Natural Ventilation as Passive Cooling Strategy Aimed at Summer Overheating Reduction in Heritage Buildings: The Case Study of Vleeshuis Museum in Antwerp (Belgium)

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Abstract
The challenge of reducing energy demand for historic and heritage buildings, while improving people indoor comfort is widely recognized as common economic and scientific issue.

Historic buildings are not always equipped with mechanical systems for indoor microclimatic control, therefore the indoor climate is strongly dependent from outdoor environmental parameters and specific building dynamic behaviours. Due to the building permeable system, people and exhibits thermal comfort, might drastically change throughout the year or even during a specific day.

Energy and environmental improvement, also for existing buildings is properly considered as a priority within the European energy saving Directives. Nevertheless these design purposes have to be merged with the fundamental needs of building protection. In historical and heritage buildings, each energy retrofitting strategy should be based on the minimum intervention approach.

Reducing the internal summer heating load by increasing the natural cross ventilation or by allowing air mass exchange between different building parts, responds to the double aim of improving the indoor comfort for people and artworks while reducing the energy cooling demand. Furthermore the building architectural integrity may be retained.

In the proposed contribution, Computational Fluid Dynamics (CFD) simulations are performed for investigating people and artworks thermal comfort enhancement after implementing passive cooling strategies.

Keywords: Passive cooling strategies, Heritage buildings, Museums, CFD simulations

1. Introduction

Ensuring simultaneously optimal microclimate for preserving collections or embedded artworks[i] and thermal comfort for staff or visitors in heritage buildings and museums is still an unsolved conflict [1][2].

In such buildings type, artefacts and architectural envelope components, have been acclimatized to the indoor climate the building has from Centuries. Building materials, whether they appertain to artworks or constructive elements, have been adapted throughout the years to the specific building *historic microclimate*[ii].

If the *historic microclimate* is not taken into account during the whole design process, a completely different indoor quality may emerge after the refurbishment.

In this cases, the indoor climate variations induced by the new schedules and systems set points, can cause short and long-term fluctuations far from the ones previously experienced by the building[iii]. In such situations, the new conditions, although theoretically safer, might lead to temporary materials behaviour variations[iv] or either to their premature decay. For instance, the hygrothermal changes into an architectural enclosure, affects the materials seasonal drying cycles.

Materials after the retrofitting actions, might have different time-intervals for fully drying than the ones which would have had the same materials under the previous environmental indoor circumstances. This condition occurs mostly because of the equilibrium moisture content (EMC) alteration [3][4][5].

However, although the original *building historic microclimate* should not be drastically distorted, sometimes it is not adequate for ensuring people thermal comfort, therefore HVAC systems might be required.

Nevertheless, the documented drawbacks of HVAC systems [6][7], combined with the needs of: reducing installations energy cost, equipments invasiveness [8] and, considering at the same time, the main concern of non compromising the original microclimate, have currently raised the interest in implementing passive cooling[v] measures also in heritage buildings [9][10][11]. The option of preferring passive solutions before any mechanical ones is suggested by the EN 15251.2007[vi] .Indeed the Standard proposes to solve the problem of summer overheating firstly by means of passive solutions and only later by proposing active cooling technologies [12].

1.1 Passive Indoor Climate Management In Historic Buildings

The use of passive solutions such as the air stack effect, for natural building ventilation and overheating reduction was an already practised method during the past Centuries, before the customary use of mechanical installations [13][14]. Often historic buildings were equipped with integrated technologies for exploiting heat or mass flow to enhance the indoor climate comfort. Obviously in the past, only the accomplishment to thermal comfort for people was taken into account [15][16].

More recent successful passive cooling applications, seeking to reduce cooling loads by exploiting both: *solar* or *cold chimneys effect*[vii] with minimal initial economical investment, have been widely discussed by C. Ancay in [10]. In the documented cases, the proposed cooling passive systems were based on straightforward design intuitions: the monitored basements, during summer, have shown air temperature far lower than the one in the upper levels, therefore the already existing air ducts (chimneys and shafts) have been reused as *solar chimneys* enabling an upwards air movement from the basement to the attic. In summer period, the air temperature in the attic rooms, was lowered by 14.5°C only by means of passive cooling strategies.

Proposition of adaptive ventilation systems, for improving indoor hygrothermal quality during short year periods in cold climates have been published by P. K. Larsen and M. Wessberg et al. in [17][18]. Furthermore examples of reusing existing architectural features for minimize the installations invasiveness and maximise the indoor quality in heritage buildings are discussed in [8][19].

Although, several case studies have proven the effectiveness of such passive solutions also with regard to heritage buildings, not every times a free running microclimate management is sufficient to ensure the compliance of microclimate requirements for collections preservation: such as controlling the short hygrothermal fluctuations.

Nevertheless, it has to be pointed out that a stringent indoor climate which doesn't admit any dynamic parameter fluctuations is not feasible and not energetically and economically sustainable [20][21][22]. The safer indoor environment is not the one with stringent theoretical temperature and relative humidity thresholds, but is the one iteratively controlled and rigorously evaluated in its short and long-term moisture-thermal dynamics.

Very often the damage to artworks is caused by improper or non-existing climate control. Therefore the activities aimed at controlling and certifying the indoor climate enable, by definition, a safer microclimate.

E. Neuhaus in [6] reported cases in which the threats to the collections were caused by the negligence of curators which did not regularly checked the hygrothermal parameters. If the physical environmental parameters are regularly controlled (frequencies over the time and their spatial distribution), optimal indoor quality may be ensured also by only implementing passive solutions; allowing in the same while, a consistent energy demand reduction, as largely documented by J. Kaferhaus in [23].

2 Research Aims and Methodology

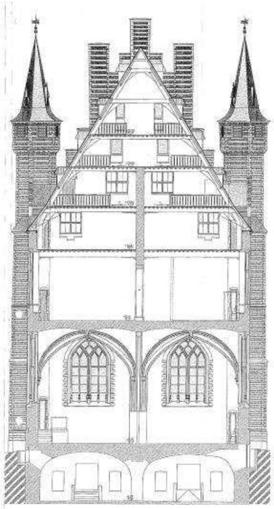
This study investigates possible passive solutions for lowering the overheating, often experienced by the hypogeum exhibition space of Vleeshuis museum during the summer period. Since the building has not air conditioning or mechanical ventilation systems, the people thermal comfort belongs to the adaptive theories [24]. However in the museum, due to the objects preservation and safety requirements, beside the people dress code, there are no other allowable adaptive behaviours. Indeed none window is operable, and fans for allowing air movement are not installed.

The research aims at proposing two passive cooling strategies and evaluating them on the basis of a general thermal comfort improvement.

In the next paragraphs, after a building description and a report on the current ITQ state, the passive strategies will be explained as well as the simulation methodology. Finally the ITQ after simulating the passive cooling strategies will be commented and final conclusions will be drawn.

2.1 Building Characteristics

The Vleeshuis Museum is a typical medieval Flemish slaughterhouse [25]. Although the original use destinations have changed across the Centuries, it is still possible to observe the original architectonic volume. The building was built with the following functions per level:



- The slaughter space was built in the basement level in order to allow the blood and waste disposal; currently it is used as exhibition space (object of this study).
- The covered market space, where the product was sold, is localized at ground floor; this space is currently used as main exhibition space.
- The merchant house, at the first floor, has big rooms and spaces for reception and trade activities. In this space, fireplaces were designed to increase punctually the indoor thermal quality; this level is mainly used either for temporary activities or for artworks storage.
- The upper levels (from the second to the fifth) were built for storing the products; currently these levels are used with offices functions (second floor) and artworks storage.

Image 2.1 Transversal section of Vleeshuis Museum

Although the basement level and the ground floor have the same surface (7.00m x 7.30m), the vertical proportion are completely different: 3.45m the maximum height in the basement level and 8.48m the maximum height in the ground floor. In basement level, high sensible gains from lamps, necessary due to the low day lighting, causes pronounced summer overheating.

The vertical distribution throughout the levels is ensured by five towers with staircases: one in each building corner and one extra tower in the middle of the South facade. The latter tower is the unique one connected to the basement level, therefore considered in the computational domain of the presented CFD simulations.

2.2 Indoor Thermal Quality Evaluation

The Vleeshuis Museum is not equipped with cooling and air mechanical ventilation systems and it has not centralized hygrothermal control, therefore during the hottest summer period, indoor temperature in the basement may reach peaks of 29-30°C.
Reasonably the Indoor Thermal Quality (ITQ) evaluation has been based on the adaptive theories[viii] [26] as considered within the EN 15251 [12].

2.2.1 People Comfort

The thermal classification in EN 15251, is based on the calculation of the operative temperature for three category intervals against the exponentially weighted running mean of the daily mean external air temperature. The exponentially weighted running mean outdoor temperature (θ_{rm}) is calculated from the formula (1)[ix] as reported in [12].

$$\theta_{rm} = (1-\alpha)(\theta_{rd-1} + \alpha\theta_{rd-2} + \alpha^2\theta_{rd-3} \dots) \quad (1)$$

where:
θ_{rm} = running mean outdoor temperature for today
θ_{rm-1} = daily mean external temperature for the previous day
θ_{rm-2} = daily mean external temperature for the day before, and so on.
α = constant between 0 and 1 (0,8 recommended value)

In the EN 15251 is stated: "*the level of* (people) *adaptation and expectation is strongly related to outdoor climatic conditions'*[x]. Basing the comfort expectations on the outdoor temperature in its dynamic profile instead of a given interval, may lead to a less expensive energy management. Therefore acceptable indoor temperature thresholds have been calculated on a dynamic profile throughout the whole monitored period (July- August 2013) on the basis of the six equations reported in *Table 2.2.1.1* taking into account the calculated mean outdoor temperature.

	COSTANT	CATEGORY I	CATEGORY II	CATEGORY III
UPPER LIMIT	*Θi max = 0,33θ_{rm}+ 18,8…*	*+2*	*+3*	*+4*
LOWER	*Θi max = 0,33θ_{rm}+ 18,8…*	*-2*	*-3*	*-4*

Table 2.2.1.1, Acceptable indoor design temperatures for buildings without mechanical ventilation in [12]

NB the design upper and lower temperature ranges reported in Table 2.2.1.1, are expressed in operative temperature instead of air temperature; however within the EN15251 the air temperature might be considered as design temperature[xi] when the surface components temperature do not differ significantly from the air temperature[xii] (temperature difference lower than 4°C) and when the occupants are involved mainly in sedentary activities and they may adapt their dressing code[xiii]. The three categories correspond to different level of comfort expectations, from high (I) to moderate (III). To allow the indoor thermal quality (ITQ) certification, two basic statistical indexes have been introduced: Performance Index (PI) and Failure Indexes (FI). The first (Pi) expresses the percentage (of time) in which the monitored parameter is within an acceptable interval; the second (Fi) expresses the percentage (of time) in which the monitored parameter is out of the acceptable interval. The Failure Index is composed by two deviation indexes for temperature and two for relative humidity[xiv]. Failure warm (Fwi) and Failure cold (Fci) express whether the temperature is higher than the upper category level or lower than the lower category level. Failure superior (Fsi) and Failure Inferior (Fii), represent whether the Relative Humidity is higher than the upper category level or lower than the lower category level.

2.2.2 Collection Wellbeing

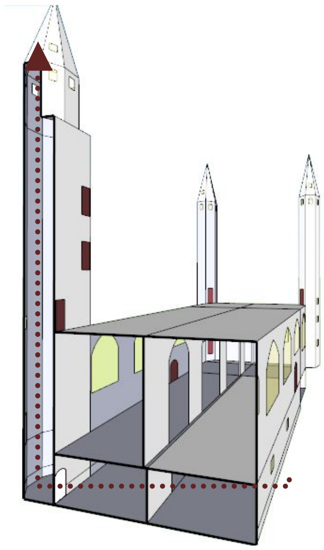
In order to consider a ITQ certification methodology comparable to the one discussed for people comfort, three hygrothermal category intervals have been defined for certifying the microclimate quality with regard to collections wellbeing. The three categories, reported in *Table 2.2.2.1* classify the microclimate quality on the basis of air temperature (T) relative humidity ranges (RH) and their maximum daily fluctuations (Δ).

	Temp (C°)	RH (%)	Δ Temp (C°)	Δ RH (%)
I CATEGORY	19-21	50-55	1,5	6
II CATEGORY	18-24	40-60	1,5	6
III CATEGORY	17-27	≤40; ≥60	1,5	6

Table 2.2.2.1, Hygrothermal categories Artworks

The first two categories represent respectively optimal and acceptable hygrothermal quality level, while the third represents a risky environment. Therefore a Pi higher than 0 in this category represents the percentage of time in which the exhibition spaces have risky indoor climate.

3 Passive Strategies



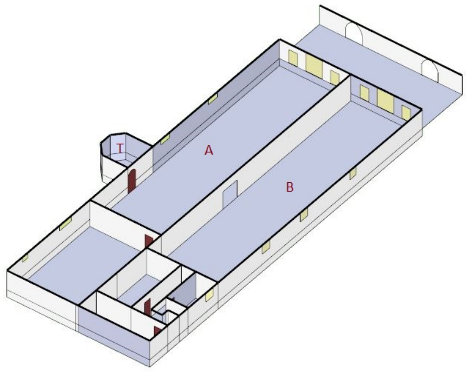
On the basis of the research aims already discussed in 2, two passive scenarios for reducing the summer overheating have been simulated and evaluated in this contribution. In Image 3.1 the three-dimensional representation of the building section shows the research hypothesis, as below explained[xv].

In the first configuration (1), the tower connected to the basement is considered as solar chimney; this configuration may reduce the basement air temperature by air stack effect and thermal buoyancy between the upper tower part and the lower basement part. The above described chimney effect is coupled with basement cross ventilation. Indeed the windows from the North facade[xvi] of the basement level are kept opened[xvii] seeking to enhance the indoor air velocity. In the second configuration (2), the same windows are closed. The air velocity and the relative humidity increase, as a direct consequence of the natural ventilation rise, may pose a problem either for people comfort or for artworks preservation. Therefore both the parameters have been controlled during the strategies evaluation.

Image 3. 1, Three-dimensional representation of Vleeshuis Museum; South oriented tower and exhibition spaces: ground floor and basement level.

4 CFD Methodology

For this study, *VE2014* (Virtual Environment) and its integrated CFD computational module *MicroFlo* was used. The CFD software uses the primitive variable approach, which requires the solution of the three velocity component momentum equations together with equations for pressure and temperature (conservation equations). The set of conservation equation is, linearized and discretized according to the discretization of the computational domain. The whole computational domain is subdivided in finite non overlapping and contiguous volumes constituting a geometrical grid; for each volume the conservation equations are expressed as linear algebraic equations. Hence solved on a iterative calculations. For investigating the fluid flow, in the specific case, the *k-ε* turbulence model has been taken into account[xviii].



4.1 Computational Domain and Modelling Assumptions

In order to reduce the calculation time, the computational domain, has been geometrically simplified: the two exhibition spaces are considered as parallepiped 2.75 high[xix] and the south oriented tower is considered as unique cave structure.

Image 4.1.1; Three dimensional representation of the basement level; South oriented space (A), North oriented space (B); South tower (T)

The exposition space is divided in two, namely A (South oriented) and B (North oriented) by a continuous bricks wall 100 cm tick, see Image 4.1.1. The presence of a large opening in the middle of the wall allows the continuous mass flow through the spaces; while the operable door of the tower allows the controlled mass transport through the exhibition spaces and the tower. A summary of the geometrical characteristics for the simulated spaces is reported in Table 4.1.1.

GEOMETRY SUMMARY	Max. Length (m)	Max. Width (m)	Max. Height (m)	Volume (m^3)	Floor Area (m^2)	Floor Perimeter (m)	Window Area (m^2)	Windows
Exhibition -1 A	25.00	7.20	2.75	629.885	179.981	64.47	7.792	5
Exhibition -1 B	27.00	7.20	2.75	678.750	193.934	68.35	8.222	6
Tower South	3.30	3.40	30.09	329.824	10.899	12.64	6.816	14

Table 4.1.1;Geometrical characteristics summary computational domain

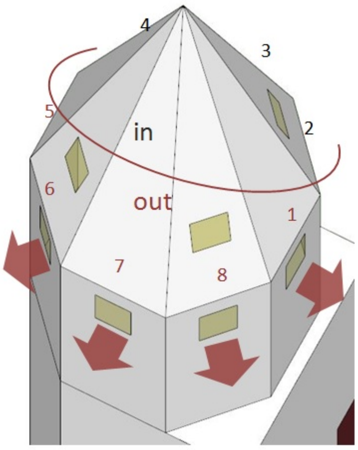
The computational domain for the CFD simulation has been gridded considering 0.10 m grid spacing (homogeneously distributed).

The exhibition spaces are equipped with halogen lamps from 100W (dimmer constantly set at 50%) and small lamps 50W (dimmer variously set), furthermore neon lamps 48W are installed in the showcases. The current sensible heat gains from the lighting system are modelled as uniformly distributed temperature increase on each space surface; the radiant fraction for the specific lamps has been considered 0.45. Since this study aims at generally assessing the hygrothermal characteristics of the exhibition space, no punctual heat sources have been modelled.

People metabolic activity in the museum is reasonably low, sensible heat gains and latent heat gains per person are considered respectively 67W and 50W[xx], the exhibitions spaces are considered with a occupancy factor 0.5. However, the people activity incidence in the whole temperature increasing especially during the summer period in the basement level is negligible.

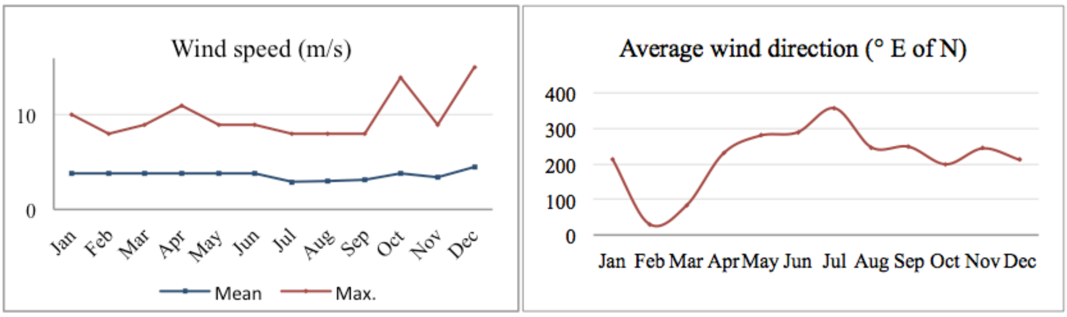
4.2 Passive Solutions

The average wind direction during the summer period in Antwerp is W-NW, while the average wind velocity during the same period is 4m/s, with possible peaks of 8m/s, see Graph 4.2.1 and Graph 4.2.2. For this study, a specific day during the monitored period (31st July 2013) has been considered with the aim of testing the effectiveness of both the proposed passive cooling solutions during typical summer conditions.



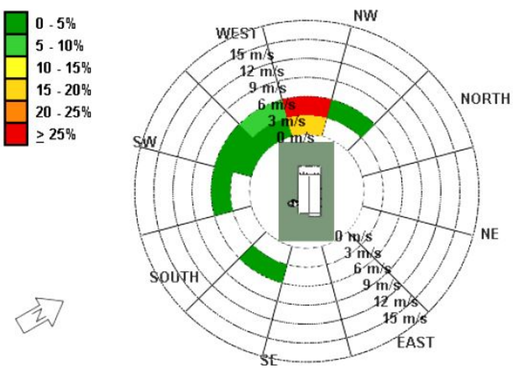
For a better understanding of the impact of external ventilation on the building, a wind rose diagram is proposed in Image 4.2.2. The highest wind frequency, for the selected day has orientation W-NW and air velocity between 3 and 6m/s. On the basis of this diagram it is possible to detect which tower window(s) should be used, as outlet, during the CFD simulations. Although more convenient for the geometrical and physical configuration of the solar chimney, the windows on the roof are not operable, hence with the aim of delivering more realistic scenarios, solely the contribution of the windows: 5,6,7,8;1 (See image 4.2.1) has been considered in *MicroFlo*. The air-flow rate through the windows non directly exposed to the ventilation (5-6-7-8-1) was therefore investigated for evaluating the air flow rate.

Image 4.2. 1; South tower Vleeshuis Museum, detection of outlets; the windows on the roof are not operable

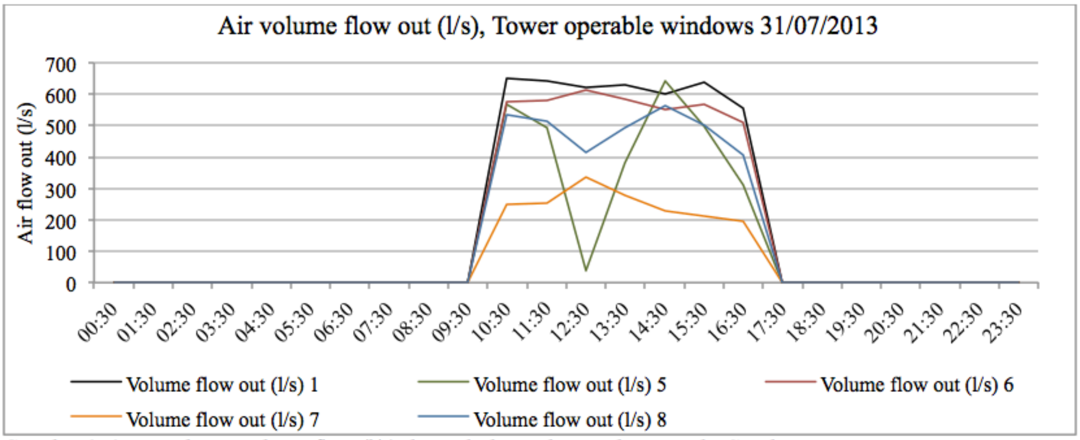


Graph 4.2.1(left) -Graph 4.2.2 (right) Monthly wind direction- Antwerp 2013 (left side), Monthly wind speed and peaks- Antwerp 2013 (right side); from Meteonorm V7.0.22.8.

Image 4.2. 2; Wind rose- Average wind direction and frequency at the studied site during 31 July 2013

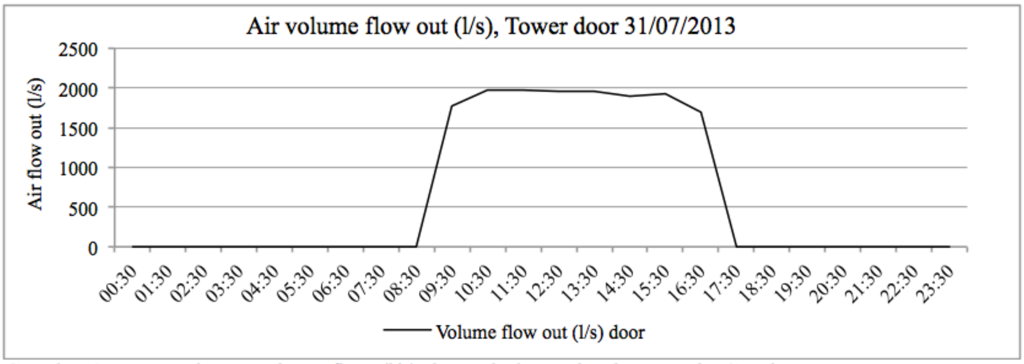


The flow rate for the different modelled window is plotted in Graph 4.2.3. The highest air flow frequency is from 9.30 in the morning to 17.30 in the afternoon. This condition allows a good natural ventilation during the museum opening hours (10.00-17.00), but it does not allow night ventilation. Although night cooling has been proven high effective among the passive cooling techniques to lower the indoor daytime temperature [27], it cannot be applied to the specific case since it is not possible to leave windows open during the nights in the studied museum. Three of the five investigated windows (1,6,8) have high air flow rate (>400l/s), for the whole time interval, while two of them (7,5) have lower or discontinuous ventilation.



Graph 4.2. 3; Hourly air volume flow (l/s) through the outlet windows on the South tower

As the South oriented tower is connected to the basement via an operable door. The air flow rate through the door, during the same time period considered for the windows, is plotted in Graph 4.2.4. Through the door, up to 2000l/s can be blown out from the basement by exploiting the natural stack air effect. The surface opened percentage for the door has been simulated equal to 100% for the entire studied interval of time. Obviously this percentage may be reduced if the air velocity in the basement level will result too high.



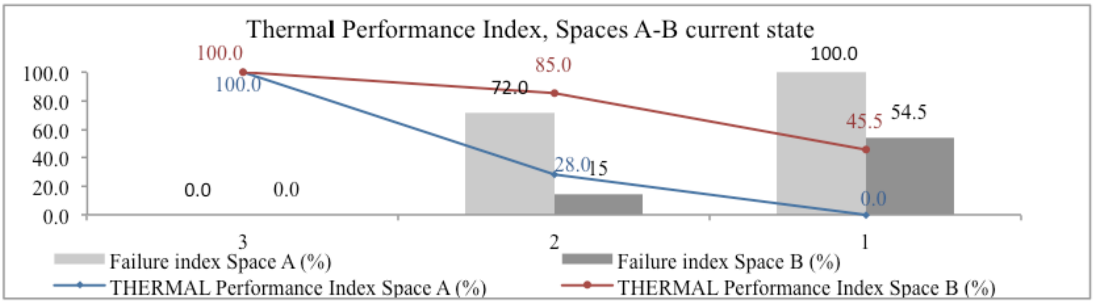
Graph 4.2. 4; Hourly air volume flow (l/s) through the outlet door on the South tower

5 Results Discussion

The ITQ has been verified before and after the passive cooling strategies for both the exhibition spaces (A,B) and both the proposed passive cooling solutions (1,2) either with regard to the artworks *comfort*[xxi] or to people thermal wellbeing. For sake of brevity, the solely first solution will be further discussed as been found the most performing[xxii].

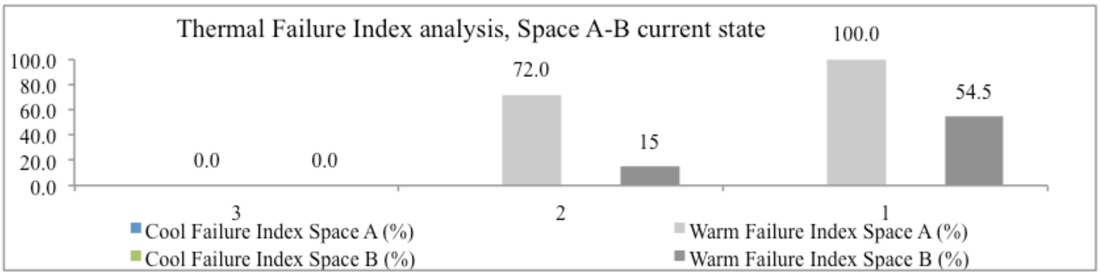
5.1 Thermal Improvement for Artworks, Results Discussion

The current thermal quality certification considering the categories proposed in 2.2.2[xxiii], is plotted for space A and B in Graph 5.1.1. The optimal microclimate (I) is reached for less than half the period in space B (45.5%) and never in space A. The scan thermal quality is consequence of both high internal sensible gains and spaces orientation. Acceptable microclimate (II) is reached for 85% of time in space B and for 28% of time in space A.



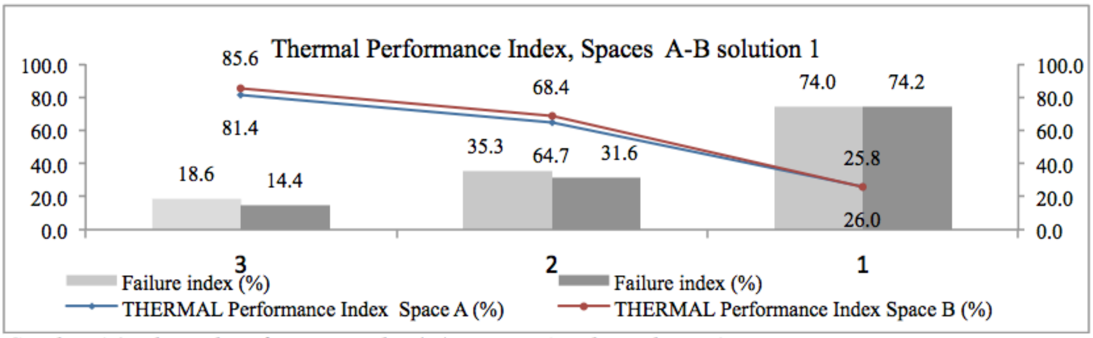
Graph 5. 1.1; Thermal Performance Index (Pi) in space A and B; current state

By breaking down the general Failure index, in the specific deviation indexes, becomes clear, as plotted in Graph 5.1.2, that the real cause of indoor discomfort is given by the high indoor temperature.



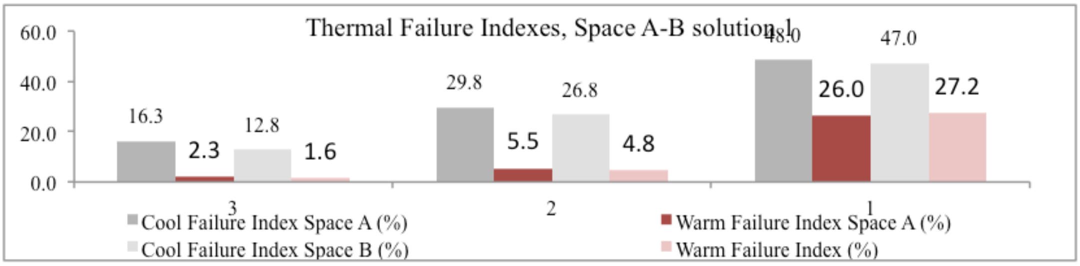
Graph 5.1. 2; Thermal Failure Index (Fi) in space A and B; current state

The indoor thermal quality after the simulations, if analyzed by considering the artworks thermal needs, shows a general improvement, (see Graph 5.1.3). Indeed, beside the increasing of thermal discomfort in space B, the Pi values for space A show an unmistakable quality enhance. The frequency of time in which the indoor air temperature falls into the risk category (III) is reduced in both the exhibition spaces, producing an overall increase of thermal quality.



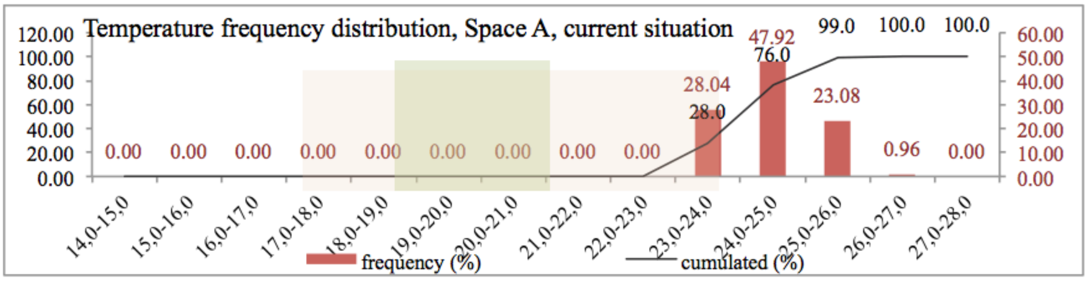
Graph 5. 1.3; Thermal Performance Index (Pi) in space A and B; solution 1

After the passive scenarios implementations, however, a slight discomfort for artworks caused by too cold temperature, on the basis of the intervals given in Table 2.2.2.1, may occur. Indeed after the strategies implementation, the composition of the general Failure index (Fi) is not longer given merely by the Failure warm index (Fwi), as it was in the current state, but mostly by the Failure cold index (Fci). Although there is a general thermal improvement, it might happen that the air temperature sometimes is too low; See Graph 5.1.4.

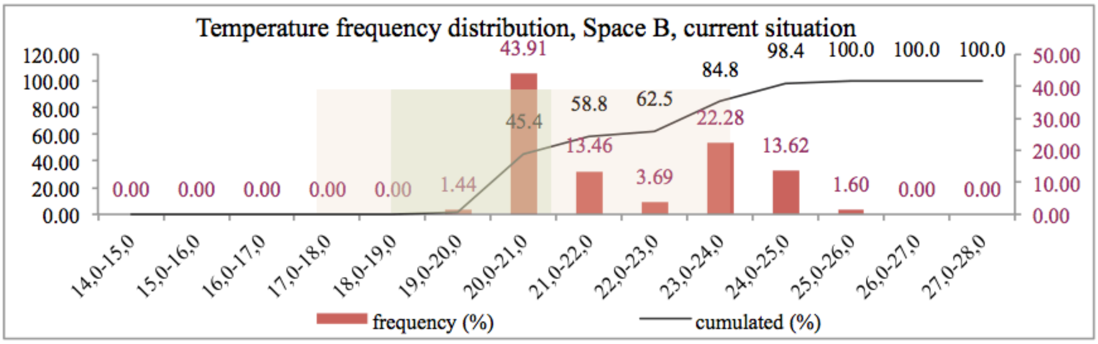


Graph 5.1.4; Thermal Failure Index (Fi) in space A and B; solution 1

In order to study more in details the temperature descreasing in the exhibition spaces, the cumulated frequency of the air temperature, for space A and B, before the passive cooling proposition is plotted in Graph 5.1.5 and 5.1.6. In the above mentioned graphs, the green and yellow squares indicate the optimal and acceptable indoor air temperature (categories I and II). In the current situation, it is evident the shifting of the air temperature frequencies from the safety ranges. In space A, during up to 72% of time, the indoor temperature is out from the acceptable microclimate thresholds; while in space B the temperature deviating from the acceptable interval is 15.2%.

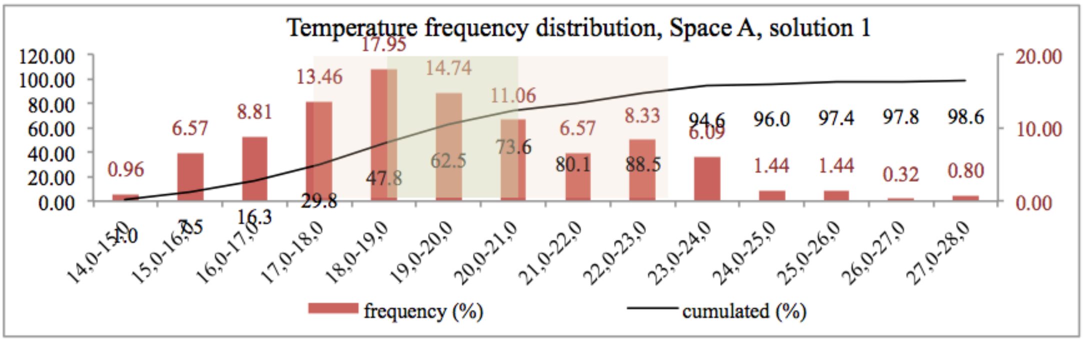


Graph 5.1.5; Frequency distribution space A current state; Indication of first category (green) and second category (yellow)

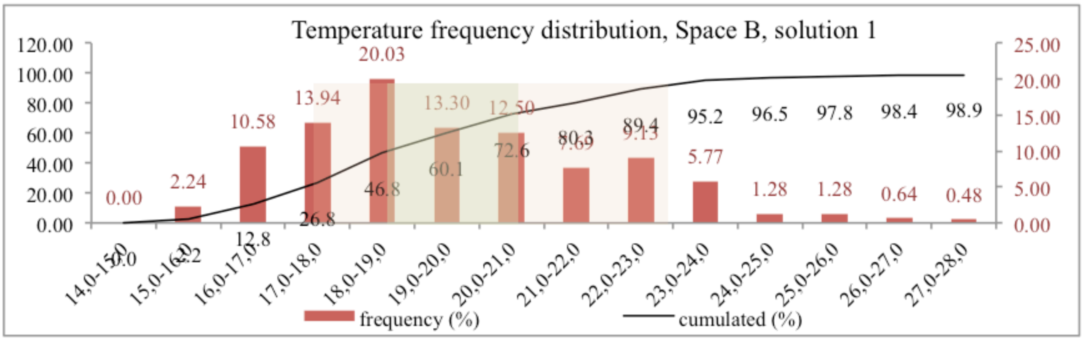


Graph 5.1.6; Frequency distribution space B current state; Indication of first category (green) and second category (yellow)

The Graph 5.1.7 and 5.1.8 show the temperature deviation after the passive cooling strategies simulation. The temperature deviation from the safety interval is reduced up to 26.4% in space A and 5.9% in space B, this shows the high potential of passive cooling strategies in reducing the daily temperature overheating.



Graph 5.1.7; Frequency distribution space B simulations; Indication of first category (green) and second category (yellow)



Graph 5.1.8; Frequency distribution space B simulations; Indication of first category (green) and second category (yellow)

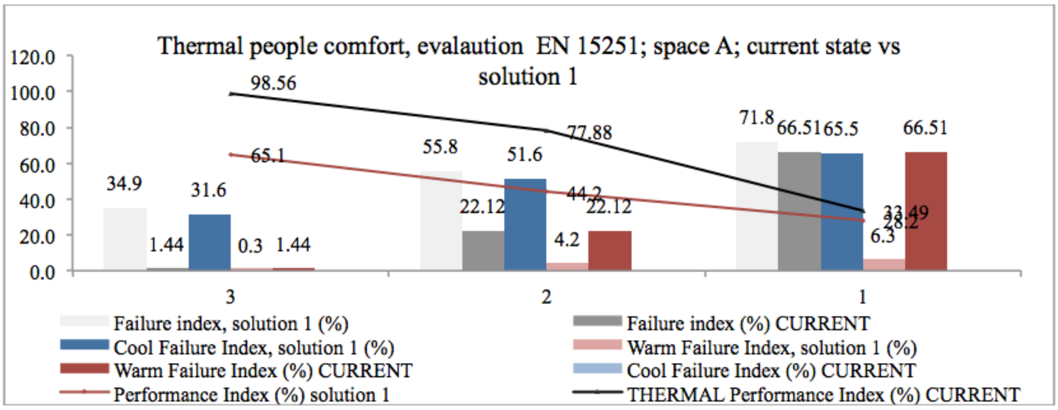
However the general overheating reduction is not the unique factor to be analyzed when evaluating passive cooling scenarios effectiveness. Indeed, the consequent relative humidity and air velocity increase may raise the risk of humidity damage and people local discomfort. The uncontrolled humidity increase is generally the biggest backward of passive technologies and it has to be evaluated case by case. The problem may be solved by installing vents opening systems, equipped with loggers for external-internal temperature and specific or absolute humidity control, as documented by Kaferhaus in [23]. In Table 5.1.1 the percentage of relative humidity out from the safety range (II category) is reported with regard to space A and B in the current state and after the CFD passive cooling strategy 1 simulation.

	SPACE A	SPACE B
Current state	49.60%	57.00%
CFD solution 1	69.80%	69.90%

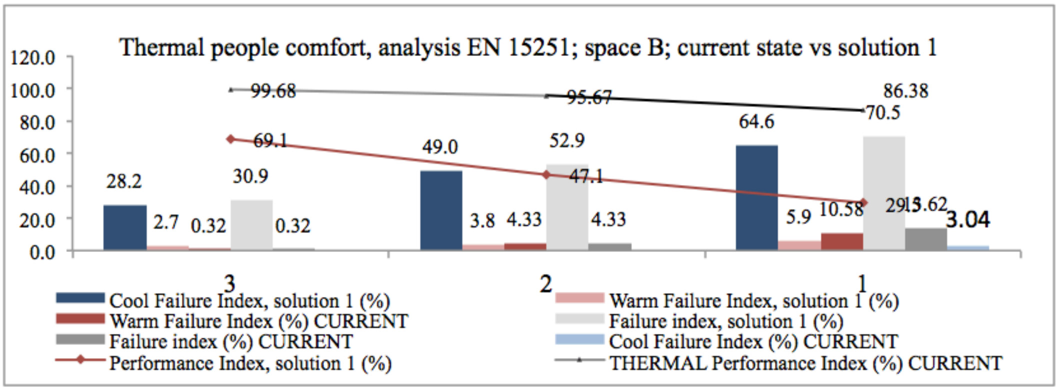
Table 5.1.1; Frequency of relative humidity deviating from the safety levels (II category); current space and after the CFD simulation

The increase of relative humidity deviation from the safety level due to the passive solution simulation is up to 20.2% in space A, however the temperature amelioration in the same space is up to 45.6%. Therefore the passive cooling strategies should be selected on the basis of building priorities and incidence risk evaluation.

5.2 Thermal Improvement for People, Results Discussion



Graph 5.2.1; Thermal Performance Index (Pi) analysis EN 15251, space A current state versus solution 1



Graph 5.2.2; Thermal Performance Index (Pi) analysis EN 15251, space B current state versus solution 1

The methodology presented in 2.2.1 has been applied for evaluating the people thermal comfort before and after the passive cooling strategies simulation. In Graph 5.2.1 and Graph 5.2.2, the Performance Index (Pi) and the Failure indexes (Fi) for each of the three comfort categories, before and after the intervention, are plotted for space A and B. By decomposing the Failure index it is possible to evaluate the discomfort causes before and after the scenarios proposition.

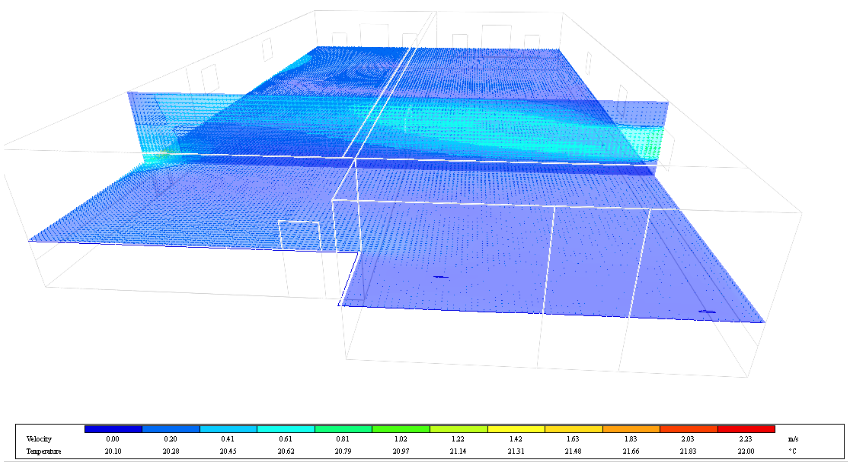


Image 5.2.1; Vertical and horizontal plans for air temperature and velocity tracking

The thermal discomfort (Fi), for the building current state, is caused by the too warm temperature; while in strategy 1, the (Fi) is mainly composed by high (Fci) percentages. In scenario 1, the (Fwi) is reduced up to zero.

The graphs explain the high effectiveness of the studied solution, indeed its adoption may results in a too incisive indoor temperature reduction. As discussed in 5.1 the air velocity increase has to be evaluated as a potential cause of thermal local discomfort, in Image 5.2.1 a combined vertical-horizontal plan sections shows the most perturbed part of the exhibition spaces, namely the connection between space B and A. The air velocity and temperature tracking are displayed on a vertical and horizontal plan (1.10 m high). The North facade windows are kept opened (solution 1). The air velocity field distribution shows values ranging from 1m/s and 0.2m/s. The highest air velocity occurs near the inlet and outlet (windows and tower door) while the lower air velocity is found at people legs level. In both the spaces no air stagnation occurs, the natural ventilation ensures, indeed, perfect air flows mixing. According to the plotted results for solution1, the air velocity does not generate local discomfort as the maximum velocity in the central part (where the visitors and collection are) is 0.81m/s. Higher velocity are reached only in specific boundary spots, for instance where the open windows are.

6. Conclusion

The presented study, although ongoing, delivers interesting results on the effectiveness of passive cooling strategies for lowering the summer overheating in historic buildings.

The proposed strategies have been investigated by means of Computational Fluid Dynamic (CFD) simulations and evaluated with regard to people thermal comfort (on the basis of adaptive theories) [28] and collection optimal microclimate. The indoor climate after the cooling strategies implementation is characterized by air temperature picks reduction: the temperature has been found even lower than the comfort thresholds calculated on the basis of the free running mean outdoor temperature.

However, as a consequence of the temperature reduction a sharp relative humidity increase was found. If the relative humidity increase is considered harmful for the collections or for building materials preservation, the installation of a metering systems on the automatic windows opening ironmongery might be a solution [23]. However the opportunity of investigating passive cooling scenarios before designing any air conditioning systems, especially in heritage buildings where there is the problem of installations integration, should be considered (see EN 15251), the first design option. The results of this research may be updated according to still ongoing research activities.

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[i] Embedded artworks: not movable works of art, such as: frescos, painted wooden ceilings or interior walls.

[ii] Building historic climate defined as climatic condition in a microenvironment where a cultural heritage object has always been kept, or has been kept for a long period of time (at least one year) and to which it has become acclimatized; in EN 15757:2010; Terms and definitions, pag 5. in [29]

[iii] An extensive description of the historic microclimate variation disadvantages, is reported in [3]

[iv] Physical, chemical and mechanical material behavior variations can be caused by the new boundary conditions.

[v] Passive cooling and heating strategies for retrofit design are proposed by Calderaro et. al. in [11]

[vi] The standards proposes to exploit natural ventilation, for reducing the summer overheating, before selecting any mechanical strategy, chapter 6.1 [12]

[vii] In the warm or solar chimney, the external air is drawn into the room, an upward air movement is obtained. In the cold chimney, the air is lead from the basement to the upper rooms; in [14].

[viii] Adaptation: Physiological, psychological and behavioral adjustment of building occupants to the interior thermal environment in order to avoid discomfort. In naturally ventilated buildings these are

often in response to changes in indoor environment induced by outside weather conditions, in Terms and definitions, EN 15251.2007 [12]

[ix] In: *Terms and definition; External Temperature, Running Mean* in [12]

[x] In Building without mechanical cooling, paragraph 6.1.2; EN15251

[xi] Instead of Operative Temperature

[xii] Recommended criteria for thermal environment, Annex A; EN 15251.2007 [12]

[xiii] Annex A.2 Acceptable indoor temperatures for design of buildings without mechanical cooling systems; pag 27 EN 15 251.2007

[xiv] The deviation indexes for Relative Humidity are only used during the microclimate evaluation for artworks wellbeing.

[xv] NB The upper floors are excluded from the CFD computations.

[xvi] Worth of mention: the basement level has splayed windows, different in dimension according to the facade orientation. The openings from outside correspond generally to the street level. With the exception from the West and South-West facades, where the street inclines.

[xvii] The simulated surface opening percentage is 50%

[xviii] Considering the extra equations referring to turbulence kinetic energy and turbulent viscosity.

[xix] The exhibition spaces are 0.65m lower than the reality as they have been interrupted before the vault.

[xx] From Table 6.2 Benchmark allowances for internal heat gains in typical buildings; Internal heat gains-Section 6; CISBE Guide A 2006

[xxi] The authors, with artworks comfort, mean optimal microclimate condition for avoiding hygrothermal stress in artwork materials

[xxii] With higher Performance Index in the first and second category.

[xxiii] Results of current situation refer to the simulations of the exhibition space without the implementation of passive retrofitting strategies.