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Collana fondata e diretta da Carmine Gambardella

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Numerical evaluation of environmental performance of a renaissance building to address a comprehensive retrofit strategy: the case of Palazzo Tassoni Estense in Ferrara (Italy)

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Abstract
Energy retrofit of historic heritage has become a priority of Member States in order to reach new level of sustainability. Strategies to enhance the energy performance of historic building, however, mainly aim at improving indoor comfort and reduce their energy consumption. The scale of interaction among the indoor climate, building envelope's and outside microclimate is still disregarded, although their relationship is very important to i) improve the indoor comfort levels; ii) enhance the outdoor fruition quality (i.e. in museum where the outside perceived temperature and relative humidity may affect the tourist's appreciation); iii) to control the heat urban island effect. Hence, awareness about both indoor and outdoor performances is relevant to address effective strategies to improve natural ventilations, absorption of heat wave, shading, to select finishing materials or add natural elements (water and vegetation). Historic buildings present often a courtyard or porches, which play a strategic role to control the outdoor microclimate. Many authors have studied their performance in hot and arid climate (i.e. Islamic houses) but deepening the knowledge on their contribution in temperate climates and in other architectural typologies is still required. Using ENVI-met® simulations the paper presents a numerical environmental analysis to address design solutions for Palazzo Tassoni Estense in Ferrara (Italy), an example of renaissance typology widely spread in the European area.

Keywords: environmental analysis, outdoor thermal comfort, historic buildings, courtyards, porches, ENVI-met

1. Introduction and state of the art
Energy retrofit of historic heritage has become a priority of Member States in order to reach new levels of sustainability within European Community. Strategies to enhance the energy performance of historic building, however, mainly aim at improving indoor comfort, reduce their final energy consumption and CO_2 emissions. From this assumption, the main solutions of intervention interest the most suitable technologies of insulations and HVAC systems. The scale of interaction among the indoor climate, building envelope's and outside microclimate is still disregarded, although their relationship is very important to improve the indoor comfort levels (i.e. reduction of thermal dispersion, improvement of heat gains); ii) enhance the outdoor fruition quality (i.e. in museum where the outside perceived temperature and relative humidity may affect the tourist's appreciation); iii) reduce the undesirable effects of urban heat island phenomenon and heat waves events for which the single buildings may play an important role in term of impact at urban scale; iv) find suitable mitigation strategies for urban contexts in relation of their characteristics, and v) support a sustainable and energy efficient urban planning from an environmental point of view [1] .
In historic context the impact of the buildings on the environmental conditions is very significant because, in the past, the passive strategies to control the indoor and outdoor microclimate were based mainly on the building's morphology, orientation and materials. Since the ancient times, public spaces were designed to attract people and outdoors activities and make them more pleasant possible [2]. Santamouris, in [3], asserts that, in the current era, characterized by a renewed sense of sustainability, urban planning is addressed to an approach which he defines as "vernacular urban living", searching to propose again some climate-responsive principles, as the location of settlements

along easy transport routes (e.g. waterways), or surrounded by high walls (a barrier against enemies, winds and sand [4]). Hence, the author suggests reviewing the origin of modern cities, based on an incremental growth from a nucleus, in order to solve the problems of city design and make it resilient to future transformations, starting from the revision of the vernacular approach.
In a historic city, where the townscape should be preserved, transforming building morphology or modifying street width is a very difficult issue [5]. However, in historic districts, the environmental performance of outdoor spaces may be effectively enhanced by adding vegetation and green areas or water pools, by improving natural ventilation, by absorption of heat wave and new shading systems, or by selecting more suitable finishing materials for roof or floors.
Thanks to this new point of view, the rehabilitation of historic urban centre could become a strategy for a sustainable balance between the safeguarding of cultural heritage, the recycling of the old city, instead of the use of new “virgin” soil for building expansion [6], the bioclimatic enhancement of urban spaces and the quality of life of the inhabitants. As stated in [7], due to the fact the cultural heritage can be adversely affected by severe weather events and by climatic changes, the outdoors microclimate control could became an important issue of urban heritage preservation strategies.
Several authors in literature have described historic building’s stocks in term of outdoor performance in order to propose suitable strategies of intervention. These studies may be classified by 3 main topics: simulation, monitoring campaigns and surveys for the assessment of i) the influence of urban configuration; ii) the impact of environmental condition on tourist (for museums and archaeological areas) and final users; iii) the analysis of the single building’s shape (courtyards and porches, mainly).
Regarding the urban configuration, authors have analysed the streets/building’s fronts ratio [7], [8], [9], [10], the use of different finishing materials [1] [8], building’s density [1], [10] and the presence of green areas [5]. The output of these researches demonstrated the robust dependence of the distribution of temperature and relative humidity at street level, for the pedestrian thermal comfort, on aspect ratio, street orientation and building’s density in balance between winter solar gains and summer shading. The rehabilitation of old cities has necessarily move from these urban characteristics but, when modifications are not allowed due to preservation aspects, the use of innovative materials or vegetation for the original surfaces plays an important role to mitigate local microclimate at streets canyon level. Some studies, e.g. [9], indicate that improving microclimate by interrupting building’s density with open areas encourage wind speed but did not change surface temperature or the average radiant temperature, advantaged, on the contrary, by the addition of vegetation.
In other documented case studies [1], in presence of a great density, a night urban heat island intensity phenomenon may be registered in the urban historic area compared to the suburban green ones, mainly due to the lack of green areas and the presence of surrounding new neighbourhood, growth following different proportions and with materials which present the highest mean radiant temperature values both during daytime and nigh time.
Many of the already cited studies in addition of other as [11] [12], are focused on the impact of outdoor conditions on human comfort, together with the one on urban space. They provide some design solution for the enhancement of touristic vocation of most historic districts.
The last category of analyzed studies is focused on the assessment of the environmental performance of buildings in relation of their morphology and outdoor spaces. Historic buildings present often a courtyard or porch [3], which have a specific role to control the outdoor microclimate.
Zamani et al. in [13] provide an extensive review about the thermal and microclimatic function of courtyards underlining the importance to study the influence on temperature, relative humidity and natural ventilation of the following characteristics: its width and length ratio, its geometry, the front’s orientation, the presence and position of openings, surfaces materials, and presence of vegetation and water. As authors recognize, the interactions between built spaces and the courtyard has effects at the building, neighbourhood, and urban levels. Other interesting reviews about the function of courtyard as microclimatic system are given by [14], [15], [16] and [17]. The height and the orientation of the courtyard are the two most influencing geometrical characteristics and their most efficient proportion depends strictly on the climate in which the building is located. For this reason, starting from the geographical location of the project is crucial to understand and reinterpret the role of the courtyard to involve it in the retrofit actions or for the design of new urban contexts inspired by it. Reading literature, it is clear that many authors [18], [19], [20] have studied their performance in hot-dry climate (e.g. Islamic houses) or tropical areas with warm-humid climate, where the presence of outdoor enclosed spaces may be strategic over the year.
Deepening the knowledge on their contribution in temperate climates and in other architectural typologies is still required [21]. Only few studies [2], [22], indeed, show the importance to understand their functioning also at different latitudes, where self-shading of the courtyard building causes a cooling load reduction in summer while causing heating demand in winter [13].
Stating the outlined background and this last need of in-depth analysis, the paper presents a preliminary numerical environmental simulation by using ENVI-met® software [23] to assess the current performance and to address design solutions for Palazzo Tassoni Estense in Ferrara (Italy),

an example of renaissance typology widely spread in the European temperate climate.

2. Methodology

2.2 Case study

The selected case study is Palazzo Tassoni Estense, a renaissance Palace, built between the XIV and XV Century, in Ferrara (Italy), nowadays headquarters of the Department of Architecture of the University of Ferrara. For its architectural and historical features, it is listed as part of a UNESCO site. Two main portions, connected by a courtyard, compose the entire complex. The courtyard has three fronts with French and traditional windows and one served by a porch. The latter is made of four arches supported by decorated columns (Fig. 1). After the last restoration works (2000), the courtyard and the porch have been restored adding new finishing for the building's elevations and the external floor, recalling the ancient materials: lime plaster for external wall with whitewashing and old brick for floor. As defined in [14] and [19], the courtyard is an enclosed space which is delimited by buildings and open above and it represents one of the oldest architectural forms. The typical plan of the Renaissance is based on the central scheme, giving the courtyard an important role of symmetry and connection's system of functions and spaces. Furthermore, it had been used mainly in hot-dry regions around the world to provide natural lighting and ventilation as a microclimate modifier for its environmental potentials.

Fig. 1: The courtyard with porch of Palazzo Tassoni Estense (Ferrara).

2.3 Aim of the research and environmental simulation

The aim of the presented study is to analyse the current environmental performance of the courtyard under study, to understand its role in term of hygrothermal influence on outdoor spaces in a temperate climate. The final goal is to suggest some preliminary intervention strategies to enhance its contribution on the whole environmental system of the architectural complex. With these premises this paper aims at testing local microclimate environment inside the courtyard, evaluating benefits and criticalities deriving from different architectural and bioclimatic solutions, by evaluating which effects they can produce typical microscale effects (i.e. thermal loads variations, human outdoor comfort perception modification). Hence, environmental design can be used as a tool to improve the local microclimate to create agreeable conditions for the potential users of the open spaces. The reported analysis is the first step of the research and it moves from some simplified environmental simulations carried out by using ENVI-met® software. In this first phase the simulation have not been calibrated with monitored data or local weather stations, due to the monitoring campaign is still on-going.

2.4 Environmental Simulation Methodology

This paper describes a modeling analysis of the role of different environmental factors in enhancing hygrothermal conditions in a transitional space (courtyard with one side porch), in order to evaluate some mitigation solutions that can promote outdoor comfort for final users during retrofit intervention.

The study has been carried out under summer hottest day, considering the Italian summer as the most critical situation, due to high temperature and high rate of Relative Humidity (RH), and during winter coldest day in some simplified conditions, although, in furthers evaluation phase a proper building, including monitored environmental local data (i.e. local air temperature, local RH, Mean Radiant Temperature MRT) model will be set up, to perform an exhaustive environmental assessment.

In order to perform these evaluations, authors relied on ENVI-met® software, a 3D CFD numerical model, widely accepted [24] as the most capable software in simulating the built environment, surface-air- plant thermal interactions, based on the principles of fluid dynamics and thermodynamics and heat transfer data, on solar irradiation model and vegetation databases. ENVI-met® has got many proven advantages [25] over other built environment simulations packages but it also has some limitations [26]. Simulations for the Palazzo Tassoni Estense courtyard were run for a designated 12h period, from 08.00–20.00 on the 26th July, the hottest day in Ferrara, and on 22nd January, considering winter season coldest day, according to Meteo System Osservatorio Meteorologico di Orto Botanico di Ferrara (FE) [27], considering those times of the day when the courtyard and the south porch are most likely to be occupied. Every data used in the simulations are shown in Table 1. All analyses share a common analysis grid on which the final results are mapped. The boundary model considers 43pixelx43 pixel, with pixel of 1mx1m, with Start Simulation at time 08.00 a.m. and a Total Simulation Time in Hours: 12.

No.	*Parameter*	*Summer Value*	*Winter Value*
1	Ta min	22.3 °C	0.6 °C
2	Ta max	37.1 °C	6.1 °C
3	RH min	28%	63%
4	RH max	75%	87%
5	Wind $_{avg}$ velocity	2.94 m/s	1.7 m/s
6	Prevailing Wind Direction	Est	West
7	U value Walls	0.07 W/mK, λ= 1.6 W/mK	0.07 W/mK, λ= 1.6 W/mK
8	U value Roofs	λ= 0.8 W/mk	λ= 0.8 W/mk
9	Albedo Walls	0.5	0.5
10	Albedo Roofs	0.04	0.04
11	Albedo Pavement	0.3	0.3
12	Pavement Emissivity	0.9	0.9

Table 1: Meteorology, Biometeorology inputs used in simulations.

Besides those data, authors also consider some supplementary criteria, as shown in Table 2, used for assessing outdoor conditions, especially to evaluate the comfort level, in terms of Predicted Mean Vote (PMV) [28] [29].

No.	*Parameter*	*Summer Value*	*Winter Value*
13	Age of person	35 year	35 year
14	Gender	male	male
15	Weight	75 kg	75 kg
16	Height	175 cm	175 cm
17	Base rate	84.49 W	84.49 W
18	Work metabolism	80.21 W	80.21 W
19	Sum metabolic work	142.69 W	142.69 W
20	Walking speed	0,9 m/s	0,9 m/s
21	Pedestrian Clo	0.3	1.6

Table 2: Body, clothing and activities properties used in BIOmet.

Starting with these parameters, simulations for summer and winter condition have been run, and among many parameters, the most suitable ones have been extracted to address an environmental analysis for the current situation. MRT, RH, PMV and predicted percentage of dissatisfied (PPD) parameters have been assessed in this primary environmental analysis. Among many more, those 4 parameters have been evaluated in the Base Case (BC) and, furthermore, the most evident criticalities have been detected.

Wind flow has not been considered, since the courtyard is very narrow with no openings towards the city, therefore there is no effective results in calculation wind flow distribution in this building.
Palazzo Tassoni can be considered a building with very low wind speed and stagnating air masses that unfortunately cannot influence the effect of heat stress, the accumulation of pollutants and any other wind-related mitigation effects. From the BC, authors have set up three different Mitigation Scenarios, MS1, MS2, MS3, that would be used in order to relate any differences and to identify the most suitable solutions to improve outdoor thermal conditions for users. The BC layout (Fig.2) is described in 2.2 Case Study, considering the inputs in Table 1.

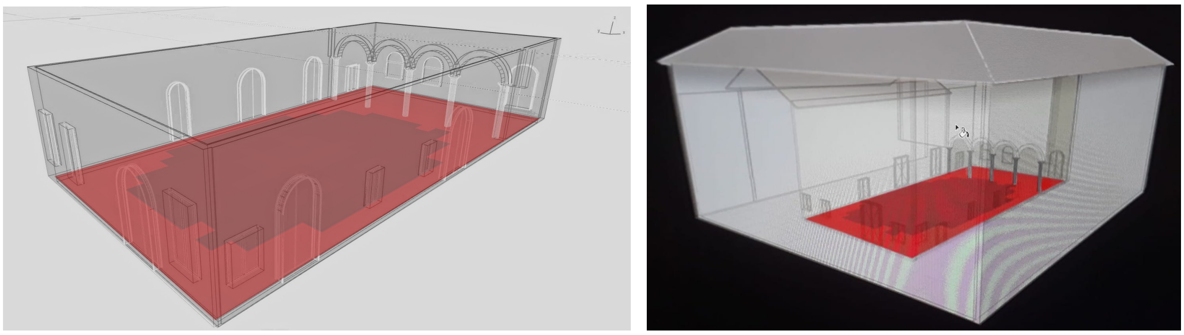

Fig. 2: ENVI-met® model's views for the Base Case of Palazzo Tassoni Estense in Ferrara.

MS1 layout (Fig.3, left) considers a shallow pool in the middle of the open courtyard (13m long and 5m wide, 1m depth), since urban water bodies, such as ponds or pools, are assumed to cool down their surroundings during daytime and nigh time [30] [31] (Fig.4, left).
MS2 layout (Fig.3, middle) considers replacing the current courtyard brick pavement with a green lawn (10m long and 13m wide), with 6 simple plants (2m high) and a central conifer plant (6m high), that are numerically modelled (Fig.4, middle) in arrangements using respectively a leaf area index LAI 5 and a leaf area density LAD 2.5 and LAI 7 and LAD 1.4.
MS3 layout (Fig.3, right) considers replacing the current courtyard brick pavement with modular pavement (14m long and 22m wide) with high draining capacity, in order to evaluate the cooling advantage in comparison (Fig.4, right) to the higher heat capacity of conventional urban pavement's materials that contributes to heat islands at night, when they release the stored heat.

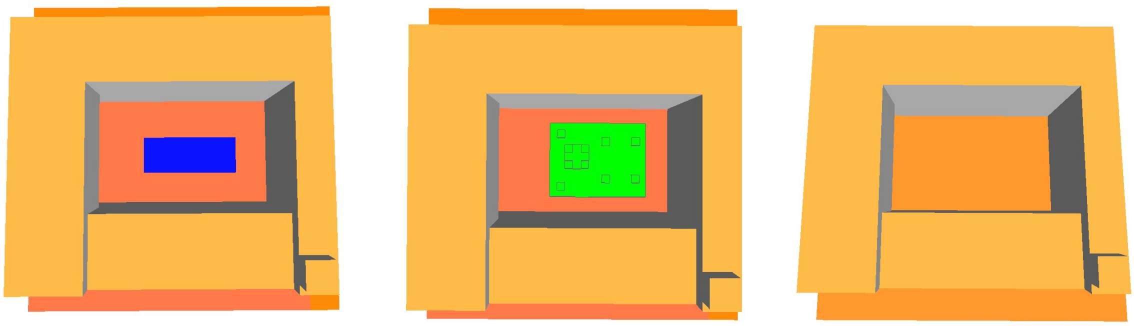

Fig. 3: MS1, MS2 and MS3 configurations in the modeling tool interface of ENVI-met® – 3D view.

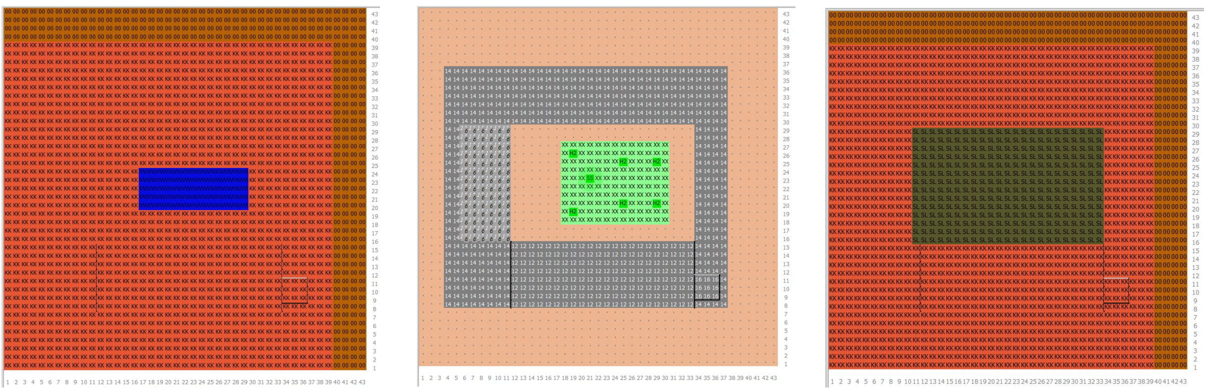

Fig. 4: MS1, MS2 and MS3 configurations, in the modeling tool interface of ENVI-met® – plan view.

3. Results

The selected parameters (RH, MRT, PMV and PPD) have been evaluated for each scenario configuration and calculated in three different sections (S1, in the middle of the porch; S2, 3m from the porch and S3, in the geometric middle of the courtyard), at 1.5m height from the ground and for a time period of 12 hours (from 08:00 to 20:00). In order to provide a plausible study, and in order to summarize the great amount of data calculated for each scenario, authors present the main values for each parameter, by aggregating the average values for BC and for MSs, on July 26th and on January 22nd (Fig. 5-8).

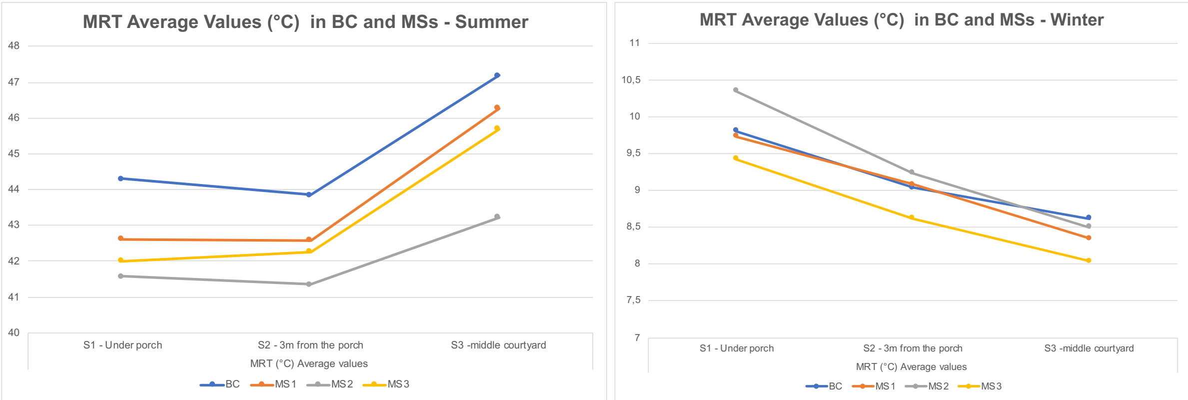

Fig. 5: Mean Radiant Temperature MRT average values, for the BC, MS1 (with water fountain), MS2 (with green pavement) and MS3 (with high draining capacity pavement), summer values (left) and winter values (right).

Fig. 5 illustrates the MRT values of the 3 courtyard layouts (MSs) compared to the BC, on the hottest day (on the left), and on the coldest one (on the right). With regards to MRT, in summertime the most critical value is registered in the middle of the courtyard for every scenario, with a peak value in the BC, where the existing pavement is responsible for raising the MRT till 47.19°C. Conversely, MRT values drop significantly in MS2, thanks to the presence of green masses, which contribute in decreasing MRT from 47.19°C to 43.23°C, with a difference of almost 4°C (3,96%), thanks to the introduction of low-trunk trees and lawn. A similar trend can be read in MS3, that registers lower temperature than BC, with a greater decrease (-2.3°C) under the porch. It is also noted that in MS1 the drop in temperature (compared to BC) is almost identical in the section S1 under the porch and in S2, three meters away from the porch, as the water pond is located far from the porch itself and the evapotranspiration effect is not that effective under the porch or in its immediate vicinity. Therefore, in the summer, replacing the existing flooring with large green surfaces has been assessed as the most effective solution in reducing MRT.

Based on winter assessment (Fig.5, right) MS2 is, nevertheless, the most effective solution in raising MRT, since the green lawn assures an increasing of 0.54°C in S1, 0.2°C in S2 and a slight increase in S3 (+0.1°C). Differently from the summer trend, MS3 impairs local temperature with respect to BC; this information thus suggests that a high drainage pavement does not help in increasing winter MRT inside the courtyard. Outwardly, the presence of a draining pavement, as planned for MS3, is quantitative worsening also with respect to the existing one, as in the BC.

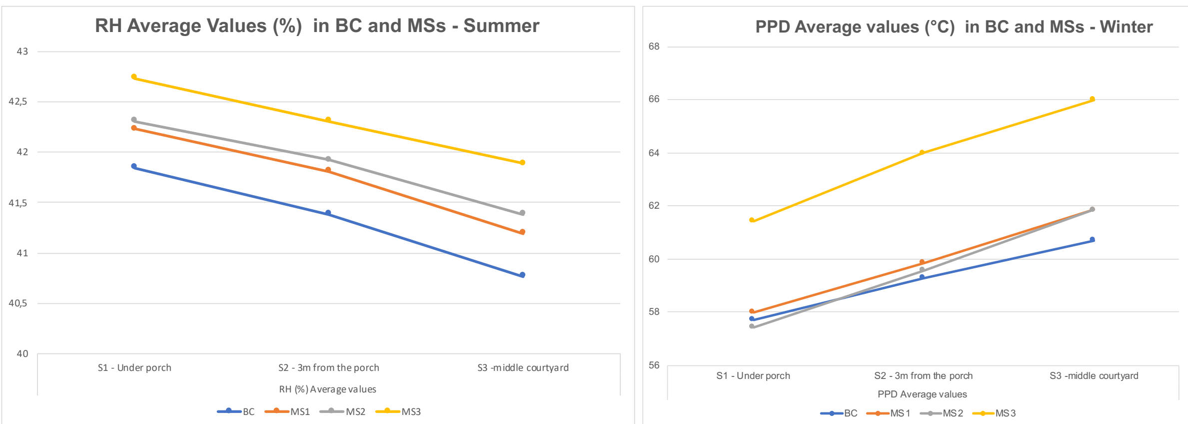

Fig. 6: Relative Humidity RH average values in the BC, in MS1 (with water fountain), in MS2 (with green pavement) and MS3 (with high draining capacity pavement), summer values (left) and winter values (right).

Fig. 6 illustrates the values of RH as the urban layouts were altered, at three different sections, on summer hottest day, as represented on the left, and in winter coldest day, on the right.
With regards to RH, evaluated at three different sections, Fig. 6 clearly states that every mitigation scenario is slightly more humid than BC, in particular MS3 is the one responsible of the largest rise in RH (+0,98%).
RH data cannot be assessed individually, but the trend should be read in relation to temperatures' trends and air flow ones. Since air flows can be here neglected, due to the narrowness of the courtyard and due to the absence of openings towards outdoor environment, RH can be read along with MRT information.
Fig.6 on the left shows that the lowest value in RH is calculated in the middle of the courtyards, on the hottest day, for each of the MSs and it reaches the lowest value, in MS1, where RH is 41.2%.
Those data show that, during the hottest day, without taking into account the contribution of air flows, none of the tested MSs is truly effective in reducing RH, against BC percentage.
With reference to winter evaluation, RH values can be considered within an acceptable range in BC (average value assessed in three section is 64.23%) for northern Italian climate.
MS2 is the only scenario in registering lower RH, with the lowest value under the porch (63%). All MSs increase their RH values in the centre of the courtyard.

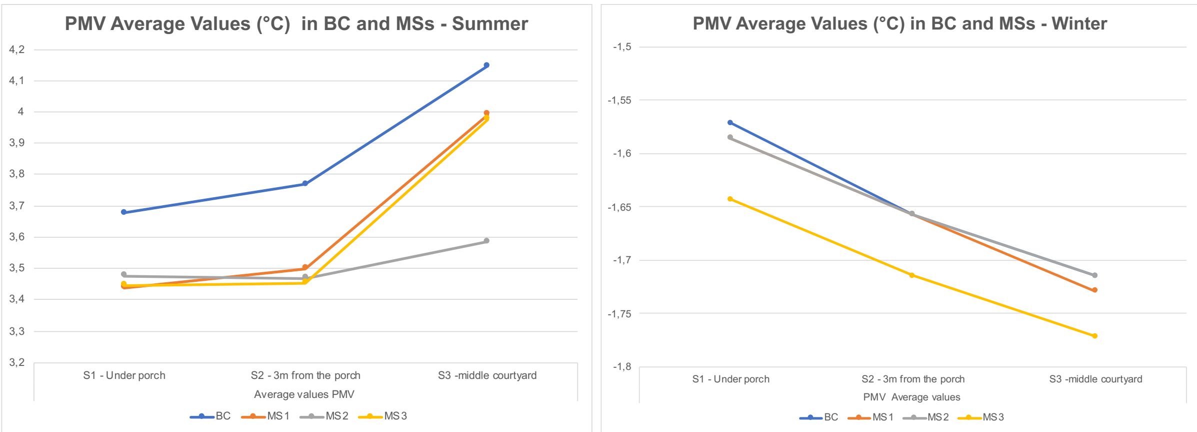

Fig. 7: Predicted Mean Vote PMV average values in the BC, in MS1, in MS2 (with green pavement) and MS3 (with high draining capacity pavement), summer values (left) and winter values (right).

Fig.7 illustrates the values of PMV registered in the 3 layouts compared to the BC, on July 26th (on the left) and on January 22nd (on the right). As PMV index predicts the mean response of a larger group of people according the ASHRAE thermal sense scale [32], it can be noticed that MS1, MS2 and MS3 show some enhancements in subjective comfort parameter, compared to BC, which registers the worst outdoor comfort condition and the highest PMV values.
PMV calculated for BC is 3,7 – very hot – in S1 and, even more critical in S3, where PMV average value for 12h is 4.1 – extremely hot –, that can cause a strong heat stress, as ISO 7730 standard [33] defines the hard limit as ranging between -2 and +2.
At S2 (3m beyond the porch), as well as in S3 (in the middle of the courtyard), MS2 scores a decrease, improving comfort conditions, since in S1 (just under the porch) PMV is 3,37 and in S3 PMV is 3,58 (-0.56 against BC). MS2 shows almost identical values in all calculation sections, whilst MS3 is more effective in lowering PMV values in S1 (- 0,53) and S2 (-0,52).
PMV, calculated for the coldest day, shows that MS3 registers the lower values, in each section. MS3 considerably worsens the index for ratings of thermal (dis-)comfort. MS1 and MS2 are completely comparable to BC in terms of outdoor comfort, as rated by final users.
Eventually, in Fig. 8 the values of PPD are represented for the 3 layouts, compared to the BC, during summertime on July 26th (on the left), and on January 22nd (on the right).
At the neutral temperature as defined by the PMV index, PPD usually indicates that 5% of users will still be dissatisfied with the thermal environment: PPD in BC registers an average value around 89%, regardless of where it is detected. PPD values are almost unchanged in MS1, MS2 and MS3, unless some minor variations, that can be detected in MS2 in the middle of the courtyard, where the PPD is 87.23%.
In BC layout the majority of subjects is extremely dissatisfied in every calculated section, MS1 appears the most appreciated under the porch (S1 with PPD average value of 87,57%) while, in MS2, middle of the courtyard section, is the most effective in lowering the percentage of dissatisfied (-2.11).

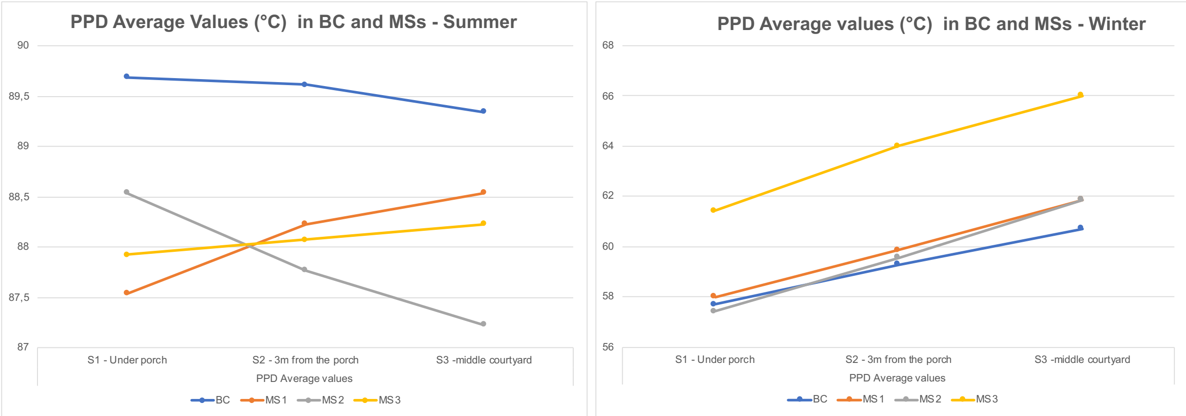

Fig. 8: Predicted percent dissatisfied PPD average values in the BC, in MS1 (with water fountain), in MS2 (with green pavement) and MS3 (with high draining capacity pavement).

During winter day, PPD registers a lower percentage of dissatisfied, that still accomplish neither ASHRAE 55, nor ISO 7730 standard. BC and MS2 list the lower value in S1, under the porch, with a PPD of 57% each, deviating from the acceptable value, by 37%. The worst-case scenario is represented by MS3, with an increase of dissatisfied people around 6%.

4. Discussion

As evident from the graphs of summer and winter evaluations, each MS can offer differently some benefits and disadvantages.
This means that, applying bioclimatic control strategies for heat mitigation or RH reduction cannot always be considered successful, both in summer and in winter.
Generally, increasing evapotranspiration, as in MS1, or increasing the degree of permeability for built surfaces, as in MS3, does not offer the same effects during the hottest day and in case of the coldest one. As MS2 and MS3 (summer) share design solution of increased perspiration and permeability, their PMV curves show the same trend, reducing the thermal summer discomfort, as in BC, thus also proving to be the most effective in lowering temperatures locally.
According to summer evaluations, MS2 is the best solution in slightly reducing MRT, but MS2 does not reduce RH (due to the presence of green mass) as much as MS1 does. In winter scenario it can be said that MS2 offers the most relevant hygrothermal improvement strategy, both in enhancing MRT and in RH, as PMV also emphasises.
The most effective scenario tested so far, generally both for the hottest day and for the coldest one is therefore the MS2, that uses green masses, vegetation and a vast lawn as a passive control strategy to reduce MRT in summer, to increase MRT in winter and in order to enhance the PMV values.
Nevertheless, using vegetation as a bioclimatic solution can have some negative effects on RH percentage, especially in summer.
Regardless the examined factors, the south porch is the area slightest affected by the changes offered by the three mitigation scenarios, conversely, the middle of the courtyard shows the largest variations among MS1, MS2 and MS3.
It remains understood that more evaluations have to be performed, involving many more parameters, in order to offer a complete assessment in case of severe weather events and in order to better depict the complex variations in seasonal weather, in temperate climate.

5. Conclusion and future developments

As evident in results of ENVI-met® evaluations, the main factors that influence an environmental outdoor assessment in case of temperate climate derives from the significant seasonal differences in air temperatures, relative humidity levels, air flows, of each season, as well as materials' albedo values for finishing and pavements.
In the BC here presented, the local influence related to air flows has been neglected due to the morphology of the courtyard itself. The improvement effects related to the variations in MRT, RH and PMV are here presented: in case of retrofit actions outdoor comfort and energy saving measures has been derived from the presented scenarios.
Nevertheless, the environmental results need to be further investigated to outline the main differences between the role as microclimate tool of the courtyard in hot and arid climate compared to the temperate ones. In the next phase of the research, a more sophisticated model will be provide, validating it thanks to some in situ monitored data (the monitoring campaign is still on-going) to verify all analysed data. A new numerical evaluation should be run by taking into account more

environmental factors, building materials features, and by calculating also indoor environmental energy behaviour, for a designated 24h period. The next level of analysis may be focused on the influence of outdoor conditions (especially the ones surveyed under the porch) on the indoor one, to quantify the energy performance of the building, taking into account both envelope and HVAC performance and heat exchange given by outside conditions. This last aspect, indeed, is still not studied in depth in the literature but may be crucial to address suitable retrofit actions.

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