Designing Environments

Alessandra Battisti
Serena Baiani *Editors*

ETHICS: Endorse Technologies for Heritage Innovation

Cross-disciplinary Strategies

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Designing Environments

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Contents

Chapter 12
Passive Cooling Strategies for Overheating Reduction and Indoor Comfort Optimization in Architectural Heritage

Andrea Canducci, Angelo Figliola, Livia Calcagni, Alberto Calenzo, and Alessandra Battisti

Abstract Given the significant number of buildings on both national and European territories, the enhancement of environmental quality and indoor comfort and the reduction of the energy footprint of existing buildings, in particular historical ones, have gained increasing importance. Meanwhile, the need to align existing architectural heritage with several international and national policies on climate change adaptation and cultural heritage preservation has emerged. According to the most recent climate change projections, dense and established urban environments, in particular historic centres in the Mediterranean region, will be affected by considerable increases in extreme temperatures and heat waves. As a result, it is crucial to adapt existing architectural heritage, including the historical and cultural one, to achieve optimal indoor comfort and energy efficiency standards, in compliance with relevant constraints. In this regard, the study investigates the level of indoor comfort in historical-cultural buildings located in the historical centre of Rome which are characterised by excessive indoor overheating during summer, resulting in users' discomfort and increased energy and economic consumption related to air conditioning. The study is carried out through bioclimatic analysis and dynamic simulations of the indoor environment. The objective is to identify passive and evaporative cooling strategies for indoor environments, specifically through the optimization of natural ventilation levels, in order to propose different design scenarios evaluated through a multi-criteria decision analysis based on thermal performance, low environmental impact, and low energy costs. The research highlights how a careful assessment of the users' needs and of the characteristics of the historical building, as well as synergistic and interdisciplinary collaboration among restoration, architecture, and engineering experts, significantly contributes to the identification of optimal and integrated design solutions.

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12.1 Introduction

Long-term changes in weather patterns and temperatures, known as climate change, are considered one of the most serious threats of the twenty-first century (Mitchell et al. 2016). This natural process, which has been occurring for millions of years due to variations in the solar cycle, has been accelerated in the last two centuries as a result of excessive anthropization and greenhouse gas concentration, upsetting the natural balance and increasing global surface temperature (EEA 2018). Every decade since the 1980s has experienced rising temperatures, with the 2011–2020 period being the hottest on record, reaching in 2019 a global average temperature 1.1 °C higher than pre-industrial levels (IPCC 2022).

This phenomenon emerges as an increase in the frequency and intensity of extreme weather events such as heat waves, droughts, and heavy rains, increasing the risks for ecosystems. The Intergovernmental Panel on Climate Change Sixth Assessment Report (AR6) provides a detailed assessment of the impacts of climate change on cities, settlements, and infrastructure and clearly states that without urgent, effective, and equitable mitigation actions, this phenomenon will increasingly threaten people's well-being and health on a global and regional scale (IPCC 2023). To mitigate the severe impacts of climate change, all sectors of society must collaborate, mobilizing all fields, including education, research, and innovation, and openly encouraging shared responsibility for action (UNESCO 2019). In reality, microclimate change-related events affect the overall environment of cities and therefore residents' well-being (Pioppi et al. 2020).

The risk of an increase in extreme temperatures and heat waves affecting populations and high-density urban settlements, including cultural heritage sites, emerges as one of the four risk categories that characterize Europe, the Mediterranean region, and Italy, as identified in the Euro-Mediterranean Center on Climate Change report (Spano et al. 2021). According to the UNESCO Climate Action Policy Paper, climate change has become one of the most significant threats to natural and cultural World Heritage sites, with the potential impact on their Outstanding Universal Value (OUV), including their authenticity, integrity, and capacity for economic and social development at the local level, as well as the quality of life of communities linked to World Heritage sites (UNESCO 2021). If sites are not adequately prepared or radical climate actions are not taken at the international, national, and local level, World Heritage sites may be irremediably damaged by extreme weather events (UNESCO 2017). As a result, the International Council on Monuments and Sites (ICOMOS), a UNESCO advisory body, emphasizes the importance of adequately responding to, and preparing for, climate change risks for architectural, historical, and cultural heritage. It highlights the need for effective conservation, use, and management of tangible and intangible cultural resources, considering heritage as a source of resilience and climate mitigation (ICOMOS 2019).

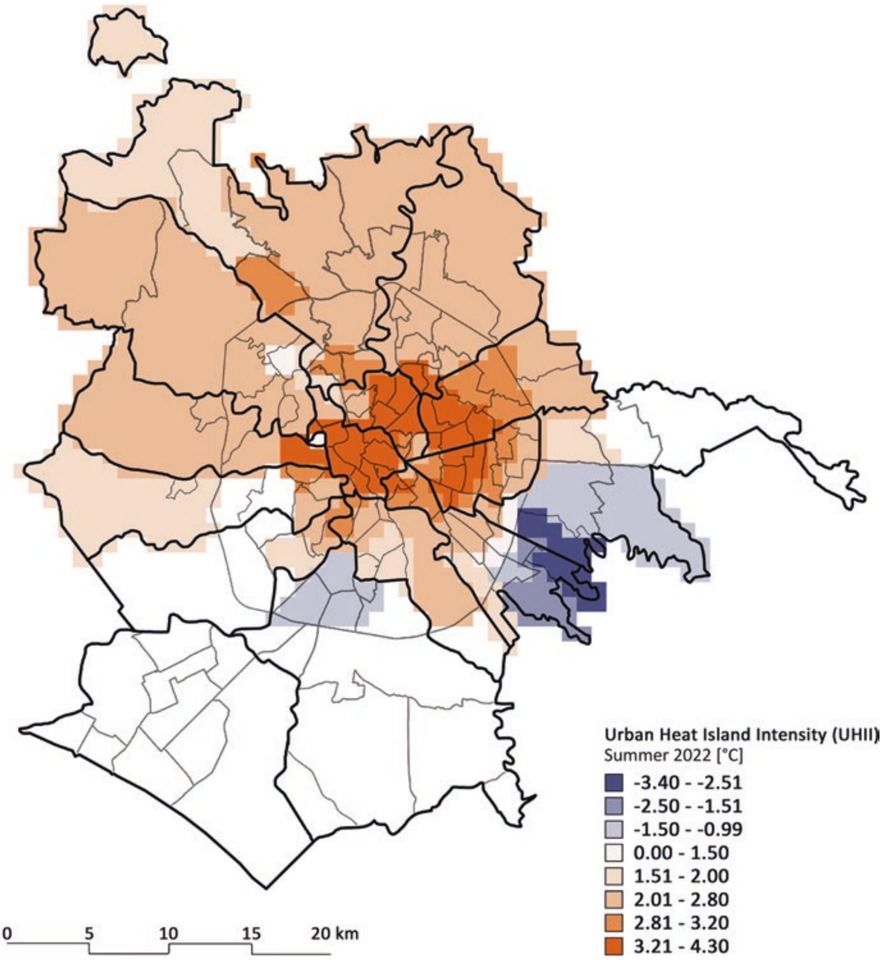

Fig. 12.1 Data mapping through GIS (Geographic Information System): urban heat island intensity (UHII) within the city of Rome

As outlined in the CMCC report, temperature and rainfall are the two major climate change drivers for Rome (CMCC 2021). The processing of hourly temperature data acquired from the Functional Center of the Lazio Region (CFR) for the period June–September 2022 allowed us to map the urban heat island intensity (UHII) within the city and highlight the variations of urban overheating (Fig. 12.1), which is more pronounced in the central urban areas, particularly in the historical centre. This phenomenon affects the urban livability of the city with multiple impacts on the environment and outdoor comfort, on the economy, and on tourism (MASE 2023). It causes discomfort within historical-cultural buildings and high energy and economic consumption due to increased usage of ventilation and air conditioning systems (Battisti 2016). Other negative effects of urban heating include hazards to human health and an impact on human mental well-being and thermal perception, especially heat and cold stress (Fedorczak-Cisak et al. 2022).

12.2 Case Study: Basilica of Santa Maria in Trastevere, Rome

The present research is the result of a multidisciplinary collaboration carried out within the PDTA Department of the Faculty of Architecture at Sapienza University of Rome. The study uses bioclimatic analyses and dynamic simulations to assess the level of indoor comfort in historical-cultural buildings located in the historic centre of Rome that witness excessive indoor heating issues during summer.

More specifically the research focuses on the Basilica of Santa Maria in Trastevere in Rome (Fig. 12.2), located in Trastevere area, one of the city's most characteristic and dynamic districts. Trastevere is characterized by anthropic discomfort under several aspects – intense traffic in the main roads and overtourism – and microclimate discomfort especially in summer (Skotis and Livas 2022). Since its foundation under Pope Callixtus I, the Basilica has undergone a series of restoration and renewal interventions, such as the construction of the portico based on a design by Carlo Fontana, or demolition works and reconstruction from scratch of the floor plan by the architect Virginio Vespignani (Pittaccio and Ricci 2013). To limit the degradation caused by rainwater infiltration, between 1980 and 1990, the wooden structure was restored, structural consolidation was carried out, and the roof was partially reconstructed (Luciani 1991). This intervention, however, resulted in excessive overheating of the environment and consequent indoor discomfort.

12.3 Methodology

The paper presents an analytical and forecasting workflow aimed at identifying design strategies and comparing different intervention scenarios for the improvement of indoor comfort in the Basilica (Fig. 12.3). Indoor comfort is evaluated using

Fig. 12.2 Outside and inside of the Basilica of Santa Maria in Trastevere, Rome

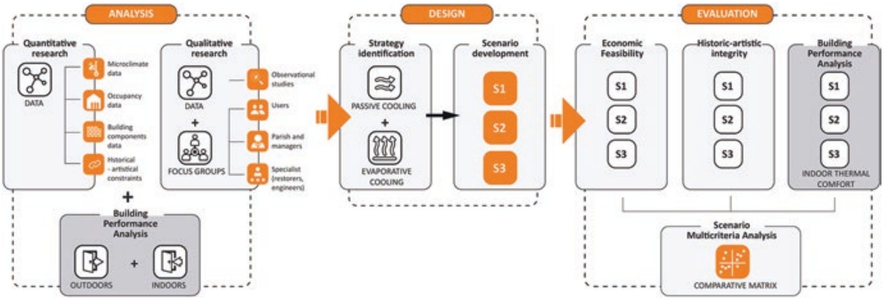

Fig. 12.3 Analysis and forecasting workflow aimed at identifying project strategies and comparing different intervention scenarios

an investigation protocol developed specifically starting from an approach previously experimented by the authors (Battisti et al. n.d.). The research is structured in three phases.

12.3.1 Analysis and Data Collection

Quantitative analysis related to the climatic and microclimatic data of the site (temperature, radiant temperature, relative humidity, wind direction, and speed), occupancy data (number of people and flows, behaviour patterns, and activities/functions), building technological units (stratigraphy, materials, transmittance), and historical-artistic constraints is combined with qualitative analysis including direct observation methods (site inspection) and focus groups with building managers, users, and some restoration, architectural, and engineering specialists.

A building performance study of the current status of both the outdoor and indoor environments was done using the data obtained. In fact, given the undeniable effect of the outdoor environment on the indoor space, the analysis of outdoor conditions is necessary for an accurate assessment of indoor comfort.

12.3.2 Design

This phase involves the research and development of passive and evaporative cooling solutions for indoor environments in order to provide different intervention scenarios aimed at increasing comfort and preserving cultural heritage.

12.3.3 Evaluation

The construction of a multi-criteria analysis matrix allows for the evaluation of each scenario on the basis of three categories (each made up of sub-parameters): respect for artistic-historical integrity, increase of indoor comfort (by building performance analysis), and economic feasibility of intervention.

Artistic-Historical Integrity Since the Basilica of Santa Maria in Trastevere is classified as an archaeological-monumental pre-existence (quality charter, General Regulatory Plan of the city of Rome) and falls within the perimeter of the historic centre of Rome designated as a UNESCO heritage site, the identified intervention scenarios are evaluated in terms of impact on the historical-artistic integrity of the building. Within the historic city, construction and urban planning interventions on "architectural and urban cornerstones" must be aimed at conserving and improving existing values while preserving the unique characteristics of each component. As a result, preservation, repair, and enhancement are allowed and encouraged, also through the adaptation of pre-existing typological, formal, and constructive features that add to the historical-architectural interest of the building. Since there is no standard for evaluating the impact on historic buildings in terms of historical-artistic integrity, four of the five key principles of restoration (Carbonara 1997) were chosen as evaluation parameters: recognizability, reversibility, compatibility, and minimum intervention. The interdisciplinarity parameter has not been considered since dialogues with experts from the fields of restoration, archaeology, structural engineering, and material chemistry will take place once the scenarios have been defined and evaluated. The four criteria are scored on a low-medium-high scale, which correspond respectively to 1-2-3 points.

Indoor Comfort Improvement In order to map indoor comfort, a performance-based approach has been adopted in a forecasting perspective which develops in consequential phases (Fig. 12.4).

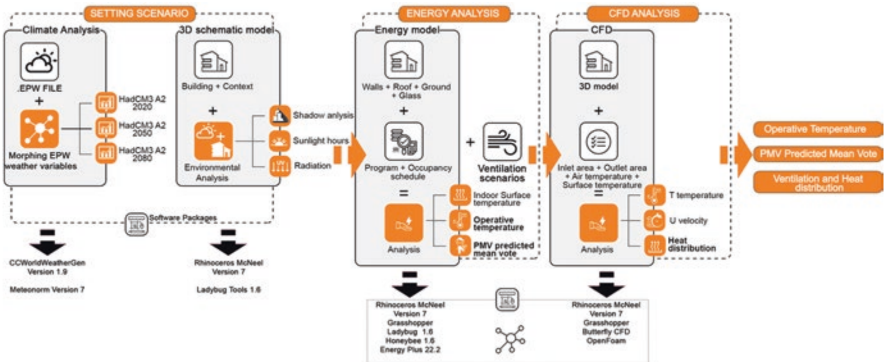

Fig. 12.4 Improving indoor comfort: performance-based process phases

The first phase involves the configuration of the scenario: starting from the current climate file (.epw file) of the city of Rome with a reference period ranging from 2011 to 2021, a morphing was carried out to transfer the data to the 2020–2050–2080, according to the IPCC classification A2, adopting the forecasting model HadCM3.

Scenario A2 depicts a very heterogeneous world with a progressive rise in population, where economic development is essentially regional and per capita economic growth and technological advancement are very fragmented and slower than in the other scenarios (IPCC report). The CCWorldWeatherGen – Climate Change Global Weather File Generator – Version 1.9 software created by Southampton University's Sustainable Energy Research Group (Jentsch et al. 2008) was used to carry out the procedures outlined above.

In the second phase, a three-dimensional urban scale model was created in order to evaluate the interaction between the Basilica and the surrounding urban fabric using a series of environmental analyses based on previously elaborated climatic files. The analysis involved mapping dry bulb temperatures, relative humidity, natural ventilation (with regard to which the prevailing direction, speed, and frequency were evaluated), and shadows on an annual basis, from 01 January to 31 December. These analyses were carried out in order to identify the time period with the highest criticalities in terms of heat stress. For this reason, the study was limited to the summer period between 21 June and 21 September. Furthermore, incident solar radiation on the building envelope was measured in Kwh/m^2 per year to identify critical issues related to transparent unshielded surfaces.

Rhinoceros software was used for the elaboration of the 3D model. For the environmental analyses, Ladybug Tools[1] suite (Roudsari et al. 2013) (a plugin of the visual scripting Grasshopper Gh[2] editor integrated in Rhinoceros) was adopted.

A simplified energy model was built in relation to which the spatial, functional, and construction aspects of the Basilica were defined according to the information gathered during the preliminary phase of the research (Table 12.1):

– The building system and performance parameters of vertical opaque walls, ground slab, roof, and vertical transparent closures which identify the identified thermal zone.
– The building program useful to define occupation patterns and loads related to the presence of thermal, electrical, and lighting systems.
– Urban context that interferes with shade on the defined thermal zone.

Grasshopper Honeybee plugin (Roudsari et al. 2013) (Ladybug Tools suite) was used to set up the energy model, and EnergyPlus software version 22.2.0 was used as a calculation engine. The energy analysis of the Basilica was carried out on an annual basis in order to examine the results from 21 June to 21 September. This process highlights the basic parameters both for the evaluation of indoor comfort and for the definition of the model used for the CFD fluid dynamics analysis. In the first case, the outputs analysed are operating temperature (To) – as the average value

[1] Roudsari, M.S., LadyBug e Honeybee, http://www.ladybug.tools/

[2] Rutten, D., Grasshopper, version 0.9.0072, http://www.grasshopper.com/

Table 12.1 Functional elements in the construction of the energy model

Church	Santa Maria in Trastevere
Location	Rome, Italy
Opening hours	From 7:30 AM to 9 PM From 7:30 AM to 1 PM – From 3 PM to 9 PM in August
Crowding index (people per m^2)	1.2 (max)
Technological components	Roof = concrete slab, wooden truss, brick, and tile top layer Wall = load-bearing walls made of solid bricks, internal stucco, and external exposed brickwork layer Fixtures = iron and glass Floor = marble elements and decorations
U-value (W/m^2 k)	Roof = 1.2, wall = 1.8, glazing = 6, floor = 2
Window to wall ratio (%)	South = 7, north = 7, east = 3, west = 1
Surface (m^2) and volume (m^3)	Surf = 10,521, vol = 43,140
Lighting power (W m^2)	10
HVAC system	Without heating and cooling system. Naturally ventilated

of indoor air temperature and the average radiant temperature of the thermal zone – and predicted mean vote (PMV) for evaluating indoor comfort through a percentage value that indicates the conditions of thermal stress from hot and cold and neutrality. In order to calculate the PMV, in addition to the energy analysis values such as air temperature and speed, relative humidity, and mean radiant temperature, the metabolic rate value equal to 1 (seated person) and clothing level equal to 0.5 (shorts and t-shirt) have been used.

A further output of the analysis is the temperature of the different surfaces that make up the thermal zone: this data has been used to inform the model and carry out the CFD analysis in the next step in order to evaluate the indoor air temperature, speed, and above all the distribution of heat in the indoor space.

Butterfly plugin by Gh and OPENFOAM were used as calculation engines for the fluid dynamics analysis. The wind rose diagram from 21 June to 21 September reveals that the prevailing wind direction with a speed higher than 3 m/s is south-west, with an angle between 220 and 250 degrees, while the maximum temperature is about 38 ° C. These data have been used to define the boundary conditions of the CFD model:

– Wind speed = 3 m/s.
– Direction = 230°– south-west.
– Inlet surfaces of ventilation flows (*inlet)* = central nave openings oriented towards south.
– Outlet surfaces of ventilation flows, *outlet* = central nave openings oriented towards north.

Butterfly provides an automatic mesh generation process. This process interactively refines the mesh based on the simulation results to find a stable solution with a minimal margin of error. After several iterations (572 executions) convergence was achieved with 0% error. The *Reynolds-averaged simulation* (RAS) turbulence model was used for the simulation with a static pressure equal to zero ($p = 0$). Five vertical planes were set up in the critical points of the Basilica or in correspondence with the central nave, long and short sides, transept, and apse to map the following values: heat distribution in the indoor space, air speed, and ventilation flows.

The given methodological framework was used to undertake a state-of-the-art study for the three temporal scenarios, 2020, 2050, and 2080, highlighting the To, PMV, and indoor heat distribution for each of them. Thereby it was possible to ascertain the increase in the operating temperature, and the evolution of the comfort level could be determined as the intensity of climate change increased.

The psychrometric diagram was used to support the choice of implementing passive cooling strategies for the 2080 scenario since it highlighted the effectiveness of passive cooling solutions for the indoor environment. The diagram indicates that 11.8% of the hours per year are in the comfort range. Evaporative cooling is the most effective passive strategy, accounting for 40.65% of the hours. It has the advantage of being compatible with all other cooling solutions (e.g. natural ventilation).

The multi-scalar and integrated configuration of the performance-based process allows for environmental and energy analyses to be carried out within the same software platform with a linear input-output data flow. This is critical in order to provide total interoperability between the design phase of the project scenarios and the analysis of the results (Figliola 2023).

Economic Feasibility The metrics established for assessing the economic viability of the interventions are the construction cost and the operating and maintenance costs. Given the complexity of some of the assumed technologies, especially in terms of installation and management during the construction phase together with the specialized nature of the maintenance work to be provided, at this stage of the present study for all the metrics, rough cost estimates have been made taking into account only the main elements, processes, and interventions that characterize each scenario. This operation allowed an initial comparison of costs for the different scenarios and gave the opportunity to score each one qualitatively from an economic point of view. As a result, the assessment ranges have been simplified according to the low-medium-high scale, which correspond respectively to 1-2-3 points.

12.4 Results

12.4.1 Strategies and Intervention Scenarios

Strategies for passive and evaporative cooling – design techniques used to cool indoor environments without the use of mechanized systems, in particular through natural ventilation (Al-Shamkhee et al. 2022) – have been defined in order to improve indoor comfort during summer, safeguard cultural heritage, and reduce energy consumption and management costs. The identified strategies are (Fig. 12.5):

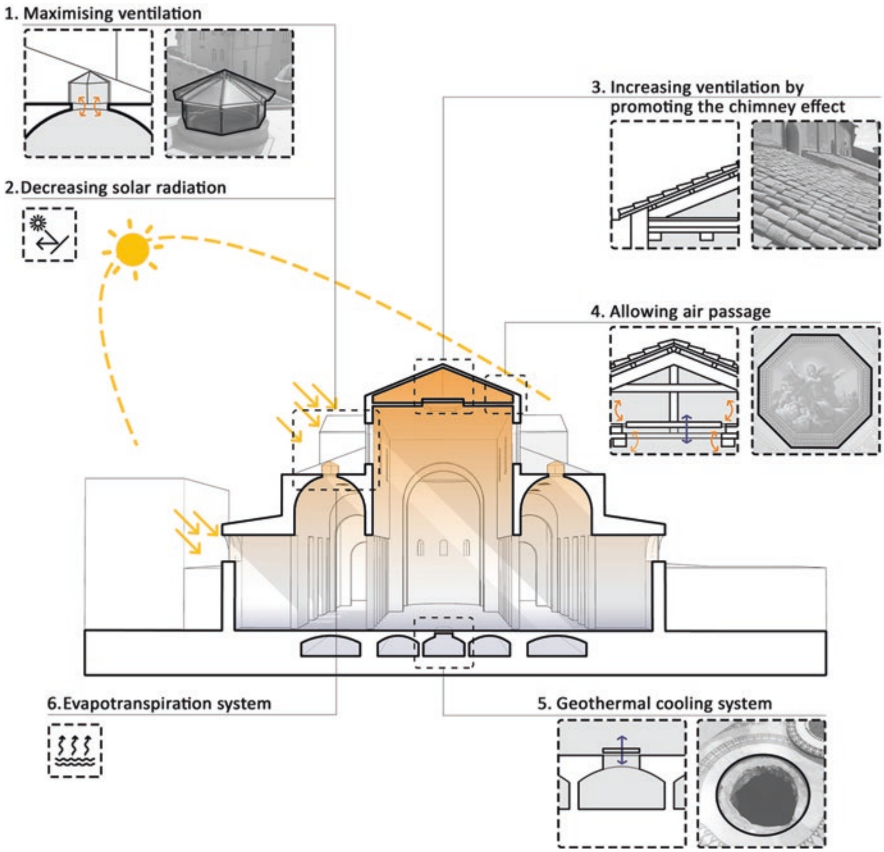

Fig. 12.5 Passive and evaporative cooling strategies for reducing overheating and optimizing indoor comfort

- Maximize ventilation by opening windows of the central nave and of the light chimneys on the vaults of the side naves.
- Reduce solar radiation through shielding devices placed on existing glass surfaces.
- Increase ventilation by enhancing the chimney effect on the roof by creating new openings on the sloping roof tiles of the central nave and transept.
- Allow air to enter through the mobile octagons in the wooden ceiling, planned and designed by Domenichino (1916).

In addition to the listed strategies, the design provides for the implementation of:

- A geothermal cooling system using earth pipes running through the existing holes visible beneath the Basilica’s floor, with collector heads positioned in the western backyard, where wind speed is stronger (2 m/s).

– A misting system located along the south and west facades (where the openings are) and in front of the geothermal collector heads.

Four scenarios have been defined, each of which combines several strategies. The first scenario integrates strategies to maximize ventilation and decrease solar radiation. The second scenario is similar to the first scenario with the addition of the misting system; in the third, the geothermal cooling system is integrated. The last scenario considers all the listed strategies, with the exception of the misting system along the south and west facades and the opening of windows.

12.4.2 Scenario Analysis

Historical-Artistic Integrity Given the need to improve the indoor comfort of the Basilica inside comfort, the architectural, historical, and cultural heritage must be regarded as a non-renewable resource that requires specific attention. Microclimate (temperature and relative humidity) affects materials and materials in turn influence microclimate (Camuffo 2014). With a view to conservation, it is necessary to take into account not only the impact of the construction phase but also the long-term consequences. Therefore, in the assessment of the scenarios, particular attention was paid to the potential irreversible environmental damage and alterations to the historical-artistic identity that strategies for improving microclimatic conditions could cause, in order to avoid or slow down the mechanisms of material deterioration (Camuffo 1998). Another important element to consider is the deposit of particulate matter on the frescoes and delicate materials, which may be indirectly caused by some microclimatic improvement measures. In fact, since all of the scenarios use natural ventilation in various ways to reduce summer overheating, it was hypothesized to lay resilient vinyl-type carpets capable of absorbing dust introduced into the Basilica by users before it is diffused in the environment due to the induced air motions.

Scenario 1. Recognizability: the intervention preserves the volumetric layout and the historical-artistic identity of the building. The added parts (shading devices) are distinguishable from the original and do not interfere with the visual aesthetics and enjoyment of the building. Since the Basilica is physically and aesthetically accessible only from the main front (east), as it is entirely integrated within the urban fabric, the shading devices applied to the side windows are not visible.

Reversibility: the added elements (shading devices) can be easily removed without damaging the original parts on which they are applied.

Compatibility: the materials used do not cause physical or chemical damage to the original materials.

Minimum intervention: the intervention is limited to the bare minimum.

Scenario 2. Recognizability: the intervention preserves the volumetric layout and the historical-artistic identity of the building. The added parts (shading devices and misting nozzles) are distinguishable from the original and do not disturb the visual enjoyment of the building, as per scenario 1.

Reversibility: the added elements (shading devices and misting nozzles) can be easily removed without damaging the original parts on which they are applied.

Compatibility: risks associated with nebulization in the presence of windows are reduced by integrating systems to protect the surfaces involved from the likely deposit of water and therefore humidity caused by the water vapour produced by the nozzles. It is crucial to reduce the risk of biological colonization on the original surfaces of the Basilica (window sills, facade) due to the presence of water, which creates an environment suitable to the proliferation of microorganisms. To avoid physical-chemical alterations of the original materials such as the timber coffered ceiling, frescoes, masonry, and so on, it is important to pay special attention to the degree of humidity of the air that enters the environment.

Minimum intervention: the intervention is limited to almost the bare minimum, as it does not involve structural changes.

Scenario 3. Recognizability: the intervention preserves the volumetric layout and the readability of the historical-artistic identity of the Basilica. The added parts (shading devices, grates on the new geothermal wells, geothermal collector heads) are distinguishable from the original and do not interfere with the visual enjoyment of the basilica, as per scenario 1. The grates of the geothermal wells are in metal and distinguishable from other similar elements present in the Basilica. Geothermal wells are obtained from existing underground cavities, which currently have mobile closing elements. The collector heads are located in the inner courtyard of the Basilica, which is not visible from the outside.

Reversibility: some added elements (shading devices and grates) can be easily removed without damaging the original parts on which they are applied. The construction of underground ducts for the geothermal cooling system is not reversible.

Compatibility: in terms of physical-chemical compatibility, particular attention must be paid to the degree of humidity of the air entering the indoor environment in order to avoid physical-chemical alterations of the materials such as the wooden coffered ceiling, the frescoes, the masonry, etc. In terms of material compatibility, the grates must be of aesthetically and physically suitable material in order to fit into the *cosmatesque* marble floor.

Minimal intervention: the intervention favours the improvement of the indoor microclimatic conditions to make the building usable at the expense of minimal intervention.

Scenario 4. Only the differences compared to scenario 3 are described hereafter.

Recognizability: the added parts (shading devices, grates in correspondence of the new geothermal wells, misting system in front of the geothermal collector heads) are distinguishable from the original and do not interfere with the visual enjoyment of the Basilica. The misting system is realized with contemporary materials and integrated into the inner courtyard of the Basilica.

Reversibility: The misting system can be easily removed without causing any damage to the courtyard it is placed in.
Compatibility: as per scenario 3.
Minimum intervention: as per scenario 3, with optimized effects.

Indoor Comfort Improvement

In order to assess indoor comfort, the operating temperature (To) and the predicted mean vote (PMV) were chosen as benchmarks, in accordance with the previously illustrated methodological framework and 2080 as the reference time scenario, specifically the period of greatest criticality ranging from 21 June to September 21.

Both parameters are crucial in determining the degree of improvement obtained by implementing the different design strategies. The evaluation process starts from the performance-based analysis of the current condition which presents the following reference parameters (Fig. 12.6):

– To: 37.19 °C.
– PMV = 100% hot (heat stress).

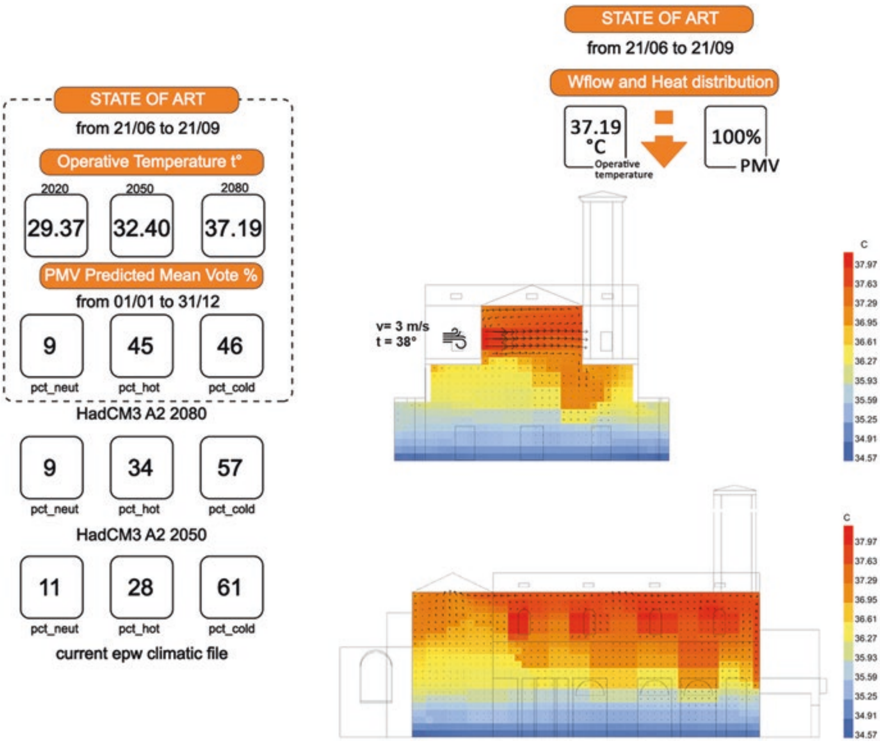

Fig. 12.6 Building performance analysis: state of the art

Scenario 1. The application of shading devices and permeable technological devices (75% opacity, 25% transparency) and the use of natural ventilation through the partial opening (80%) of all transparent surfaces result in a 1.15 °C improvement in To due to a reduction in solar radiation incident on the indoor surfaces, with a 3% PMV reduction. The physical layout of the Basilica and the prevalence of opaque vertical closures over transparent ones both contribute to the limited incidence of the scenario.

To reduction: from 37.19 °C to 36.04 °C = 1.15 °C.
PMV reduction: from 100 to 97 = 3% (heat stress).

Scenario 2. It corresponds to the previous scenario integrated with technological devices for indirect evaporative cooling in order to reduce the temperature of the incoming air and activate natural ventilation flows by exploiting the thermodynamic principles that regulate them. The following formula was used to calculate the temperature of the outlet air of the evaporative cooling system:

$$\text{T, Outlet air} = \text{Db} - \left(\Delta\text{T} \times \text{eff}\right)$$

- Dry bulb temperature (Db): ambient air temperature.
- Wet bulb temperature (Dw): lowest temperature that the air can reach by evaporating the water in the air.
- Wet bulb depression (ΔT): difference between dry bulb temperature and wet bulb temperature (Db−Dw=ΔT).
- Efficiency (eff): ratio of the actual air temperature drop across the support to the wet bulb depression, expressed as a decimal percentage.

Once the temperature values of the evaporative cooling system outlet air were determined, the climatic file was adjusted by replacing the previous values with the present ones corresponding to the dry bulb temperature (Db). The latter was used to carry out the energy analysis. A significant improvement in To of about 5.17 °C with a 15% reduction in PMV can be recorded. Thanks to the opening of the light chimneys on the roof of the side naves and the arrangement of two mobile openings in the central nave and in the transept, a better natural ventilation of the spaces is achieved, triggered by the cooling of the incoming air in the upper part of the central nave (Fig. 12.7).

To reduction: from 37.19 °C to 32.02 °C = 5.17 °C.
PMV reduction: from 100 to 85 = 15% (heat stress).

Scenario 3. It includes a passive horizontal geothermal system that uses earth pipes to cool outdoor air, exploiting the heat exchange with the ground and activating vertical air movements to increase indoor comfort. The EnergyPlus function, which allows to measure the effectiveness of the system associated with a specific thermal zone by defining its characteristics (Table 12.2), was used to determine the outlet temperature of the air exiting the geothermal system.

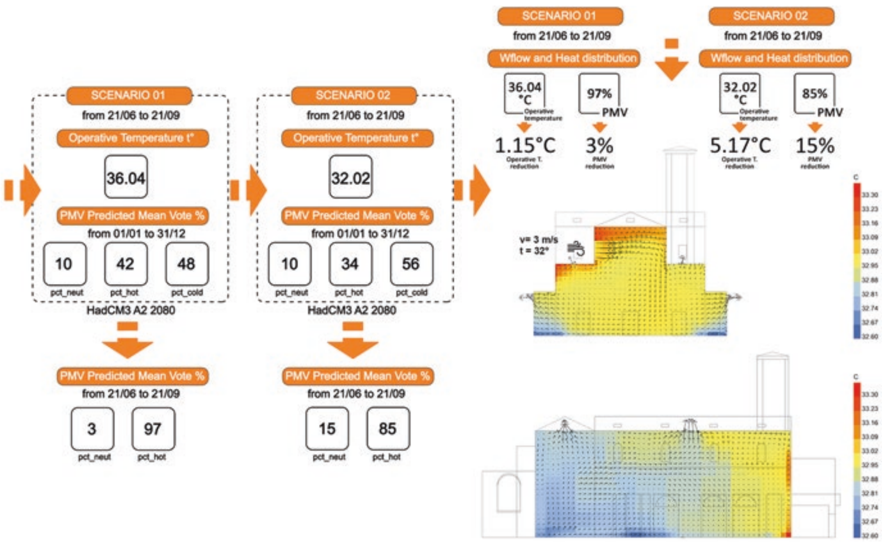

Fig. 12.7 Building performance analysis: scenarios 1 and 2

Table 12.2 Properties and characteristics of the geothermal system using earth pipes

Zone name	ZoneEarthtube
Schedule name	Zone_1
Design volume flow rate	EarthTube
Minimum zone temperature when cooling	3.425198
Temperature when heating	50.0 °C
Delta temperature	1.0
EarthTube type	Natural
Fan pressure rise	350.0
Fan total efficiency	0.9
Pipe radius	0.50 cm
Pipe thickness	0.2 cm
Pipe length	50.0 m
Pipe thermal conductivity	200.0
Pipe depth under ground surface	3.5 m
Soil condition	SurfaceHeavyAndDamp
Average soil surface temperature	15.0 °C
Amplitude of soil surface temperature	5.6
Phase constant of soil surface temperature	0.0
Temperature	0.6060000
Constant term flow coef	2.0199999E-02
Temp term flow coef	5.9800001E-04
Velocity term flow coef	0.0000000E+00

By setting "Earth Tube Zone Inlet Air Temperature" and "Earth Tube Zone Flow rate" as the output of the analysis, the temperature and speed of the inlet air of the system for the CFD simulation were obtained. This strategy provides a slight improvement in To of about 3.73 ° C with a reduction in PMV of 21%.

To reduction: from 37.19 °C to 33.46 °C = 3.73 °C.
PMV reduction: from 100 to 79 = 21% (heat stress).

Scenario 4. The two strategies previously described are combined using a climatic file suitably modified with respect to the dry bulb temperature values in relation to the effectiveness of the two systems which work in a consequential manner. Through the combined effect of indirect evaporative cooling and the horizontal geothermal system, a reduction of To of 8.84 °C and a reduction of heat stress of 45% are obtained. Furthermore, the arrangement of the openings at the floor level and the opening of the octagons in the upper part of the basilica guarantee an excellent natural ventilation of the spaces (Fig. 12.8).
To reduction: from 37.19 °C to 28.35 °C = 8.84 °C.
PMV reduction: from 100 to 55 = 45% (heat stress).

To conclude the evaluation of the indoor comfort increase, the overview table (Table 12.3) shows the results of different scenarios on comfort metrics in 2080 compared to the state of the art.

Economic Feasibility For the evaluation of intervention costs, the 2023 Lazio Region pricing list was used. More specific interventions and processes were deduced from a nationwide market analysis. For each scenario, annual costs related to the operating phase and routine maintenance interventions were estimated, and a summary calculation of total costs was developed.

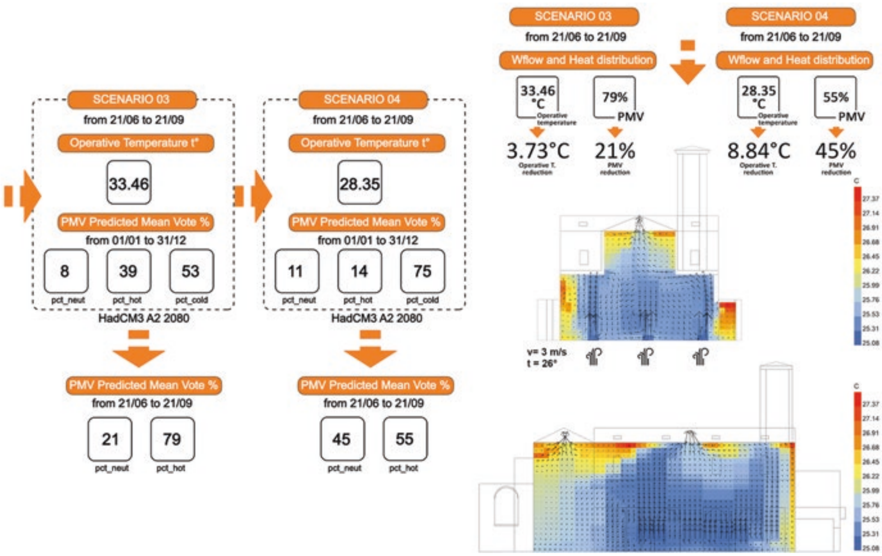

Fig. 12.8 Building performance analysis: scenarios 3 and 4

Table 12.3 Results of different scenarios on comfort metrics in 2080 specifically the period of greatest criticality ranging from 21 June to 21 September

Scenario	Operative temperature (To)	To reduction	Predicted mean vote (PMV) heat stress	PMV reduction
State of the art	37.19 °C	–	100% hot	–
Scenario 1	36.04 °C	1.15 °C	97% hot	3%
Scenario 2	32.02 °C	5.17 °C	85% hot	15%
Scenario 3	33.46 °C	3.73 °C	79% hot	21%
Scenario 4	28.35 °C	8.84 °C	45% hot	55%

Scenario 1. Intervention cost: the estimate of intervention costs only concerns the replacement of existing window openings with more performing and mechanized ones.

Operation and maintenance cost: operating costs are related to the power supply of the window automated system. In terms of maintenance, mechanized window opening requires regular cleaning of the tracks, frames, and sensors to avoid blockages that could affect the functioning of the system, applying a lubricant to the hinges, rollers, and tracks to minimize minimum friction, and periodic inspections to check the correct condition of the motor and gears. The screens only require regular cleaning.

Scenario 2. Intervention cost: compared to scenario 1, costs related to the misting system (nozzles, circulation pump, water treatment unit, and control device) and masonry protection elements placed where the misting system is were also considered. Considering the air motion generated by the temperature difference, resilient vinyl-type carpets with the function of absorbing dust introduced inside the building by users are also included in the calculation.

Operation and maintenance cost: in operational terms, compared to scenario 1, the energy consumption for the operation of the misting system needs to be considered. Considering an average operating time of 4 hours per day for 90 days per year (from 21 June to 21 September), the annual consumption is related to the operation of the circulation pump for 18–20 nozzles (0.5 kW) and the controller (0.05 kW).

Additional maintenance costs compared to scenario 1 are related to periodic checks of the misting system components.

Scenario 3. Intervention cost: compared to scenario 1, the additional costs concern the geothermal cooling system passing through underground ducts. For this intervention the costs related to preliminary geological-archaeological surveys were taken into account. Finally, costs related to the temporary removal of the painted octagons, their relocation, and the demolition of portions of the concrete slab and roofing in order to provide new openings were considered. As in scenario 2, the cost for resilient vinyl-type carpets was also estimated.

Operation and maintenance cost: compared with scenario 1, operation costs include the energy consumption required to activate the heat pump.

Maintenance activities may include cleaning or replacing air filters, inspecting and cleaning the heat exchanger, checking refrigerant liquid levels, and verifying the general system operation. In addition, underground ducts also require periodic inspection and maintenance.

Scenario 4. Intervention cost: compared to scenario 3, the cost items relating to the misting system to be applied near the collector heads of the geothermal cooling system have been added. The calculation also includes the cost items for vinyl-type resilient carpets.

Operation and maintenance cost: the consumption and consequent costs described for scenario 2 together with those for scenario 3 must be considered.

12.4.3 Results Discussion

The comparative matrix created for the multi-criteria analysis (Fig. 12.9) provides an immediate, clear, and rigorous comparison of intervention scenarios based on the evaluation criteria described above.

The multi-criteria analysis reveals that there is no single ideal solution, but that the choice depends on the priority assigned by the stakeholders to each category of analysis (Fig. 12.10a) or even more specifically to each parameter (Fig. 12.10b).

Scenario 1. It is certainly the most cost-effective and least damaging (in terms of historical-artistic impact) solution, as it is a minimal intervention with very low operating and maintenance costs (automated opening of windows), completely reversible and compatible in physical-chemical terms. The effectiveness in terms of improving indoor comfort is clearly limited when compared to other scenarios that involve the integration of several compatible strategies.

Scenario 2. It is a slightly more expensive option with some minor compatibility issues (integration of protection systems for the surfaces in contact with nebulized air and attention to the degree of humidity in the air to avoid physical-chemical

	Microclimate optimization			Historic-artistic integrity					Economic feasibility		
	Operative T [°C] reduction	PMV reduction	MEDIUM PAPAMETER SCORE	Recognizability	Reversability	Compatibility	Minimum intervention	MEDIUM PAPAMETER SCORE	Realization costs	Operation and maintenance costs	MEDIUM PAPAMETER SCORE
Evaluation method	1 - 3°C: 1 3,1 - 6°C: 2 > 6°C: 3	1 - 15 %: 1 16 - 30 %: 2 > 30 %: 3		high: 1 medium: 2 low: 3	high: 1 medium: 2 low: 3	high: 1 medium: 2 low: 3	high: 1 medium: 2 low: 3		high: 1 medium: 2 low: 3	high: 1 medium: 2 low: 3	
SCENARIOS S1	1	1	**1,0**	3	3	3	3	**3,0**	3	3	**3,0**
SCENARIOS S2	2	1	**1,5**	3	3	1	3	**2,5**	2	2	**2,0**
SCENARIOS S3	2	2	**2,0**	3	1	2	1	**1,8**	2	2	**2,0**
SCENARIOS S4	3	3	**3,0**	3	1	2	1	**1,8**	1	1	**1,0**

Fig. 12.9 Multi-criteria analysis and comparative matrix

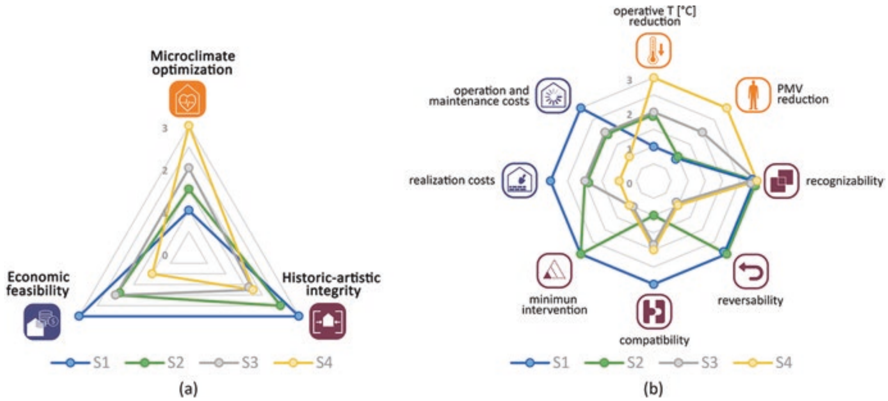

Fig. 12.10 Multi-criteria analysis of scenarios: parameters and sub-parameters

changes in the materials). Overall, it provides a slightly more significant contribution in terms of microclimatic comfort than scenario 1, considering the need for more substantial interventions, both in terms of economic costs and historical-artistic impact.

Scenario 3. It is the most balanced alternative among the three evaluation parameters. It combines reasonable economic feasibility with a significant improvement in indoor comfort conditions. However, this intervention is not entirely reversible. In addition, it is important to highlight that an archaeological interest check must be carried out to ensure that the pipes are built at a depth that does not intercept anthropic soil and elements of archaeological interest.

Scenario 4. It is undoubtedly the best solution in terms of indoor comfort, but as it involves the integration of almost all the strategies used in the other scenarios, it is also the most expensive alternative with the greatest impact on the building's historical and artistic integrity.

12.5 Conclusions

The results show how a careful assessment of the users' needs and the characteristics of the architectural heritage, as well as a synergic and interdisciplinary collaboration among all actors involved, contribute significantly to the identification of optimal and integrated strategies and design solutions.

The research highlights potentials and critical issues regarding the effectiveness of strategies and the relationship with the protected heritage in order to achieve the comfort standards required by regulations. Indeed, the presence of historical-artistic constraints prevents the implementation of some types of interventions that could be more effective in terms of building performance and indoor comfort both in winter and summer, such as the upgrading of opaque vertical closures. In accordance with the current constraints, the technologies identified by the research and applied to the case study of the Basilica of Santa Maria in Trastevere are not sufficient to meet regulatory standards. For this reason, they must be reinforced with active energy strategies. To this end, it is necessary to open a debate on the metrics of thermo-hygrometric comfort and performance with respect to the historical-artistic heritage and its functional programmes. The installation of active systems could be useful in achieving optimal levels of indoor comfort but not very functional for the conservation of materials and works of art. Equally important is the study of innovative and non-invasive technologies (e.g. nanomaterials, PCM) for intervening on the thermodynamic characteristics of the vertical closures that represent the majority of the exposed surfaces.

Another critical issue that emerged from the research is the performance-based simulation process. While the latter allows for a cursory analysis of the performance of the building in relation to indoor comfort, it is also necessary to increase the level of information used by implementing and calibrating the energy model with data processed as a result of instrumental surveys and on-site measurements using appropriate sensors.

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