3.78	SW	category II	0.9	4.8	heavy	0.87	200	0.75	84.94	15
Mantua	Apartment building	3.78	SW	category II	0.9	4.8	heavy	0.77	200	0.75	67.95	15
Mantua	Apartment building	3.78	SW	category II	0.8	2.6	heavy	0.7	200	0.75	50.96	15
Mantua	Apartment building	3.78	SW	category II	0.8	1.8	heavy	0.65	200	0.75	50.96	15
Mantua	Apartment building	3.78	SW	category II	0.9	4.8	heavy	0.87	200	0.75	50.96	15
Mantua	Apartment building	3.78	SW	category II	0.9	1.5	heavy	0.65	200	0.75	33.97	15
Mantua	Apartment building	3.78	SW	category II	0.8	1.5	heavy	0.65	200	0.75	33.97	15
Mantua	Apartment building	3.78	SW	category II	0.42	1.5	heavy	0.65	200	0.75	33.97	15
Mantua	Apartment building	3.96	SW	category II	0.9	4.8	heavy	0.87	200	0.75	84.94	15
Mantua	Apartment building	3.96	SW	category II	0.9	4.8	heavy	0.77	200	0.75	67.95	15
Mantua	Apartment building	3.96	SW	category II	0.8	1.8	heavy	0.65	200	0.75	50.96	15
Mantua	Apartment building	3.96	SW	category II	0.9	4.8	heavy	0.87	200	0.75	50.96	15
Mantua	Apartment building	3.96	SW	category II	0.9	1.5	heavy	0.65	200	0.75	33.97	15
Mantua	Apartment building	3.96	SW	category II	0.8	1.5	heavy	0.65	200	0.75	33.97	15
Mantua	Apartment building	3.96	SW	category II	0.42	1.5	heavy	0.65	200	0.75	33.97	15
Mantua	Detached house	4.32	SW	category II	0.9	4.8	heavy	0.87	200	0.75	84.94	15
Mantua	Detached house	4.32	SW	category II	0.9	4.8	heavy	0.77	200	0.75	67.95	15
Mantua	Detached house	4.32	SW	category II	0.8	2.6	heavy	0.7	200	0.75	67.95	15
Mantua	Detached house	4.32	SW	category II	0.8	1.8	heavy	0.65	200	0.75	50.96	15

Mantua	Detached house	4.32	SW	category II	0.9	4.8	heavy	0.87	200	0.75	50.96	15
Mantua	Detached house	4.32	SW	category II	0.9	1.5	heavy	0.65	200	0.75	33.97	15
Mantua	Detached house	4.32	SW	category II	0.8	1.5	heavy	0.65	200	0.75	33.97	15
Mantua	Detached house	4.32	SW	category II	0.42	1.5	heavy	0.65	200	0.75	33.97	15

4.2 Weather data

Weather data, representing present and future climate, used for the assessment of ventilative cooling potential in the case studies were generated using Meteonorm v8.

For present climate conditions, extreme meteorological years are derived from a multi-years time series (2001-2020 is the reference period) by extracting representative extreme conditions in order to have a design reference meteorological year that emphasise extremes.

Future weather data are developed based on IPCC climate projections under the RCP 8.5 high emission scenario for 2050.

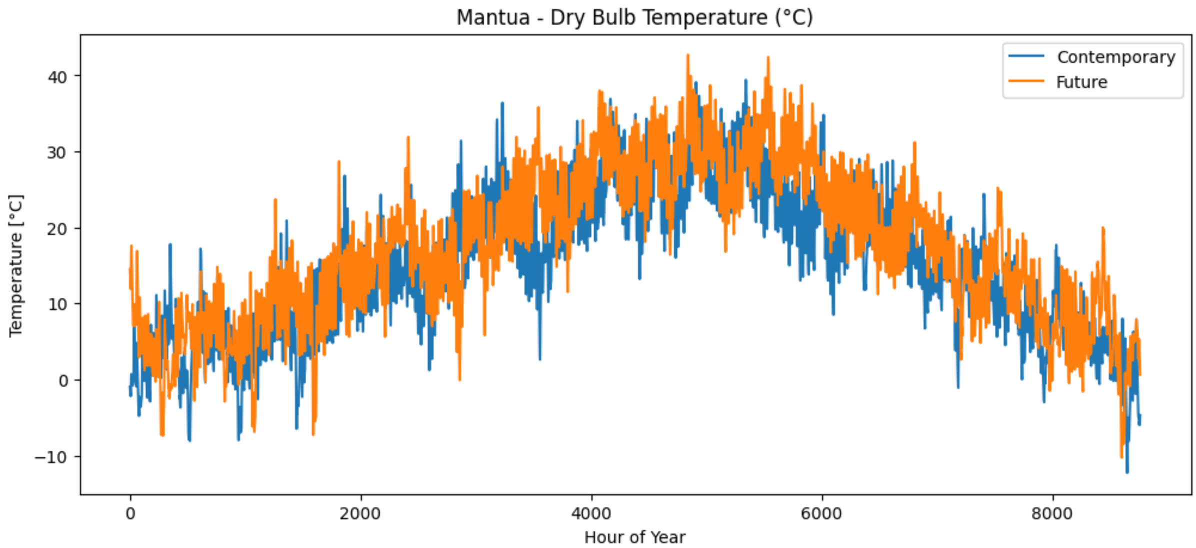

Figure 4. Temperature series of present and future weather conditions in Mantua generated by Metonorm v8.

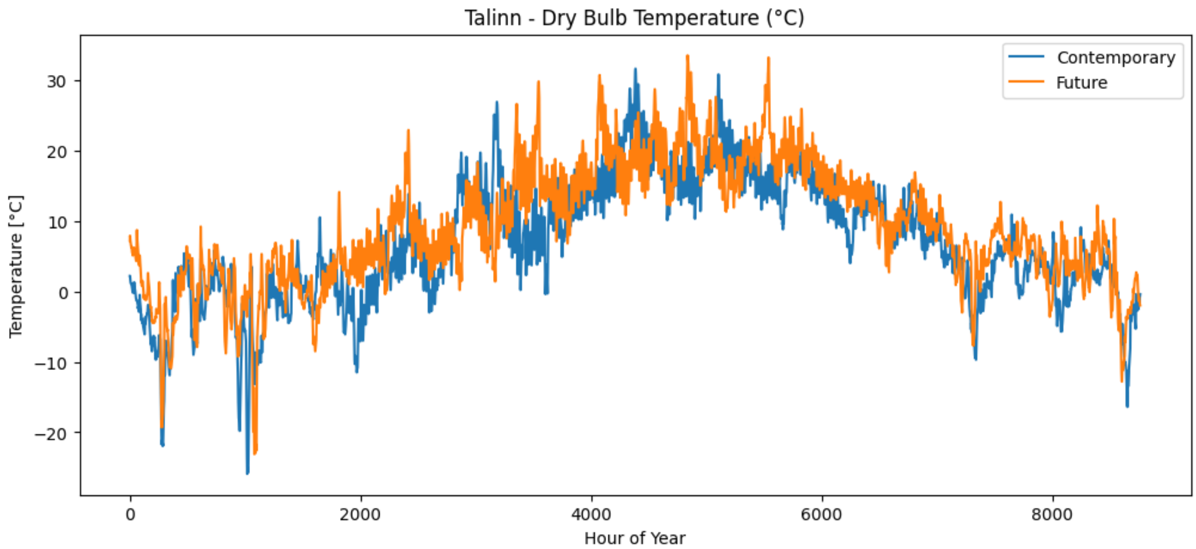

Figure 5. Temperature series of present and future weather conditions in Talinn generated by Metonorm v8.

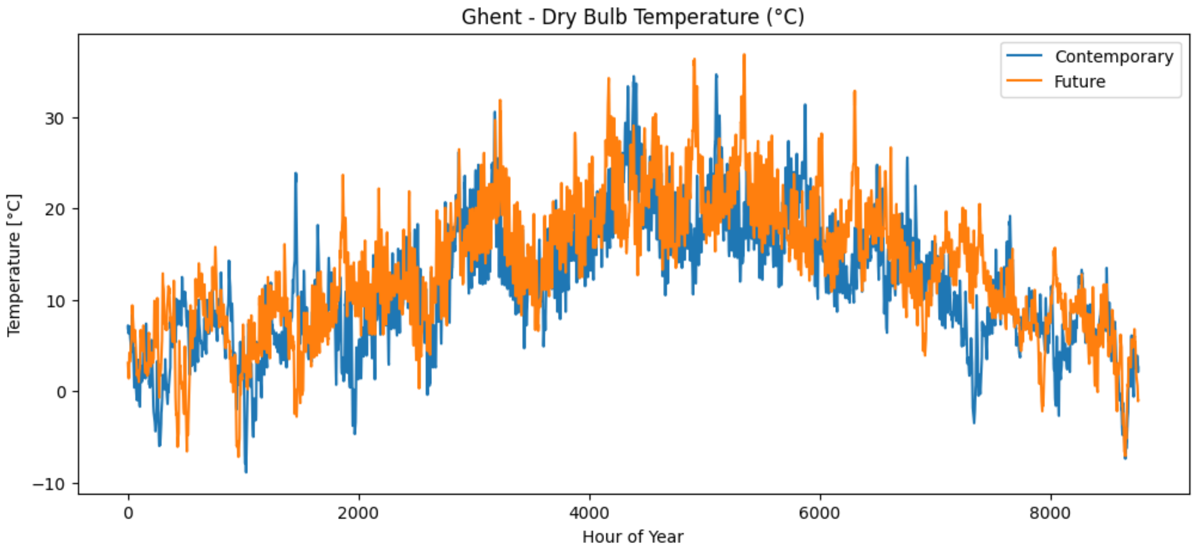

Figure 6. Temperature series of present and future weather conditions in Ghent generated by Metonorm v8.

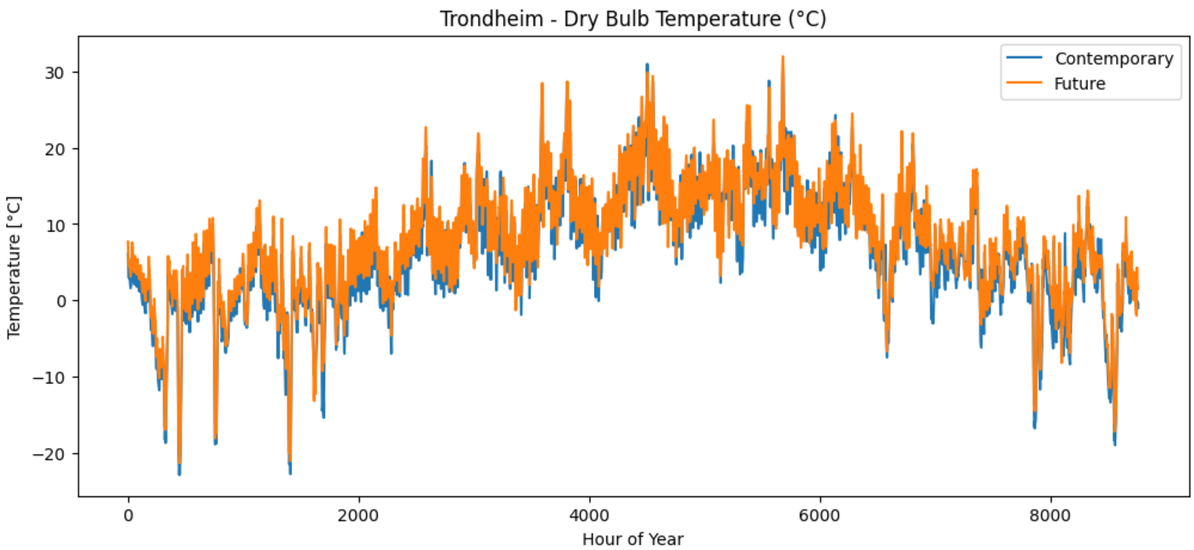

Figure 7. Temperature series of present and future weather conditions in Trondheim generated by Metonorm v8.

4.3 External obstructions from surrounding buildings

In the case of historic townhouses we can assume that the opposing building typically spans the entire field of view of the façade (continuous street wall).

The effect of solar obstructions from surrounding buildings is accounted for using a simplified urban canyon model suited to the continuous street-wall geometry of historic townhouses[4]. The method requires three geometric inputs:

H_obs – height of the opposing building (m)

[4] The urban canyon shading model described above has been developed and tested as a local extension to the venticoolpy library but has not yet been merged into the public repository (https://github.com/EURAC-EEBgroup/venticoolpy). The implementation is available from the authors upon request.

H_ref – height of the reference point on your façade (e.g. window centre) (m)

D – street width, i.e. horizontal distance between façades (m)

From these, a vertical obstruction angle is computed, and at each simulation hour the solar position is evaluated to determine whether the direct beam component is blocked by the opposing roofline. The urban canyon shading correction is applied at the irradiance pre-processing stage, before solar gains enter the hourly thermal balance of the Ventilative Cooling Potential method. The starting point is hourly weather data from an EPW file, from which global horizontal, direct normal, and diffuse horizontal irradiance components are extracted. These are transposed onto the vertical façade plane using the Perez anisotropic sky model (Perez et al., 1987), yielding unobstructed hourly beam and diffuse irradiance on the façade surface. The shading model then modifies these two components separately, following the urban canyon geometry framework established by (Oke, 1988). At each simulation hour, the solar altitude and azimuth are compared against the effective obstruction angle – which accounts for the canyon geometry and the sun's azimuth relative to the façade normal – to produce a binary direct shading factor: the beam component is either fully transmitted or fully blocked. The diffuse component is reduced by a constant Sky View Factor derived from the obstruction angle, representing the fraction of the sky hemisphere visible from the façade above the opposing roofline (Littlefair, 2001).

Accounting for exterior obstructions is particularly important when assessing the ventilative cooling potential of historic townhouses. These buildings are typically arranged along narrow streets with continuous façade-to-façade distances of 6–15 m and building heights of 12–20 m, producing height-to-width ratios well above unity and obstruction angles that can exceed 60° (Strømann-Andersen & Sattrup, 2011). Under such conditions, a significant portion of the sky dome is occluded by the opposing building, reducing diffuse irradiance by 30–50%, while direct beam radiation can be blocked entirely for several hours per day, particularly in winter and for lower-floor windows (Compagnon, 2004). In heritage contexts, where interventions on the building envelope are constrained by conservation requirements and external shading devices are often not permissible (Webb, 2017), the mutual shading provided by the urban fabric itself may represent the primary form of solar control available. Capturing this effect in the ventilative cooling potential evaluation is therefore essential for a realistic assessment of both overheating risk and the potential of ventilative cooling as a low-impact adaptation strategy for historic residential buildings.

4.4 Ventilative cooling potential of case studies

The ventilative cooling potential method was applied to 57 parametric cases across the four European heritage townhouse locations – Trondheim (Norway), Tallinn (Estonia), Ghent (Belgium) and Mantova (Italy). Each location includes multiple building archetypes, each assessed at several renovation scenarios ranging from the pre-renovation baseline (current envelope condition) to heritage-compatible renovation. All cases were evaluated under both a contemporary weather file and a future climate scenario (RCP8.5), producing a total of 114 annual simulations. The results are presented in terms of sensible cooling need per unit floor area (kWh/m²·yr), ventilative cooling reduction (the percentage of cooling need eliminated by ventilative cooling), required ventilation airflow rates at the 80th and 95th percentiles (ACH), and the number of discomfort hours when outdoor conditions are too hot or humid for ventilative cooling to be effective.

Figure 1 presents all 114 cases on a single axis, showing for each case the total sensible cooling need without ventilative cooling, decomposed into the VC saving (the darker segment, representing the cooling removed by ventilative cooling) and the residual cooling need (the lighter segment, representing the load that remains after VC). Figure 2 presents the required ventilation rates at the 80th and 95th percentiles, indicating the airflow capacity that the ventilation strategy must deliver to realise the assessed VC potential.

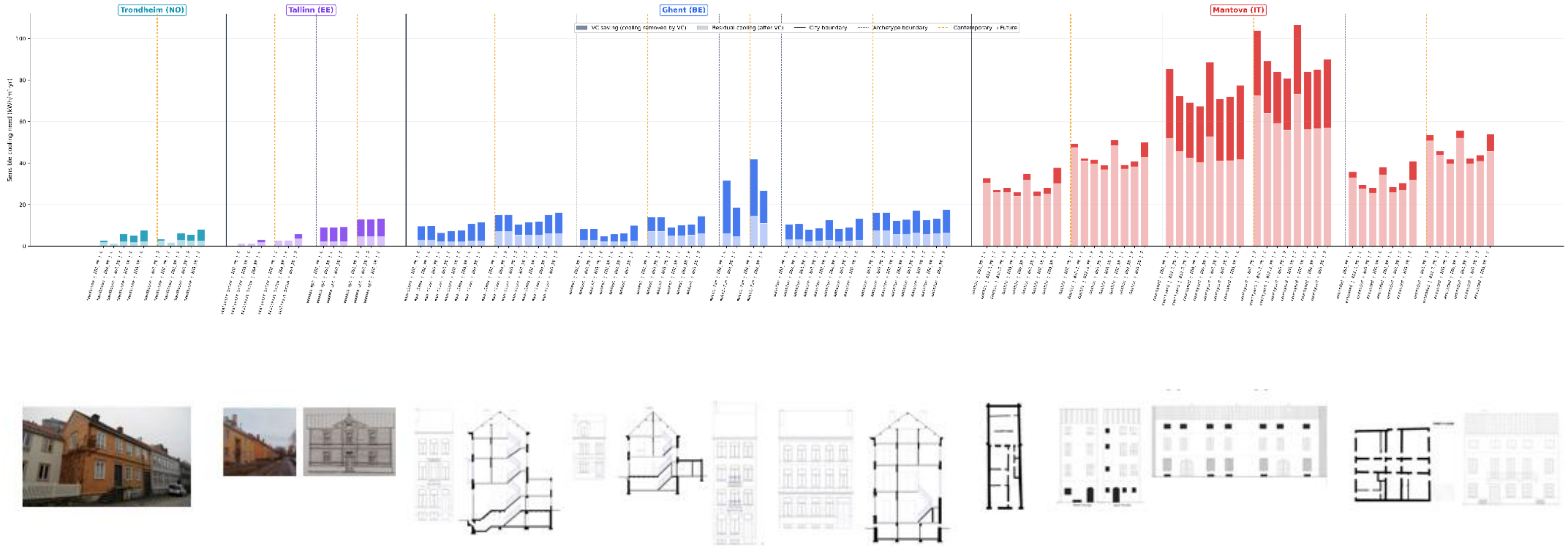

Figure 8. Cooling need reduction due to ventilative cooling in all the case studies for present and future climate scenario.

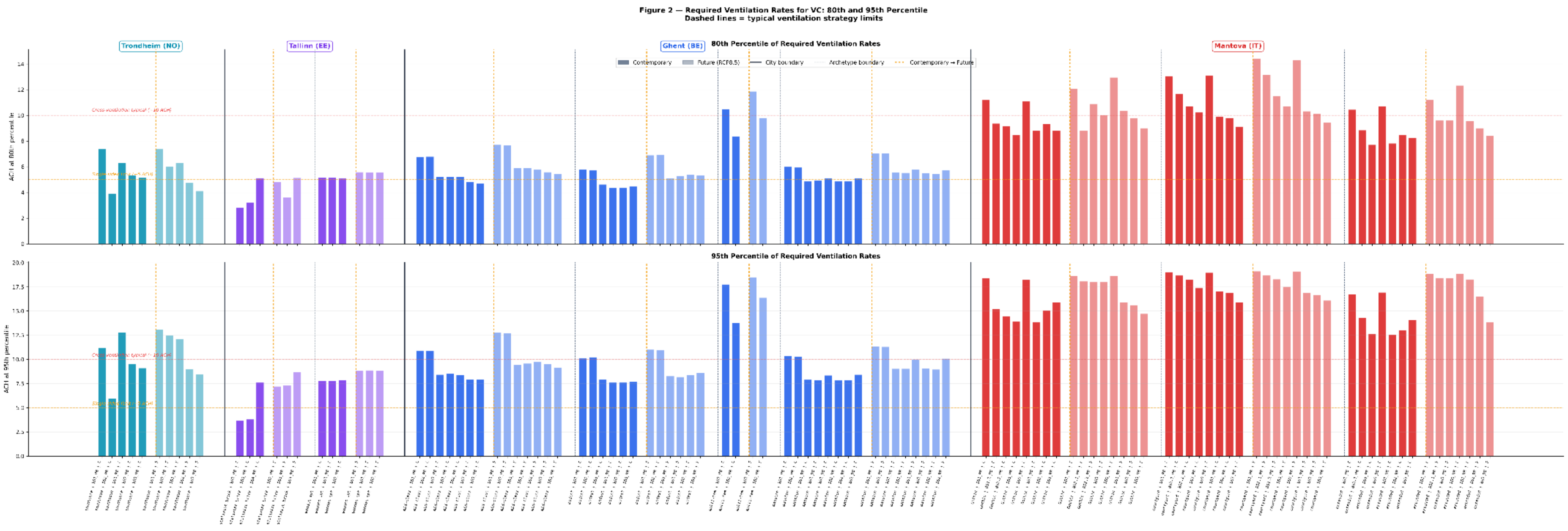

Figure 9. Required ventilation rates for ventilative cooling covering 80th and 95th percentile. Dashed lines represent typical ventilation strategies application limits.

Case studies in Trondheim (Norway) – subartic climate. In Trondheim case studies the ventilative cooling targeted Category I as it reflects the comfort level Norwegian occupants actually expect and maintain according to (De Jonge et al., 2025). The case studies has low cooling needs in both contemporary and future climate (cooling need in contemporary climate is 1-2 kWh/m² and in future climate is 2-4 kWh/m²), confirming that overheating has historically been a secondary concern in this climate. However, the renovation scenarios show that envelope upgrades can reduce heating needs by up to 80% but simultaneously triple the cooling need, as the improved insulation and airtightness trap solar and internal gains that the original leaky timber construction would have dissipated passively. By applying ventilative cooling to the renovated cases, the residual cooling need drops back to values comparable to the pre-renovation baseline, effectively neutralising the cooling penalty of insulation. Similar trend is for the future climate where ventilative cooling in renovation baseline cases reduces the cooling need down to 2.5-3 kWh/m².

Among the renovation parameters, **replacing windows with lower solar heat gain coefficients** (g-value) is particularly beneficial in the Norwegian context. The original single-glazed windows (g = 0.80) transmit a high proportion of the incident solar radiation, which in Trondheim's high-latitude summer — with extended daylight hours and low sun angles that penetrate deep into rooms — generates persistent low-level solar gains throughout the long Nordic day. Replacing these with modern glazing at g = 0.50–0.60 reduces the solar transmission by 25–38% without significantly affecting winter solar gains (which occur at even lower sun angles and are limited by the short winter day). The VCPM results show that renovation scenarios combining lower g-values with improved insulation achieve the best overall outcome: heating needs reduced by 70–80%, cooling needs kept below 3 kWh/m² thanks to ventilative cooling. The required airflow rates remain moderate for the renovation baseline cases (80th percentile 4-5 ACH), within the capacity of cross ventilation. At the 95th percentile, renovated cases sit around 9 ACH while low-insulated cases can spike to 13 ACH. **Well-insulated renovation cases require lower peak airflow rates than poorly insulated pre-renovation cases**, despite having higher annual cooling needs. In poorly insulated buildings, the lightweight timber envelope transmits outdoor heat rapidly during the few warm hours, creating sharp cooling peaks that demand high instantaneous airflow to manage. In well-insulated buildings, the envelope blocks these conductive peaks, and the cooling load is more evenly distributed through the day, producing a steadier, lower-intensity demand that the ventilation system can address at moderate airflow rates. **Envelope renovation in Nordic heritage townhouses not only reduces heating demand but also makes the ventilative cooling system easier to deliver**, because the peak airflow requirement drops into the range achievable by natural stack ventilation alone, reducing or eliminating the need for fan assistance.

Tallinn (Estonia) — cold continental climate. The case studies in Tallinn comprise two structurally distinct archetypes — the **wooden apartment building** (horizontal log or double plank construction, light mass) and the **Stalinist-style brick apartment building** (solid masonry with or without cavity, medium-heavy mass) — providing a direct comparison of how construction type affects ventilative cooling performance within the same climate. As in Trondheim, the target comfort category is **Category I** (high level of expectation), reflecting the occupant expectations documented in (De Jonge et al., 2025) on indoor environmental quality surveys for Nordic heritage residential buildings.The two archetypes show markedly different cooling behaviour.

The **wooden apartment building** has a contemporary cooling need of approximately 9 kWh/m², which is not significantly reduced by the renovation scenarios considered – the cooling need remains around 9 kWh/m² across all baseline and renovation cases, and is projected to increase to approximately 13 kWh/m² under future climate. The persistence of the cooling load despite renovation reflects the fundamental limitation of lightweight timber construction for passive cooling: the low thermal mass. Improving the envelope reduces heat loss in winter but does not create the thermal buffering that would allow heat gains to be absorbed during the day and discharged at night.

The **Stalinist-style brick apartment building** has lower cooling needs and greater sensitivity to renovation quality. Under contemporary climate, the renovation scenario with low envelope transmittance (BS4_RB) shows a cooling need of approximately 3 kWh/m², rising to 5 kWh/m² under future climate. The other renovation scenarios achieve even lower cooling needs – approximately 1.2 kWh/m² under contemporary conditions and 2.7 kWh/m² under future climate – reflecting the combined effect of improved insulation (reducing conductive gains) and high accessible thermal mass (buffering the remaining solar and internal gains across the diurnal cycle).

The required airflow rates across both archetypes are moderate to low. At the 80th percentile, most cases sit between 3 and 6 ACH under both contemporary and future climate, suggesting that natural stack ventilation alone is sufficient for the Estonian heritage cases without mechanical assistance. This is a favourable outcome for heritage compatibility: the ventilation strategy can rely entirely on existing operable windows and the stairwell stack path, with no need for fan assistance or additional openings. The wooden apartment cases show slightly higher 95th percentile rates (7–9 ACH) than the brick cases (4–6 ACH), consistent with their higher peak cooling loads, but even these values remain within the capacity of cross-ventilation through front-to-back airflow paths where the building plan permits it.

The comparison between the two archetypes reinforces the fact that **thermal mass is a decisive factor for ventilative cooling performance**, and heritage buildings with heavyweight masonry construction have a structural advantage over lightweight construction that no amount of insulation improvement can replicate. In the Tallinn context, this means that the Stalinist-era brick buildings are better suited to passive summer cooling strategies, and their solid masonry should be treated as a thermal asset to be preserved and activated rather than concealed behind interior insulation.

Ghent (Belgium) – maritime temperate climate. The Ghent case studies span four archetypes (middle-class townhouse, modest house, private mansion, multi-family townhouse) across six renovation scenarios each. The mean sensible cooling need for pre-renovation scenario is 11 kWh/m² under contemporary conditions, rising to 16 kWh/m² under future climate. The mean sensible cooling need for renovation scenario is 13 kWh/m² under contemporary conditions, rising to 15 kWh/m² under future climate. Ventilative cooling can reduce cooling need up to 64-71% of cooling need in contemporary climate scenario and 54-57% in future scenario – the highest VC effectiveness among the cases analysed, reflecting Ghent's maritime climate with moderate summer temperatures, frequent cloud cover that limits peak solar gains, and cool nights that support effective thermal mass discharge.

Within the Ghent cases, the renovation scenarios reveal a consistent pattern: pre-renovation baselines (BS1_PB to BS3_PB) have lower absolute cooling needs but also lower VC effectiveness, while renovation scenarios (BS1_RB to BS3_RB) have higher cooling needs – because the improved insulation traps more internal and solar gains – but higher VC effectiveness, because the maritime outdoor air remains cool enough to flush these gains away. The most insulated renovation scenarios (BS3_RB) show cooling needs of 15–20 kWh/m² with VC reductions of 75–80%, confirming that deep energy renovation of heritage townhouses in maritime climates does not create an unmanageable overheating problem provided ventilative cooling is incorporated into the renovation strategy.

The required airflow rates at the **80th percentile** for pre-renovation and renovation cases show similar airflow requirements – both in the range of 4–6 ACH – suggesting that the renovation does not fundamentally change the ventilative cooling operating regime. This range is at the upper limit of what single-sided ventilation can deliver and sits comfortably within the capacity of cross-ventilation. At the **95th percentile**, however, pre-renovation cases require higher airflow rates (7–10 ACH) than renovation cases (7–8 ACH). The practical implication is that **envelope renovation in Ghent heritage townhouses not only reduces annual heating demand but also makes the ventilation system easier to size.**

The **multi-family townhouse** archetype stands apart from the other archetypes, with cooling needs 2.5–3 times higher and airflow requirements nearly double mainly because of the **fenestration-to-floor ratio**. The multi-family townhouse reference room has 6.8 m² of glazing on 18 m² of floor area, giving WWR of 57% – nearly double the 24-30% WWR ratio of the other three archetypes. In the renovation scenario, the cooling need considering ventilative cooling (4.6 kWh/m²) is still double that of the other archetypes (2.5–2.7 kWh/m²), and the peak airflow requirement (13.7 ACH at the 95th percentile) exceeds what natural ventilation can reliably deliver. The design recommendation for this archetype is clear: **reducing the effective solar gain is more impactful than increasing ventilation capacity**. The multi-family townhouse is, in effect, a case where prevention measures through solar control should be considered.

Mantova (Italy) – Mediterranean continental climate. The Mantova cases span three archetypes (Gothic lotto, courtyard building, extended building) and represent the most challenging climate for ventilative cooling. The mean sensible cooling need is the highest of all locations (45 kWh/m² in contemporary climate, 61 kWh/m² in future climate), driven by high summer temperatures, intense solar radiation, and high humidity that limits the hours when outdoor air can provide effective cooling.

Among the three Mantova archetypes, the **courtyard building** stands apart with both the highest cooling need in pre-renovation scenario (85 kWh/m²) and in renovation scenario (88 kWh/m²) and the highest VC effectiveness (40-46%) – more than four times the VC reduction that can be achieved by the Gothic lotto and the extended building. This is because of the higher WWR (30% compared to circa 10% of the other cases).

Ventilative cooling removes only 10% of the cooling need under contemporary conditions and 15.1% under future climate – a meaningful contribution in absolute terms (approximately 9.6 kWh/m² saved) but insufficient to address the overheating problem alone. The limitation is fundamentally climatic: Mantova experiences approximately 800 discomfort hours per year under contemporary conditions (hours when outdoor air temperature is too high or humidity exceeds the accepted limit for VC), rising to over 1,000 under RCP8.5 scenario in 2050. During these hours, which span most of the daytime period from June to September, the outdoor air cannot provide cooling and the building must rely on its thermal mass and shading to buffer conditions passively.

Within the Mantova cases, the courtyard building archetype consistently shows the highest VC effectiveness (25–30% reduction for renovation scenarios), likely reflecting its larger room volumes, thicker walls (up to 80 cm solid masonry) and the potential for courtyard-side ventilation through a more sheltered and slightly cooler air source than the street. The Gothic lotto and extended building archetypes show lower VC effectiveness (15–20%), with the extended building cases showing the lowest values, potentially due to their more constrained airflow geometry.

The required airflow rates in Mantova are substantially higher than in the other three locations and show little sensitivity to the renovation scenario. At the **80th percentile**, pre-renovation and renovation cases require similar rates – 8–13 ACH across all three archetypes – with the courtyard building at the upper end (10–13 ACH) and the extended building at the lower end (8–10 ACH). At the **95th percentile**, the rates reach 13–19 ACH, again with minimal difference between pre-renovation and renovation cases. Unlike Ghent and Trondheim, where envelope renovation reduces peak airflow requirements, improvements in envelope insulation and airtightness in Mantova case studies have lower impact on the design ventilation rates for ventilative cooling. The VC-effective hours are concentrated in a narrow window – typically the evening and early night – when the indoor-outdoor temperature differential is small. The ventilation system must therefore deliver high peak capacity for a short operating period.

The airflow rates required in Mantova (8–13 ACH at the 80th percentile, up to 19 ACH at the 95th) exceed what conventional window-based ventilation can deliver but are achievable through a stack ventilation strategy. Where the natural buoyancy drive is insufficient during calm, humid evenings – the critical VC hours in Mantova's climate – a low-power extract fan mounted in the tower provides the necessary boost to reach the required airflow rates.

5. Workflow application on the Italian case study

This chapter applies the full ventilative cooling design workflow to one of the Mantova heritage townhouses by complementing the ventilative cooling potential assessment with detailed multi-zone building energy simulations with integrated airflow network models. The Mantova Palazzetto case study (the gothic lot archetype) was selected for this validation because it represents one of the most challenging cases for natural ventilative cooling.

5.1 Case study

The workflow was applied to the Italian case study, represented by a historic residential building belonging to the Palazzetto archetype located in Mantova. The Palazzetto is a Northern Italian townhouse typology typically characterised by three to four storeys, including a basement and attic, and a greater width, than the traditional Gothic lot, as shown in Figure 10. Details on the archetypes can be found in (Maton et al., 2024). The selected case study corresponds to a seventeenth-century masonry building located within the historic urban fabric of Mantova and is representative of the heritage townhouse stock addressed within the project.

Figure 10: Floor plans and facade of Palazzetto archetype (Source: (Maton et al., 2024))

The building is constructed primarily of solid brick masonry with lime-based plaster finishes, resulting in a high thermal mass. In addition, the building includes a central staircase connecting the different floors and the attic level, creating the potential for vertical airflow paths within the buildings. Historical documentation also indicates the presence of a tower above the staircase, which originally contributed to natural ventilation and daylighting of the building, as shown in Figure 11. These characteristics are relevant for ventilative cooling applications, since both thermal storage and airflow distribution influence the cooling potential that can be achieved through natural ventilation.

(a)

(b)

Figure 11: Top tower marked in blue within the (a) aerial view (source: (Leonforte et al., 2025)), and (b) facade view (source: (Maton et al., 2024)) of the case study building

As a heritage building, renovation measures must be compatible with conservation requirements and should minimise alterations to historically significant building elements. Therefore, preference is given to low-impact solutions that make use of existing architectural features and airflow paths. This makes ventilative cooling a particularly relevant strategy for improving indoor environmental conditions while maintaining compatibility with heritage preservation objectives.

The presence of the existing wind tower provides an opportunity to exploit stack-driven ventilation through a feature that historically formed part of the building's passive environmental design. As the effectiveness of stack ventilation depends on the available outlet area at the top of the airflow path, the sizing of the existing wind tower opening represents an important design consideration. At the same time, any intervention affecting this element must remain compatible with the conservation of the historic wind tower and associated building fabric. Since the opening is located at the top of the roof rather than on the principal street-facing façade, modifications to this element are expected to have a lower impact on the façade aesthetics.

Although the ventilative cooling potential assessment (in the previous sections) was carried out using the Meteonorm-generated weather files, the dynamic simulations were performed using the TMY weather file for Verona (Valerio Catullo Airport) (2009-2023), adopted for the Italian archetypes within the project due to the absence of a suitable TMY dataset for Mantova. The use of a common climatic dataset for both the reference case and the case implementing the natural ventilation strategy ensured that the differences observed between the two scenarios could be attributed to the intervention itself, and not the variations in the weather input data. The modelling framework could be implemented with other climatic datasets as well in future analysis.

The input parameters required by VCPM were selected using the heritage-specific guidance tables developed in Section 3.2 and were aligned with the HV-III, BS3_PB renovation scenario adopted for the Italian case study (details of the scenarios can be found in the (Himpe et al., 2025b)). Based on the construction characteristics of the Palazzetto archetype, the building was classified as a heavy thermal mass building, corresponding to solid brick masonry construction with lime plaster finishes. Window properties were represented by replacement double-glazed windows, while the airtightness level was selected consistent with the BS3 scenario (n50 = 3 ach). Traditional external wooden shutters were considered as the primary solar-shading device. Together with the climatic conditions described above, these parameters were used to evaluate the ventilative cooling potential and determine the airflow requirements for the subsequent development of the ventilative cooling strategy.

5.2 Ventilative cooling potential assessment

The ventilative cooling potential of the Palazzetto case study was assessed with the VCPM using the venticoolpy library, adopting the input parameters selected in Section 5.1 from the heritage-specific guidance tables of Section 3.2 for the HV-III, BS3 renovation scenario: heavy thermal mass, replacement double glazing (g-value 0.65), traditional external wooden shutters (shading factor 0.75, activated above 200 W/m²) and an envelope airtightness of n50 = 3 h^{-1}. This assessment corresponds to one of the renovation scenario of the Gothic lotto archetype in Mantova analysed in Chapter 4, and therefore reflects the most challenging of the four HeriTACE climates for natural ventilative cooling. The reference room was taken as a top-floor, street-facing space, which combines high solar exposure with the comparatively lighter thermal mass of the roof construction and is the most overheating-prone zone of the building.

Figure 12 shows the distribution of the four ventilative cooling modes over the year for the present and the future climate. During the heating season and the shoulder months the building operates predominantly in VC Mode 1 (comfort maintained by the minimum ventilation rate). In the summer months the response is split between VC Mode 2, in which increased airflow can effectively restore comfort, and VC Mode 3, in which the outdoor air is too warm or too humid to deliver any cooling benefit. The VC Mode 2 hours are concentrated in the evening and early-night period, when the indoor–outdoor temperature difference exceeds the 3 °C effectiveness threshold, whereas the central daytime hours of July and August fall largely in VC Mode 3. Under the future RCP8.5 climate the balance shifts further towards VC Mode 3: the number of hours during which outdoor conditions preclude ventilative cooling rises from approximately 1000 to more than 1 300 per year. For the Palazzetto, ventilative cooling is therefore a genuinely useful but partial strategy – it captures the available night-time cooling potential but cannot, on its own, eliminate the daytime overheating risk of the Mediterranean continental climate, which must be addressed in combination with the activation of the interior thermal mass.

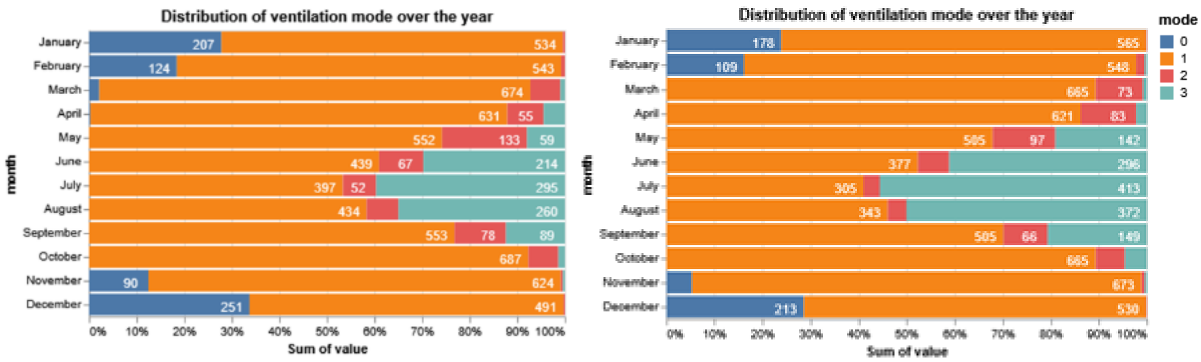

Figure 10. Distribution of ventilation mode over the year for the Palazzetto case study (renovation baseline scenario) in Mantua present (left) and future climate (right)

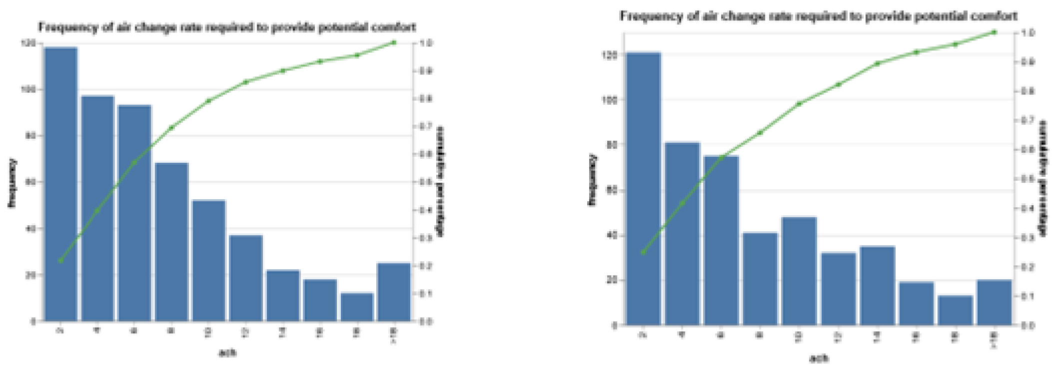

Figure 11. Frequency of air change rates required to provide potential comfort for the Palazzetto case study (renovation baseline scenario) in Mantua present (left) and future climate (right).

Figure 13 reports the frequency distribution of the air change rates required to maintain comfort during VC Mode 2 hours. The required rates are high relative to the other HeriTACE locations, reflecting both the magnitude of the cooling load and the narrow evening window during which ventilative cooling is effective: the system must deliver a large airflow over a short operating period. The 80th-percentile requirement falls in the range characteristic of the Mantova cases (of the order of 8–11 air changes per hour), with the 95th-percentile demand higher still. Rates of this magnitude exceed what single-sided or conventional window-based ventilation can reliably provide, but are attainable through a stack-ventilation strategy that exploits the full building height. The design airflow required for ventilative cooling in the critical upper-floor room, 830 m³/h is suggested as the design target (Q_target) for sizing the top tower outlet opening in Section 5.4.

The outcome of the assessment is sensitive to a small number of parameter choices that the designer fixes in Steps 1 and 2 of the workflow. The classification of the Palazzetto as a heavy thermal-mass building is the most favourable assumption for ventilative cooling: it dampens the indoor temperature swing and sustains the indoor–outdoor temperature difference that drives night cooling, and it would be substantially eroded if interior insulation or dry-lining were applied to the masonry, shifting the construction towards a lighter mass class. The low window-to-wall ratio of the Gothic lotto archetype (of the order of 10%) limits solar gains, and hence the absolute cooling need, but also limits the opening area available for natural airflow; the shading factor and activation setpoint of the external shutters strongly influence the daytime gains and therefore the proportion of VC Mode 3 hours. Conversely, the envelope airtightness and opaque-envelope transmittance have a comparatively minor effect on the required design airflow rates in this climate. The assessment should therefore be treated as a feasibility-stage estimate that establishes the airflow target and the realistic limits of ventilative cooling, to be confirmed – as in the following sections – by detailed multi-zone simulation.

5.3 Building energy model

The building energy model adopted for the Italian case study was based on the dynamic simulation model developed within the project by Politecnico di Milano (Deliverable D3.3), as shown in Figure 12 (a), using a Rhino-Grasshopper-EnergyPlus workflow. The geometric representation of the Palazzetto archetype, including the building envelope, internal spaces and surrounding urban context, was created in Rhino and parameterised within Grasshopper. The model was subsequently translated into an EnergyPlus simulation model through the Honeybee/OpenStudio interface, which generated the corresponding input data file (IDF) used for the dynamic simulations.

For the present study, the EnergyPlus model was subsequently adapted to support the assessment of ventilative cooling strategies and the implementation of detailed airflow analyses, shown in Figure 12(b). Dynamic simulations were performed using EnergyPlus version 25.1 with a timestep of six simulation steps per hour, corresponding to a temporal resolution of 10 minutes, allowing the transient response of the building in terms of indoor conditions and airflow behaviour to be captured with sufficient detail. The resulting EnergyPlus model served as the common simulation platform for both the thermal performance assessment and the subsequent airflow network analyses presented in this study.

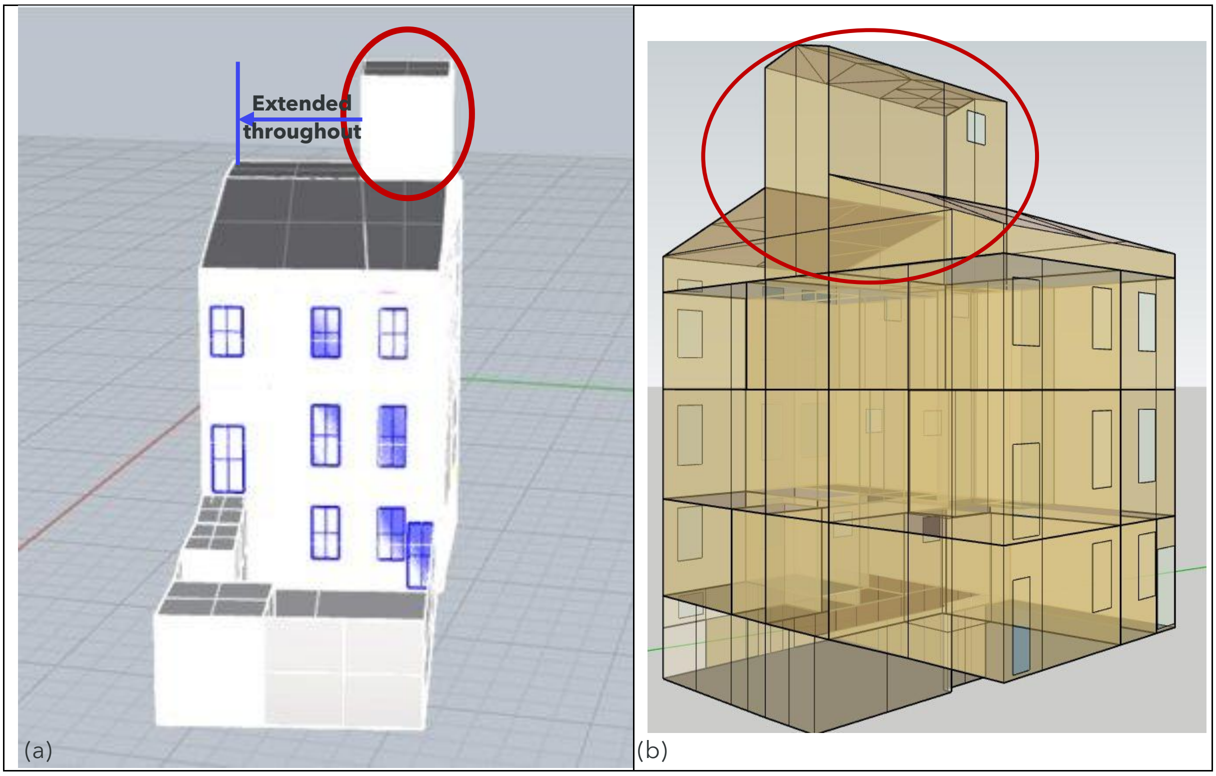

Figure 12: (a) Original building model (source: (Leonforte et al., 2025)), and (b) Modified model for AFN implementation

The Palazzetto archetype is organised over multiple levels comprising a basement, ground floor, first floor, second floor and attic level. The internal layout comprises residential spaces distributed across the habitable floors together with circulation spaces and attic rooms, reflecting the spatial organisation typical of historic Northern Italian townhouses. To represent this configuration, the building was modelled using a detailed multi-zone approach consistent with the methodology adopted for the Italian archetypes in (Leonforte et al., 2025). The Palazzetto case study was subdivided into thermal zones according to the functional organisation of the building, allowing spaces with different occupancy patterns, usage, and thermal characteristics to be represented separately. The final model comprised 31 thermal zones distributed across the basement, ground floor, first floor, second floor and attic levels. Although the complete multi-zone model was retained for the simulations, the subsequent workflow validation focused on a subset of representative occupied spaces and staircase zones to evaluate the effectiveness of the proposed stack-driven ventilation strategy.

The climatic boundary conditions were represented using the weather data described in Section 5.1. For the ventilative cooling assessment, the building was simulated in free-floating mode without active heating or cooling systems, allowing indoor conditions to respond directly to the combined effects of outdoor climate, solar gains, internal heat gains, thermal mass and airflow. Heat transfer between spaces was represented through the detailed multi-zone configuration of the model.

The boundary conditions reflected the position of the building within the dense urban fabric of Mantova. Party walls shared with adjacent buildings were modelled as adiabatic surfaces, while façades exposed to the street, courtyard and outdoor environment were assigned as external boundary conditions. For the basement level, the walls and floor surfaces in contact with the surrounding soil were represented using ground-contact boundary conditions, accounting for the partial and full ground exposure characteristic of the building. The influence of the surrounding urban context was represented through shading surfaces derived from neighbouring buildings and urban obstructions. These elements were represented as shading surfaces within the model in order to capture their shadowing effect on the building envelope and windows.

The envelope properties adopted in the simulations correspond to the HV-III, Bs3 scenario (further details can be referred from (Himpe et al., 2025b)and (Leonforte et al., 2025)). The thermal transmittance values (U-values) of the principal envelope constructions are summarised in Table 9. The external envelope consists primarily of solid brick masonry walls finished with plaster layers. Two wall constructions were considered in the model: an uninsulated masonry wall and a wall incorporating an additional 100 mm mineral wool insulation layer on the internal side. The roof assembly comprised roof tiles, timber planking, thermal insulation and an internal plaster layer. The attic floor and ground floor were represented using insulated constructions, while window openings were modelled as double-glazed timber-framed units. Traditional external shutters were retained as movable shading devices to account for their influence on solar gains and indoor thermal conditions. The adopted constructions reflect the renovation assumptions associated with the selected heritage value class and renovation scenario while maintaining the architectural characteristics of the Palazzetto archetype (further details on the heritage value class and scenarios given in (Himpe et al., 2025b)).

Table 9: U-values of constructions used in the model

	Exterior Wall	Internal Wall	Ground Floor	Interior Floor	Attic Floor	Roof	Windows
U-Value (W/m^2K)	0.39-1.56	2.49	0.28	1.94	0.27	0.65	1.4

Occupancy was represented using schedule-based inputs derived from the residential operation assumptions of the Italian case-study model (further details can be found in (Leonforte et al., 2025)). Occupied residential spaces, including living rooms, kitchens, bedrooms and bathrooms, were assigned time-dependent occupancy schedules together with activity-level profiles that account for variations in occupant presence and metabolic heat gains throughout the day. The activity schedule varied between 105 and 126 W/person during occupied periods, representing typical residential activities. Circulation spaces, including corridors and staircases, as well as the cellar and attic zones, were assigned zero-occupancy schedules. Internal gains from lighting and electrical equipment were represented using schedule-based profiles, defined with reference to EN 16798-1. The corresponding schedules modulated these design values over time, thereby accounting for the temporal variation in corresponding heat gains throughout the day.

5.4 Ventilative cooling strategy

The ventilative cooling strategy investigated in this study is based on stack-driven natural ventilation. Stack ventilation exploits density differences between warm indoor air and cooler outdoor air to generate buoyancy-induced airflow through a building. As indoor air is heated, its density decreases and the air rises towards higher levels of the building, creating a pressure difference that promotes the inflow of outdoor air through lower openings and the exhaust of warm air through openings located at higher elevations (Lei et al., 2026). The magnitude of this driving force increases with the vertical separation between inlet and outlet openings and with the temperature difference between indoor and outdoor air (Rezadoost Dezfuli et al., 2023). In addition to buoyancy effects, wind-induced pressures acting on the building envelope contribute to the resulting airflow patterns and ventilation rates (Filis et al., 2021).

The selected strategy makes use of the existing vertical organisation of the Palazzetto archetype. Fresh outdoor air is introduced through façade openings serving the occupied spaces, while the central staircase acts as the principal vertical airflow path connecting the different storeys. Air is subsequently exhausted through high-level opening located in the tower above the attic level. The strategy therefore combines wind-driven and buoyancy-driven airflow mechanisms to enhance air exchange and remove accumulated heat from the building.

To evaluate the performance of this ventilation strategy, the EnergyPlus AirflowNetwork (AFN) model was implemented using the MultizoneWithoutDistribution approach. This formulation represents the building as a network of interconnected pressure nodes and airflow components and allows simultaneous simulation of airflow driven by wind pressures, thermal buoyancy and envelope leakage. The AFN model was coupled with the thermal simulation model, enabling airflow rates and indoor thermal conditions to be solved dynamically at each simulation timestep.

Although the complete building energy model comprised 31 thermal zones, the airflow analysis focused on a representative subset of occupied spaces and staircase zones extending across the full building height. The analysed zones included the ground-floor living room, first-floor kitchen, second-floor kitchen, and the staircase zones located on the ground floor, first floor, second floor and attic level (as shown in Figure 13). This configuration allowed the complete airflow pathway from the lower occupied spaces to the upper exhaust location to be represented while retaining interaction with the full multi-zone building model.

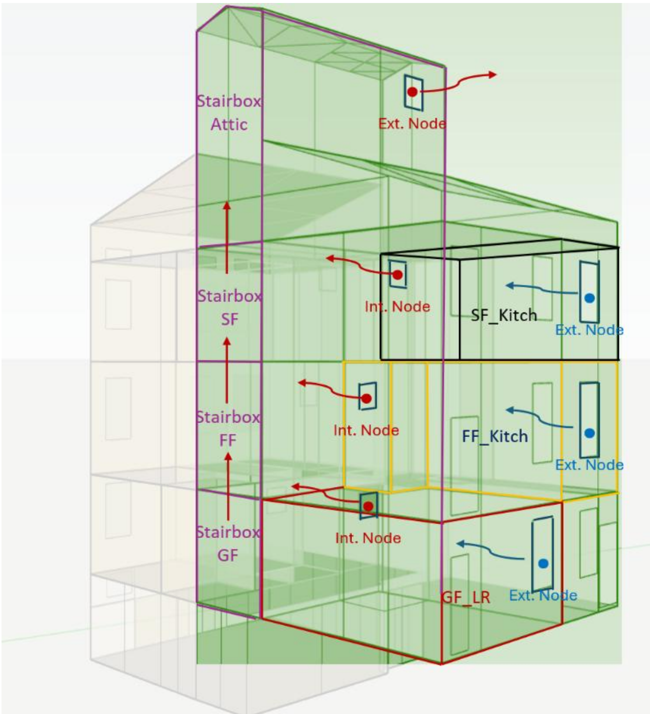

Figure 13: AFN model implementation demonstration for the case study building

Although the intended airflow pathway was from the occupied rooms towards the staircase and subsequently upwards to the tower, the actual airflow direction and magnitude were determined dynamically by the AFN solver at each simulation timestep based on the prevailing wind and buoyancy conditions.

Operable façade windows and internal openings connecting the occupied spaces to the staircase were represented using AirflowNetwork SimpleOpening components. A discharge coefficient of 0.78 and a flow exponent of 0.65 were adopted for all operable openings. This formulation enables airflow through each opening to respond dynamically to the pressure conditions calculated by the AFN solver.

External wind-induced pressure conditions acting on the building envelope were represented through façade-specific wind pressure coefficients defined at 45° directional intervals and external nodes positioned at the corresponding opening heights. The external nodes were distributed over the building height, ranging from approximately 1.8 m above ground level at the lower storeys to approximately 14.2 m at the attic level, as shown in Figure 13. This configuration allows local wind pressure and vertical pressure gradients associated with the stack effect to be explicitly represented within the airflow calculations. The combination of façade openings at low and intermediate elevations and the high-level tower exhaust creates the pressure distribution required to promote upward airflow through the staircase core under favourable buoyancy conditions.

Background infiltration through the building envelope was represented using Effective Leakage Area (ELA) components assigned to opaque external surfaces. The ELA values were derived from the infiltration characteristics adopted in the baseline energy model (refer to Deliverable D3.3) and converted to equivalent leakage areas using the AFN formulation and a reference pressure difference of 4 Pa. One external node per floor per façade was also implemented to represent wind pressures over different floor heights. Together, the operable openings, internal airflow paths and leakage elements enabled the combined influence of wind effects, thermal buoyancy and background infiltration on the building airflow behaviour to be evaluated.

Natural ventilation operation was governed through an Energy Management System (EMS)-based control implemented within the EnergyPlus model. The EMS was introduced to represent the combined temporal and thermal criteria of the proposed ventilative cooling strategy explicitly. At each simulation timestep, the control logic evaluated the time of day, outdoor air temperature, indoor temperature and indoor–outdoor temperature difference. The resulting control signal was used to determine the availability of the operable AFN openings.

During the cooling season (from April 15th to October 15th), separate daytime and night-time outdoor temperature criteria were applied. During daytime operation, defined between 06:00 and 22:00, ventilation was allowed when the outdoor air temperature was between 20°C and 26°C. During night-time operation, from 22:00 to 06:00, the allowable outdoor temperature range was extended to 18–28°C to increase the use of ventilative cooling. In addition to these outdoor temperature limits, ventilation was activated only when the indoor temperature was at least 24°C and exceeded the outdoor temperature by at least 1 K. The latter criterion ensured that outdoor air was thermally favourable for sensible heat removal and prevented opening operation when the outdoor air was warmer than, or insufficiently cooler than, the indoor environment. All the conditions within the respective daytime or night-time control period mentioned were required to be satisfied simultaneously for the openings to be enabled.

The EMS control therefore determined the opening state from the simultaneous satisfaction of the temporal and thermal activation criteria. Once the openings were enabled, the resulting airflow rates and flow directions were not prescribed by the control algorithm but were calculated dynamically by the AirflowNetwork solver. The airflow calculation consequently remained governed by the dynamic pressure distribution generated by wind-induced pressures, thermal buoyancy, opening characteristics and background envelope leakage.

The implemented airflow network configuration provides a coupled representation of ventilation control and pressure-driven airflow. The EMS defines the periods during which the proposed ventilative cooling pathway can be activated, whereas the AirflowNetwork determines the airflow established through the façade openings, staircase core and tower outlet under the prevailing climatic and thermal conditions. This modelling approach enables the performance of the stack-driven ventilative cooling strategy to be assessed under both daytime and night-time operation while accounting for the transient interaction between building thermal conditions, wind exposure and buoyancy forces.

5.4.1. Opening sizing

The building has 3 floors. All floors connect to a central staircase that should function as a ventilation chimney, terminating in a tower with one or more openings at the top. The tower outlet opening area (A_top) is sized so that:

(a) fresh air flows inward through every window on every floor (correct flow pattern),

(b) the airflow at the top floor meets a specified target value Q_target (adequate ventilation).

The top floor is the critical constraint because it has the weakest buoyancy driving pressure. Ventilative cooling potential analysis for the kitchen zone at the second floor resulted to a maximum required airflow of 830 m3/hr (Q_target).

The sizing of the staircase (tower) top opening was based on analytical equations reported in CIBSE AM10 (Benjamin Jones et al., 2026). First, the neutral pressure level (NPL) is positioned above all façade openings, ensuring inward airflow across all floors. Second, the required top opening area was determined through a static mass balance that assumes 3K difference between indoor 2nd floor and outdoor temperature, equating the total inflow through all façade openings to the outflow at the tower outlet, leading to an equivalent-area formulation.

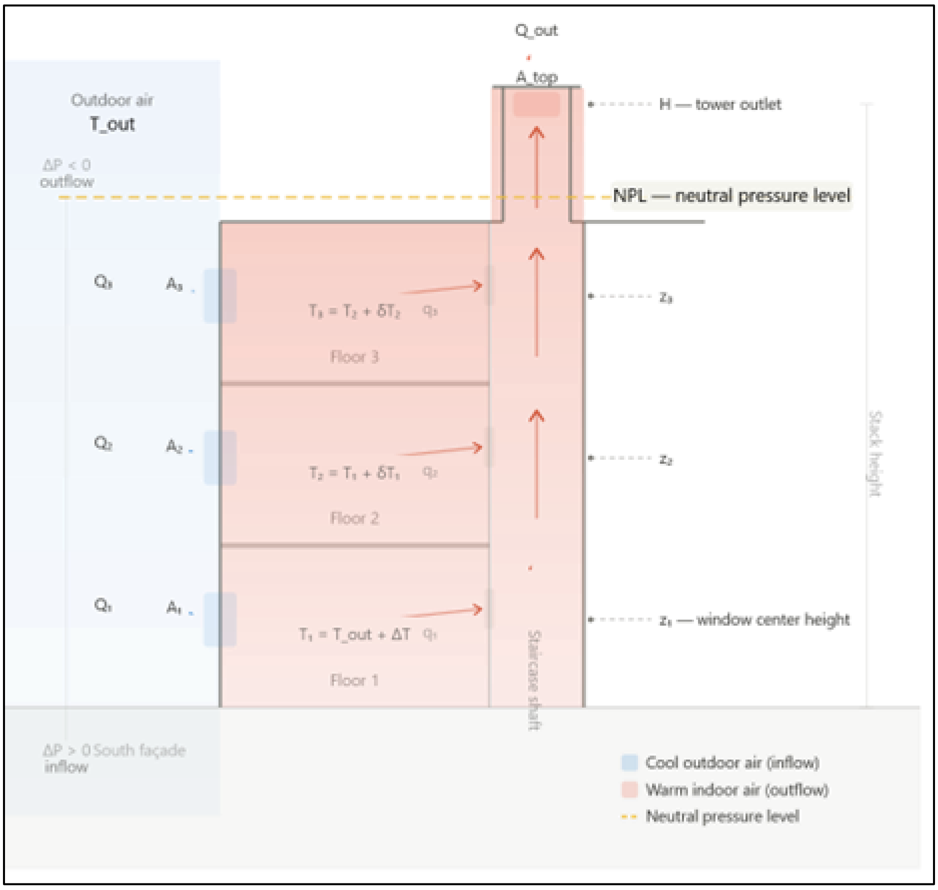

Figure 14. Building section showing the expected airflow path, the openings position and the neutral pressure level. Source: AI generated

5.4.2. Ventilation strategy performance

Airflow pathway and flow-direction assessment

The proposed ventilative cooling strategy relies on a stack-driven airflow pathway in which outdoor air enters the occupied rooms through façade openings, is transferred into the staircase core, and is subsequently discharged through the tower at roof level. The effectiveness of both the daytime direct ventilative cooling mode and the night ventilation mode therefore depends on maintaining this flow sequence throughout the building height.

Figure 15 presents the percentage of ventilative cooling operating hours during which the air flows in the intended direction across each analysed AirflowNetwork linkage. A directional compliance criterion of 95% was adopted as a reference for assessing the robustness of the airflow pathway.

Across all analysed linkages, the intended flow direction was maintained during 100% of the assessed stack ventilative cooling operating hours. The façade openings serving the habitable spaces operated exclusively as supply openings. Likewise, the internal transfer openings maintained airflow towards the staircase core, confirming that the staircase functioned as the principal vertical transport route connecting the different storeys. At roof level, the attic linkage operated continuously as an exhaust pathway, completing the intended airflow circuit between the occupied floors and the tower outlet. This airflow pathway ensures that no stale air from the staircases is entering the occupied spaces during the proposed stack ventilative cooling operation.

The complete directional compliance observed across the analysed linkages indicates that, when the stack ventilative cooling strategy is active, the pressure distribution established within the building consistently supports the intended upward airflow sequence. Despite the simultaneous influence of wind-induced façade pressures and thermal buoyancy on the AirflowNetwork solution, no flow reversal was identified across the selected airflow links during the assessed stack ventilation operating hours. The results therefore confirm the robustness of the proposed airflow configuration under the simulated operating conditions and demonstrate that the central staircase can provide a stable vertical transfer path between the occupied floors and the high-level attic outlet.

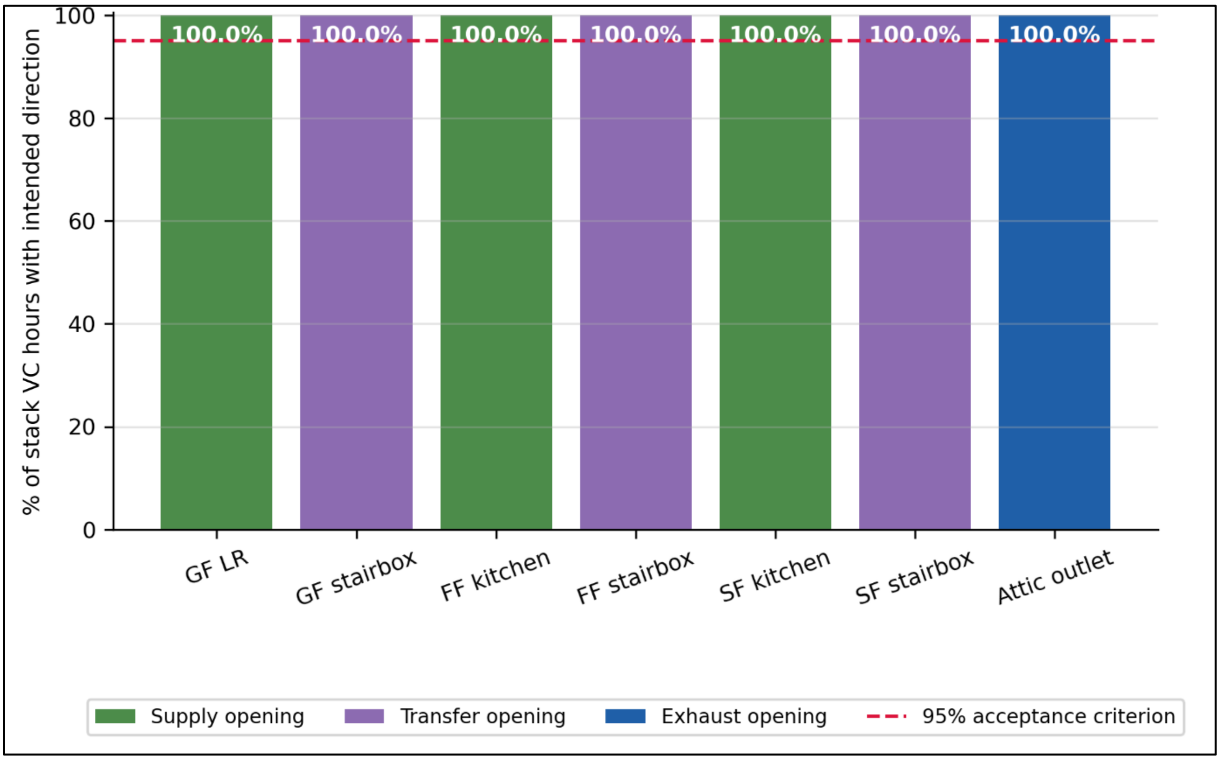

Figure 15: Percentage of ventilative cooling hours with intended airflow direction

Compliance with design airflow requirements

Figure 16 presents the airflow duration curves obtained for the second-floor kitchen, which was selected as the critical space for evaluating the proposed stack-driven ventilative cooling strategy. The design airflow requirement of 830 m^3/h, derived from the ventilative cooling sizing procedure described previously, is indicated by the horizontal dashed line. The curves are evaluated only for ventilative cooling active timesteps and are distinguished between daytime direct ventilative cooling and night ventilation.

The proposed airflow configuration achieves the design airflow requirement during the majority of ventilative cooling operating hours. During night ventilation, the airflow rate is equal to or greater than 830 m^3/h for 81.8% of the VC-active period, compared with 67.8% during daytime ventilative cooling. The higher compliance during night-time operation could be due to stronger buoyancy potential that can develop as the outdoor air cools while heat accumulated during the preceding day is retained within the building and its thermal mass. The resulting indoor–outdoor density difference contributes to the pressure gradient established along the full-height airflow path between the occupied rooms and the high-level tower outlet. A distinction between the airflow distributions of the two operating periods is also evident from the duration curves. Over most of the exceedance range, the night-time curve remains above the corresponding daytime curve, indicating systematically higher airflow rates during night ventilation. Night-time airflow remains above approximately 1000 m^3/h for more than half of the VC-active timesteps and reaches peak values approaching 1800 m^3/h. Daytime airflow is generally lower, although the design requirement is still achieved for approximately two-thirds of the VC-active period. The lower daytime airflow rates could be attributed to the generally smaller indoor–outdoor temperature differences available during the day and the resulting reduction in the buoyancy component of the driving pressure.

The decline in both duration curves at higher exceedance percentages shows that activation of ventilative cooling does not necessarily result in the design airflow rate being achieved. This is relevant for the implemented control strategy, which permits ventilation when the indoor air temperature is at least 24°C and the indoor–outdoor temperature difference is at least 1 K, subject to the corresponding daytime or night-time outdoor-temperature limits. These conditions ensure that the outdoor air is cooler than the indoor air but do not necessarily establish a sufficiently large density difference to generate 830 m^3/h through the stack pathway. Consequently, 18.2% of night-time and 32.2% of daytime VC-active timesteps remain below the design airflow requirement.

The sub-threshold periods should therefore be interpreted in relation to the available airflow driving forces. As demonstrated by the flow-direction analysis in Figure 15, the supply, transfer and exhaust links maintain the intended direction during the assessed stack ventilative cooling hours. The airflow duration curves instead show that the magnitude of the flow varies dynamically in response to the instantaneous pressure field. Under stronger buoyancy and favourable wind-pressure conditions, the proposed opening configuration is capable of generating airflow rates well above the design requirement; under weaker driving conditions, the same airflow pathway remains established but operates at a lower flow rate.

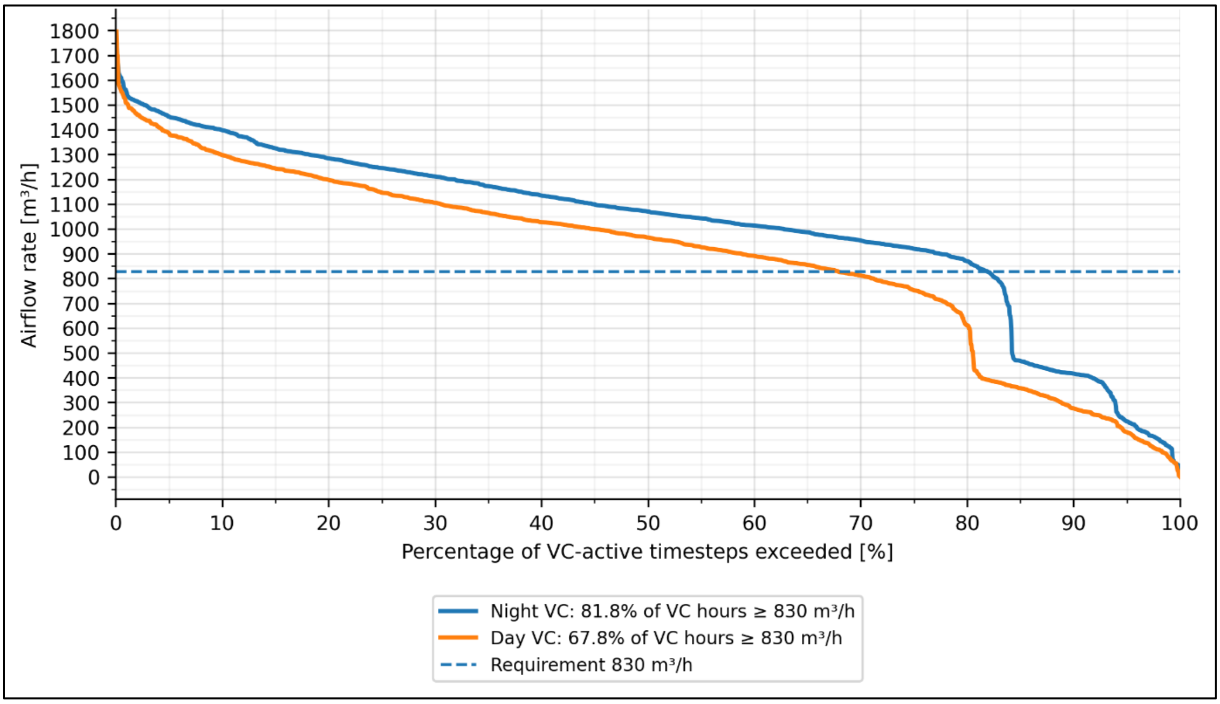

Figure 16: Airflow duration curves (zone: second floor, kitchen)

Figure 17 examines the temporal behaviour of the airflow rates achieved by the stack-driven direct ventilative cooling with night ventilation strategy for the second-floor kitchen zone, which was identified as the critical zone for the airflow requirement assessment. The figure presents both a monthly view for a typical hot month (August) and a representative hot-week period. Daytime and night-time ventilative cooling periods are distinguished to relate the resulting airflow to the operating mode of the control strategy.

The August profile shows a pronounced intermittent pattern associated with the EMS-based control of the operable openings. When the ventilative cooling criteria are satisfied, the openings are enabled and the airflow through the stack pathway is governed by the instantaneous wind- and buoyancy-induced pressure differences. At some VC-active timesteps, the resulting airflow remains below the design requirement of 830 m³/h because the available pressure difference is insufficient to generate the target flow rate. When the EMS-controlled openings are closed, a small residual airflow may remain through the same AFN linkages because they include a closed-opening air-leakage coefficient. These low flows therefore represent pressure-driven leakage through the closed windows or doors, in addition to the background envelope infiltration. During active opening periods, the linkage airflow is dominated by flow through the open area and varies dynamically with the prevailing thermal and wind-pressure conditions.

The distinction between daytime and night-time airflow identified from the duration curves is also evident in the temporal distribution. Sustained periods of high airflow occur predominantly during night ventilation. As the outdoor temperature decreases from its daytime maximum, the indoor–outdoor temperature difference can increase while heat accumulated during the preceding day remains stored within the building fabric. The resulting density difference strengthens the buoyancy-induced pressure gradient along the vertical airflow path through the staircase and tower. During these periods, airflow rates frequently exceed the design requirement of 830 m³/h and commonly reach approximately 1000–1400 m³/h. Daytime ventilative cooling occurs less frequently and is generally associated with shorter airflow events, consistent with the more limited thermal driving forces available during the warmer daytime period.

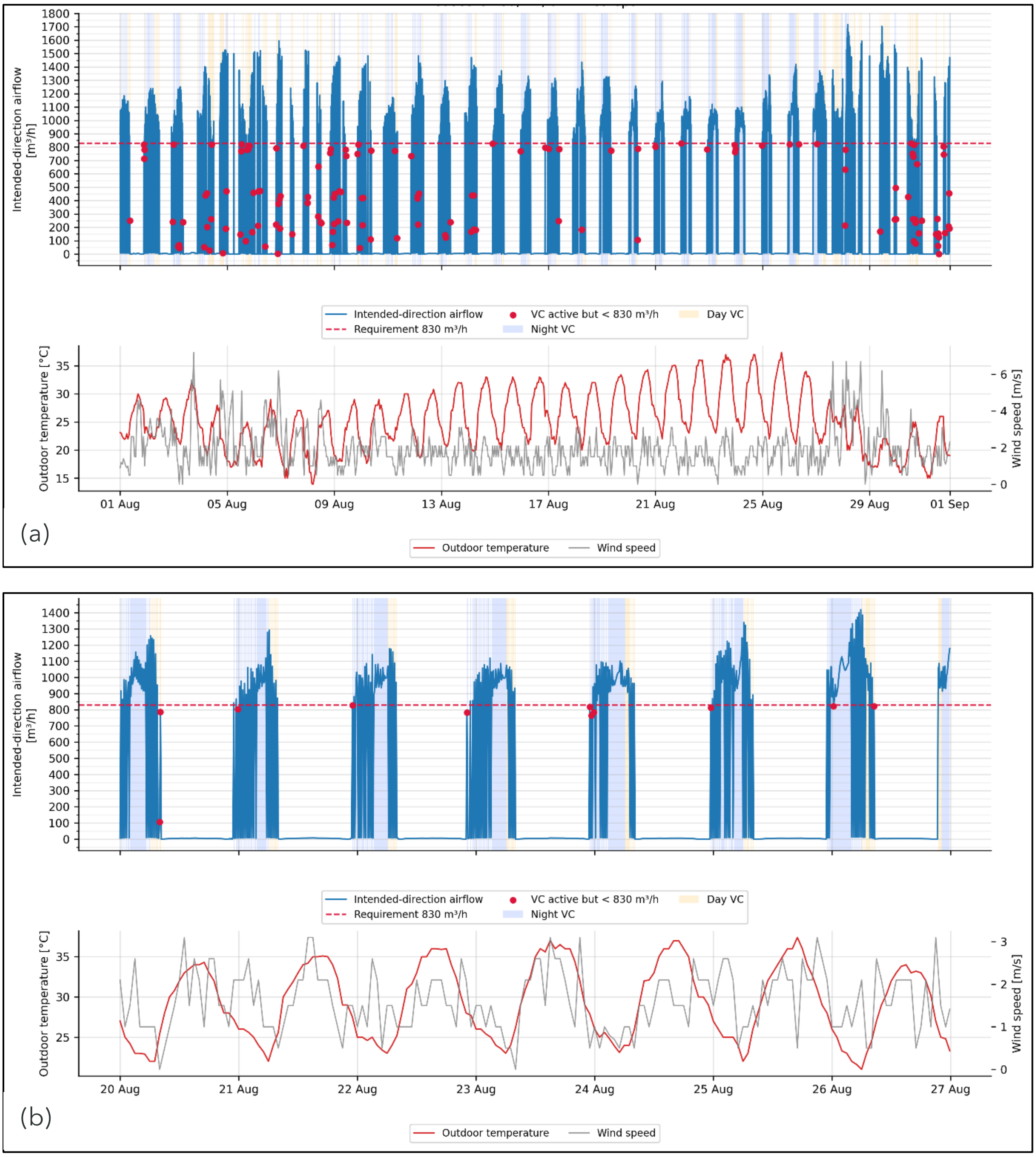

Figure 17: Temporal distribution of airflow during (a) a typical hot month, and (b) a typical 1-week hot period (zone: second-floor, kitchen)

The representative hot-week period in Figure 17(b) illustrates this diurnal behaviour more clearly. A repeated sequence of high-flow night ventilation periods is established over consecutive days. Following activation of the openings, the airflow generally reaches values above the 830 m³/h requirement and remains at approximately 900–1100 m³/h during a substantial part of the night ventilation period, with peak values of approximately 1200–1400 m³/h. The recurrence of this behaviour during successive hot days indicates that the vertical airflow pathway can repeatedly establish substantial night-time air exchange during periods of persistent summer heat.

The sub-threshold VC-active timesteps identified in Figure 17 occur mainly close to the transition between active and inactive ventilation periods. At these timesteps, the thermal criteria for ventilative cooling are satisfied, but the instantaneous pressure difference across the airflow path is not sufficient to generate the design airflow rate. As the outdoor temperature decreases and the indoor–outdoor thermal gradient develops, the airflow increases rapidly and exceeds the design requirement. A corresponding reduction in airflow is observed towards the end of some ventilation periods as the thermal driving force changes. Wind-speed fluctuations further modify the instantaneous airflow magnitude and contribute to the short-term variability observed within individual ventilation events.The hot-week results therefore show that the design airflow requirement is not maintained continuously whenever ventilative cooling is active, consistent with the airflow duration curves presented in Figure 16. Nevertheless, the highest and most sustained airflow rates coincide predominantly with the night ventilation periods, when the thermal conditions are more favourable for buoyancy-driven airflow and for removal of heat stored within the building fabric. The repeated establishment of airflow above 830 m³/h over successive nights provides the airflow mechanism required for night-time heat removal and supports the use of the staircase and tower as the principal stack ventilation pathway.

Seasonal and diurnal airflow behaviour

Figure 18 presents the seasonal distribution of inflow airflow rates in the second-floor kitchen as a function of day of year and hour of day for the combined ventilative cooling strategy, in which daytime direct ventilative cooling and night ventilation are governed by different control criteria according to the time of day. The superimposed 830 m³/h red contour identifies the operating region in which the airflow requirement derived for the space is satisfied.

The distribution of exceedance hours is not uniform throughout the cooling season. Continuous regions exceeding the design airflow threshold emerge from June onwards and persist until early September, with the largest contiguous areas occurring during the night ventilation period. During these hours, airflow rates commonly exceed 1000 m³/h and locally approach 1500–2000 m³/h, indicating that the vertical airflow path formed by the façade openings, staircase core and tower remains fully established over extended periods.

A pronounced asymmetry between daytime direct ventilative cooling and night ventilation is evident. The night-time operating window is characterised by large uninterrupted exceedance regions, whereas daytime exceedance occurs more intermittently and is fragmented across the cooling season because of unfavourable outdoor conditions.

The beginning and end of the analysed period show a markedly different pattern. During May and October, exceedance of the airflow threshold is restricted to shorter periods and occurs intermittently throughout the day. This reduction is primarily associated with the availability of suitable outdoor conditions for ventilative cooling.

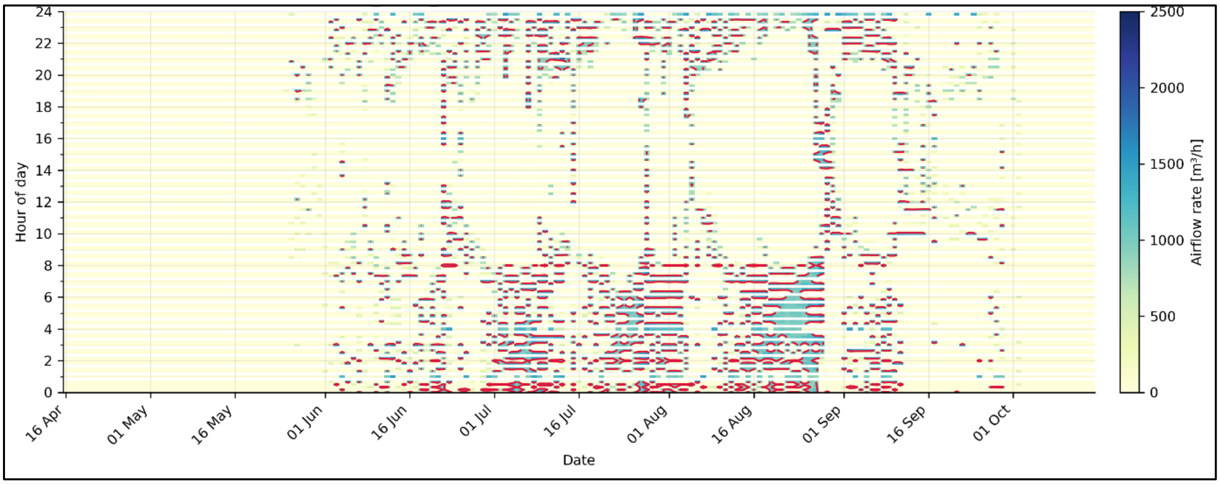

Figure 18: Hourly distribution of AFN-predicted inflow airflow rates in the second-floor kitchen as a function of day of year and hour of day. The red contour identifies the airflow requirement of 830 m^3/h; regions within the contour correspond to periods when the required ventilation rate is achieved

Indoor thermal conditions and overheating control

Figure 20 presents the operative temperatures of the principal zones involved in the stack-driven ventilation pathway over the cooling season, together with the outdoor dry-bulb temperature and the EN 16798 Category II adaptive comfort limits.

The indoor thermal response exhibits a clear seasonal progression. During the core summer period, particularly in July and August, the operative temperatures increase in response to the sustained warm outdoor conditions and remain highest in the upper parts of the building. The attic staircase exhibits the highest temperatures during the warmest periods, while the second-floor kitchen remains the warmest of the occupied spaces considered. The ground-floor living room remains comparatively cooler. This vertical variation is consistent with the different thermal exposure of the spaces, including the greater influence of roof and solar heat gains at the upper levels and the thermal buffering provided by the massive masonry construction at the lower storeys.

Despite outdoor dry-bulb temperatures periodically exceeding 35°C during the warmest summer episodes, the operative temperatures of the occupied spaces show an attenuated response to short-term outdoor temperature fluctuations. The lower amplitude of the indoor temperature variations is characteristic of the thermal inertia of the heavyweight building envelope. The ventilative cooling strategy acts in conjunction with this thermal storage capacity by promoting heat removal when the outdoor air is cooler than the indoor environment. In particular, the sustained night-time airflow identified in the preceding airflow analyses provides a mechanism for removing part of the heat accumulated during the preceding daytime period and thereby restoring part of the thermal storage capacity of the building fabric for the following day.

The temperature profiles indicate that exceedances of the Category II upper comfort limit are largely restricted to the most thermally exposed part of the airflow pathway. Repeated exceedances are observed in the attic staircase during the warmest summer periods; however, this space is unoccupied and forms part of the vertical exhaust pathway rather than an occupied comfort zone. Among the occupied spaces, the second-floor kitchen exhibits only occasional exceedances of the upper Category II limit during the most severe warm episodes, while the first-floor kitchen and ground-floor living room generally remain below the upper comfort boundary. The elevated temperature of the attic staircase is physically consistent with its position beneath the roof and its role at the upper end of the vertical airflow path, where warm air transported through the staircase is directed towards the high-level tower exhaust. The limited exceedance observed in the occupied spaces indicates that the proposed ventilation strategy is effective in controlling overheating for most of the cooling season, although short periods of residual overheating remain in the most thermally exposed occupied zone.

A different thermal behaviour is observed during the shoulder periods, particularly at the beginning of the analysed cooling season. Operative temperatures occasionally approach or fall below the lower Category II comfort limit, most notably in the ground-floor living room. This behaviour is related to the overheating-oriented formulation of the implemented EMS control. Ventilation is permitted when the indoor air temperature is at least 24 °C and the outdoor air is at least 1 K cooler than the indoor environment, subject to the prescribed daytime and night-time outdoor temperature ranges. The control therefore identifies conditions favourable for sensible heat removal but does not explicitly terminate ventilation as the operative temperature approaches the lower adaptive comfort limit. Under milder shoulder-season conditions, the thermal response of the building may continue after ventilation has been activated owing to the combined effect of cool outdoor air and the thermal inertia of the construction, resulting in occasional temperatures towards the lower part of the adaptive comfort range.

The results therefore demonstrate that the revised strategy is effective for its primary objective of limiting overheating. At the same time, the shoulder-season response identifies scope for further refinement of the control logic. The inclusion of a lower operative-temperature constraint or an adaptive termination criterion linked to the prevailing comfort limit could reduce excessive heat removal during mild periods while retaining the strong cooling response required during the core summer season. The present analysis focused on assessing the feasibility and overheating-mitigation performance of the proposed stack-driven ventilative cooling concept, whereas the above-mentioned control optimisation will be carried out to support the integration of ventilative cooling solutions in the renovation packages for historic townhouses.

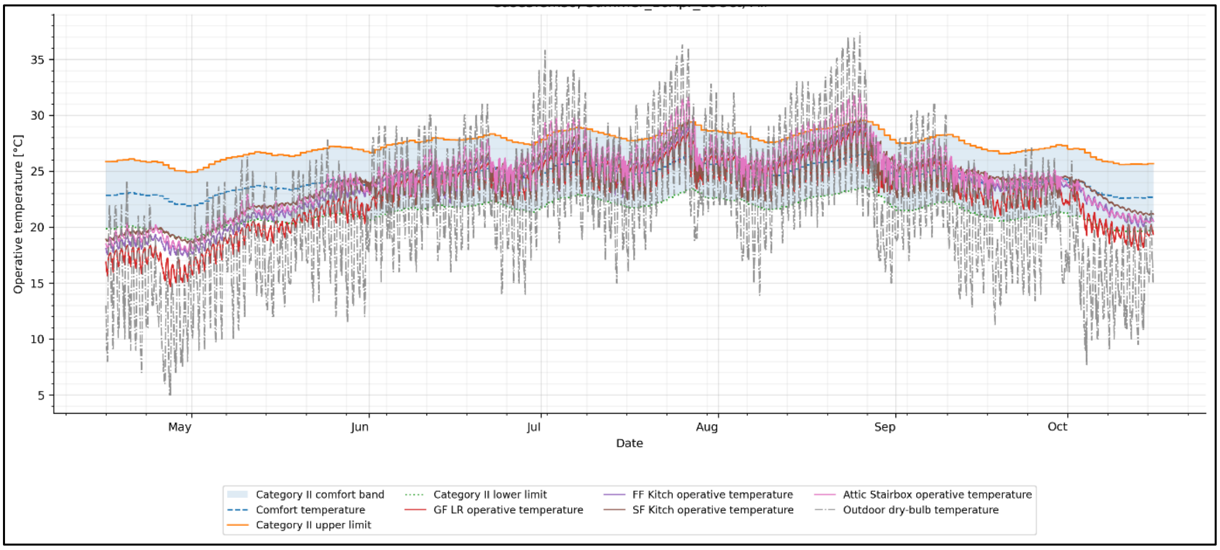

Figure 19: Seasonal evolution of operative temperature in the principal zones of the stack-driven ventilation pathway under the proposed ventilative cooling strategy

Conclusions

This deliverable establishes a decision-support framework for implementing ventilative cooling in heritage townhouses, adapting the generic nine-step workflow of FprCEN/TS 18335 to explicitly reflect the architectural, physical, and conservation requirements of protected historic buildings. It reports operational parameter tables and applies the Ventilative Cooling Potential Method across heritage townhouses archetypes in four representative European climates. The approach is further substantiated through detailed validation on an Italian case study. Together, these components provide a robust methodological foundation and a validated evidence base to support the integration of ventilative cooling strategies within heritage renovation practice.

The review of the literature established that ventilative cooling in historic townhouses is not a single technology but a coherent family of strategies – night ventilation, cross-ventilation, courtyard ventilation and stack-effect ventilation – whose effectiveness is inseparable from the high thermal mass and the spatial organisation of the traditional building. It also showed that these strategies are most strongly documented in Mediterranean Europe and least understood in Nordic and oceanic contexts, where renovation-induced overheating is an emerging rather than a historical concern. The heritage-adapted workflow addresses this by considering conservation constraints not as limitations but as key starting points for design decisions. It prioritises solutions that prevent overheating and enhance passive heat dissipation, turning to mechanical systems only as a last resort. In this approach, the building's existing features—such as its layout, materials, and openings—are treated as the main resources for cooling.

The cross-case ventilative cooling potential analysis of 114 annual simulations demonstrated a strong dependence of ventilative cooling performance on climate and construction. In Trondheim, Talinn and Ghent climates, ventilative cooling can offset the cooling penalty of deep energy renovation and, in the best cases, can be delivered by natural ventilation alone; in Mantova climate it remains valuable but is increasingly limited by hot and humid hours and must be combined with night stack ventilation.

The design workflow was then applied to the Mantova Palazzetto case study. The ventilative cooling potential analysis returned required airflow rates for ventilative cooling that are higher than those that single-sided ventilation can deliver, indicating that a higher-capacity ventilation strategy was needed. The presence of the central staircase and the top tower suggested that a stack ventilation strategy could be implemented by sizing the top openings of the tower so that the neutral pressure level lies above the second-floor opening – ensuring inward airflow across all floors – and so that the required inlet airflow rate of 830 m^3/h is met in the living room at the second floor. The detailed coupled thermal–airflow-network simulation confirmed this design: the intended airflow circuit (inflow at the occupied rooms, exhaust at the tower) is maintained almost continuously, the achievable airflow comfortably exceeds the design requirement during night ventilation, and the strategy materially reduces overheating – while also making clear that the residual daytime load in this climate justifies retaining the building's passive thermal buffering and, where necessary, providing supplementary cooling.

The work also delineates the limits of the simplified method. The single-zone assumptions of the VCPM hold well for individual heavyweight masonry rooms during occupied daytime periods, but break down for tall, stratified spaces, multi-storey stack coupling, non-uniform solar penetration and graduated urban shading; the method is therefore intended as an early-stage feasibility tool that establishes airflow targets and screens strategies, to be followed by detailed simulation as the design matures. Taken together, the guide shows that ventilative cooling is a technically credible and conservation-compatible response to the overheating of heritage townhouses under a warming climate, and that the passive logic embedded in these buildings centuries ago remains, when understood and re-activated, one of their most valuable adaptive assets.

Key take-aways and Recommendations for use

The following points summarise the main findings of this deliverable and translate them into recommendations for the principal audiences of the work – building professionals, conservation authorities and policymakers.

Ventilative cooling should be the first cooling option for heritage townhouses. The cooling-ladder logic of FprCEN/TS 18335 applies with particular force to protected buildings, where mechanical cooling is often incompatible with conservation requirements. Prevention (solar control and internal-load management) and passive dissipation through ventilative cooling should be systematically explored and exhausted before active cooling is considered.

Thermal mass is the decisive asset and must be preserved and activated. Across every climate analysed, heavyweight masonry construction outperformed lightweight construction for passive cooling, and no level of insulation could compensate for low thermal mass. Interior insulation or dry-lining that decouples the masonry from the room air should be assessed with caution, weighing the winter heating saving against the summer cooling penalty; exposing original masonry and high-mass finishes is both a thermal and a conservation benefit.

Night ventilation, enabled by cross-ventilation and the stack effect, has the highest leverage. The evidence consistently identifies night ventilation as the most effective strategy, provided a sufficient night-time temperature difference and accessible thermal mass are present. Heritage airflow paths – front-to-back cross-ventilation, the stairwell as a stack, disused chimneys and towers, and internal courtyards – should be identified and preserved as functional cooling infrastructure.

Performance is strongly climate-dependent, and the design response must follow. In Nordic, Baltic and maritime climates, ventilative cooling can offset the overheating introduced by energy renovation and is often deliverable by natural means; in Mediterranean continental climates it is valuable but partial and must be combined with solar control and supplementary measures. Renovation in cooler climates should explicitly include ventilative cooling so that improved airtightness and insulation do not create a new overheating problem.

Use the simplified method for feasibility, then move to detailed simulation. The VCPM and the accompanying parameter tables allow a credible early-stage assessment of ventilative cooling potential and airflow requirements before detailed survey data are available. Because its single-zone assumptions do not capture the full potential of stack and cross ventilation strategies, the assessment should be confirmed with a multi-zone dynamic building energy model once a strategy is selected, as demonstrated for the Italian case study.

Design for occupant behaviour and robust control. Ventilative cooling performance depends heavily on how occupants and automated systems operate windows, shutters and ventilation openings. A combination of intuitive manual room-level controls and automated building-level controls – daytime and night ventilation, humidity and rain overrides, and an extreme-heat protection mode that relies on the thermal mass – is recommended, designed around the adaptive opportunity actually available to occupants.

Evaluate climate resilience at the feasibility stage. Because heritage buildings have very long service lives, the ventilative cooling strategy should be checked against future climate scenario from the outset – comparing changes in VC-mode distribution, cooling need and required airflow rates – to avoid locking in a strategy that becomes inadequate within decades.

Finally, the systematic application of ventilative cooling in protected urban centres is currently held back less by building physics than by a regulatory gap: passive and ventilative cooling devices are not adequately addressed in heritage planning frameworks. Closing this gap, and recognising the inherent passive cooling capacity of the historic building stock in national IEQ and climate-adaptation policy, would allow the adaptive assets identified in this guide to be deployed at scale.

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