IOP Conference Series: Earth and Environmental Science

Experiments on Microclimatically adapt a courtyard to climate change

To cite this article: Emanuele Naboni *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1196** 012032

Experiments on Microclimatically adapt a courtyard to climate change

Emanuele Naboni[12], Rossella Siani[1], Marcello Turrini[1], Elefteria Touloupaki[3], Barbara Gherri[1], Francesco De Luca[4]

1 University of Parma; Department of Engineering and Architecture
2 Royal Danish Academy; Institute of Architectural Technology
3 Aristotle University of Thessaloniki; Department of Civil Engineering
4 Tallinn University of Technology; Department of Civil Engineering and Architecture

rossella.siani@unipr.it

Abstract.
Climate change impacts biodiversity, the use of public spaces, as well as building energy demand, and health in Mediterranean cities. The courtyard is a common typology of private/public open space in the area, which, according to previous research, is substantially affected by climate change. The main reasons are to be found in limited ventilation and the significant amount of radiation received by upper surfaces. A preliminary microclimate, simulation-based evaluation of mitigation strategies to adapt and capitalize on climate changes is here performed through the assessment of a series of analyses using reference year 2020 and 2080. The study addresses a representative courtyard, San Sepolcro cloister (Parma, Italy). One mitigation strategy is explored, limiting direct solar radiation. The shading system, which reduces solar radiation, arises from a process of morphogenesis based on solar parameters and exploits a strategy with vertical structures typical of some cacti, following the biomimicry approach of imitating natural strategies. In this case, the imitation regards both form and function, as well as the generative process. The research was conducted through parametric and generative design in Rhino-Grasshopper and environmental analysis in ENVI-Met. The Universal Thermal Climate Index (UTCI) was the reference index for the assessment of thermal comfort. The shading system allows for improving thermal comfort, through protection from the sun's rays and the non-obstruction of the vertical ventilation of the courtyard.

Keywords: Climate Change, Microclimatic Studies, Biomimicry, Parametric Generative Design, Courtyard, Shading.

1. Introduction
Parma, like many cities in the Mediterranean context, is a town characterized by a big number of courtyards[1], known for being thermally pleasant and rich in vegetation [11]. Urban heat island (UHI) [12] and climate change [13, 14, 15, 16] negatively affect their microclimate [17]. This has reduced their capacity of supporting biodiversity, and the energy load of adjacent spaces, often with air-conditioning units further emitting heat towards the courtyards [18].

2. Background
2.1. Thermal and microclimatic function of courtyards
With regards to the microclimatic aspects of the courtyards, shading [19, 20, 21] is one of the most relevant aspects to be considered: the amount of shadow changes in the courtyard during the day, as temperature differences in air temperature occur between building fronts and the open space [22, 23]. The thermal variations generate convective exchanges between the surfaces and the air that can greatly influence outdoor and indoor spaces of the courtyard. Furthermore, the heat gained during daytime is stored in the thermal mass of the courtyard, in the inner walls or under the arcades and it is then released at night. [24] The scarce natural ventilation contributes to dissipating only a small fraction of the heat.

In a changing climate, where UHI is enhancing its effects, numerous studies have been investigating the role of courtyards in decreasing UHI effect, and several techniques have been assessed aiming to optimize outdoor thermal comfort in these open spaces [25, 26] . In this regard, this paper evaluates the microclimatic function of a selected courtyard, to adapt it to the future projected scenario, via different parametric designed strategies.

3. Methodology
The present research identifies a recurring construction system: the courtyard building. A typical courtyard in the Italian city of Parma, region of Emilia Romagna, is selected as a case study. A comparative microclimate analysis of the courtyard of San Sepolcro cloister and its surrounding areas has been performed for the year 2020 (present) and 2080 (projected) focusing on three different levels: the urban, the neighborhood, and the building level. The initial microclimate assessment is performed using ENVI-Met [27] and reveals some climate-related criticalities to be addressed, present both for the year 2020 and 2080.

One design solution to mitigate the courtyard's criticalities is then designed accordingly. Biomimicry [28, 29] and algorithmic morphogenesis using environmental parameters are adopted as design approaches. The software used for the design phase of the project are Rhino/Grasshopper [30], together with Galapagos and Ladybug Tools. In the end, the resulting solution is subjected to new environmental simulations for verification. The methodology is based on a parametric approach; therefore, it is applicable to courtyards in other climatic or temporal zones.

3.1. The courtyard of San Sepolcro cloister in Parma – the case study.
The case study is the courtyard of San Sepolcro cloister. The convent was erected in 1257, while the cloister dates back to 1493-95. The Renaissance architecture of the cloisters features a single-storey square plan, with a loggia only on the ground floor. It has three porticoed sides, while the north side was buffered in the XIX century. Each side has six round arches in sandstone, which overlook the green

[1] A courtyard can be defined as "an area of flat ground outside that is partly or completely surrounded by the walls of a building" [1]. A courtyard building is an open space that can be partly surrounded by buildings and is traditionally part of a castle, a large house, a religious building and many more. Several studies have clarified that courtyards can generally decrease energy consumption [2] and improve the microclimate of surrounding buildings. Different factors can have a significant impact on courtyard thermal behaviour (geometry, proportion, orientation, opening features, and building materials). In addition, many other architectural elements such as shading devices, vegetation, and pools can modify the overall microclimate inside the courtyards, altering indoor, outdoor temperatures and solar radiation, and natural ventilation [3, 4, 5, 6, 7, 8, 9, 10].

interior open space, where several trees such as figs and pomegranates grew in the past. Today only a small box hedge and a decentralized well remain in the cloister [31].

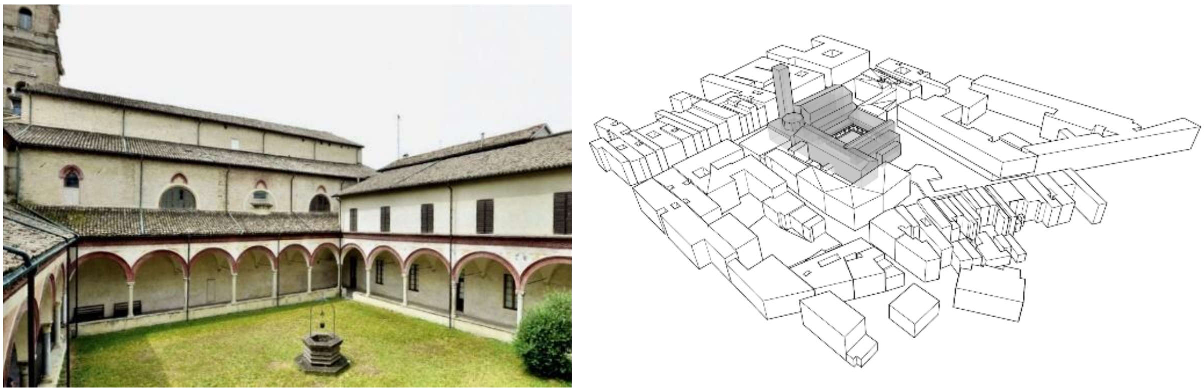

Figure 1. Cloister of San Sepolcro. Cloister of San Sepolcro overview in the urban context

3.2. Case study analysis

The first step for the analysis was downloading the EPW files for 2020 and for 2080. Using the software Meteonorm (Version 8.1.4), the location "Parma" was set as an interpolated city. The temperature values were interpolated among 6 weather stations at a distance between 48 and 124 km, while radiation was based on satellite data. The 2080 data were shifted with Meteonorm, according to the IPCC scenario RCP 8.5. These two files were used for the full forcing of radiation, temperature and humidity in the settings of ENVI-met.

One 3D model has been made importing the geometry from OpenStreetMap. Using the plug-in Dragonfly Legacy of Ladybug Tools, the geometry has been adapted for the simulation with ENVI-met. The materials of the model have been customized starting from the database of ENVI-met. After a site survey, the building materials selected for the walls were brick walls with light plaster, dark plaster and exposed, while the roofs were with tiles (Table 1).

Material description	*Absorption %*	*Reflection %*
Light plaster	*35*	*55*
Dark plaster	*70*	*20*
Exposed brick	*55*	*10*
Roof tiles	*70*	*20*

Table 1. Wall/roof materials

Analogously, the pavement surfaces were customized according to literature values and based on visual survey. Asphalt, smashed bricks, red basalts and granite have been used with the albedo values indicated in the Table 2.

Material description	*Albedo*
Red basalt road	*0.80*
Asphalt road	*0.10*
Smashed bricks	*0.75*
Granite pavement	*0.10*

Table 2. Pavements' materials

3.2.1. Mean radiant temperature

The Mean Radiant Temperature in the courtyard center will reach 54 ºC in 2080 (Fig. 2), making excessive radiation along with temperature increase the main causes of surface overheating, identified as the first critical issue.

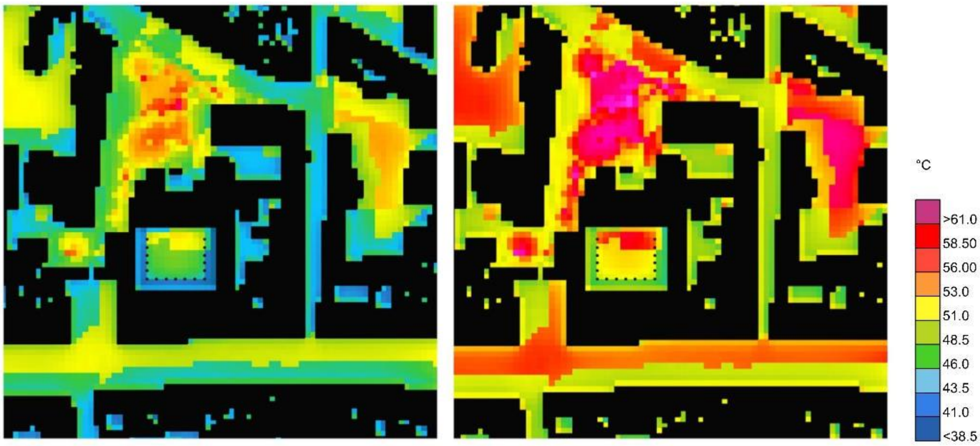

Figure 2. Mean radiant temperature in 1.15 m height from the ground in 2020 and 2080 for the hottest time of the year (5th of August-15:00).

3.2.2. Wind velocity

Wind speed analysis shows that the courtyard presents very low flow values (about 0.20 m/s at 15:00) because there are no air passages for the wind to move in and through. In contrast, over the buildings height, as well as in surrounding street canyons and open areas, the wind reaches much higher values of around 0.80 m/s at 15:00 and over 3 m/s for other times of the day (5th of August-15:00) (fig. 3).

The comparative analysis shows that these values are not expected to change much since the different profiles of temperature and radiation predicted in 2080 are locally not significant enough to achieve different barometric pressures. Therefore, lack of ventilation inside the courtyard is identified as the second important criticality.

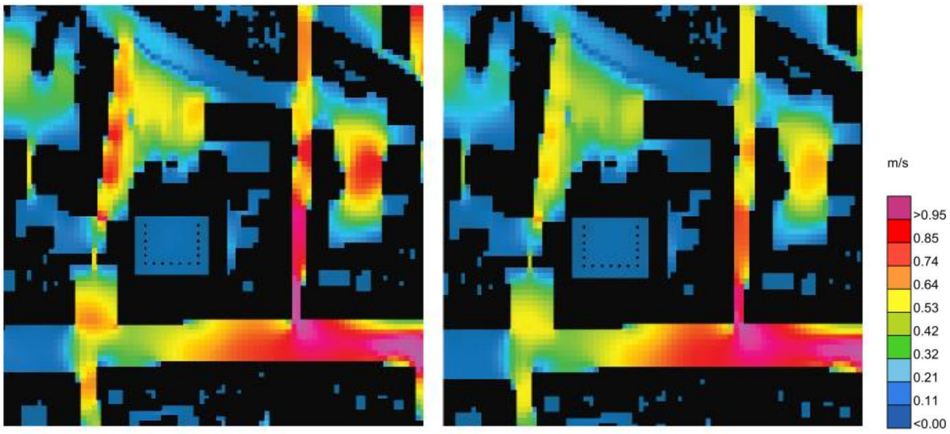

Figure 3. Wind speed maps in 2020 and 2080 at 1.15m height (5th of August-15:00).

3.2.3. Air temperature

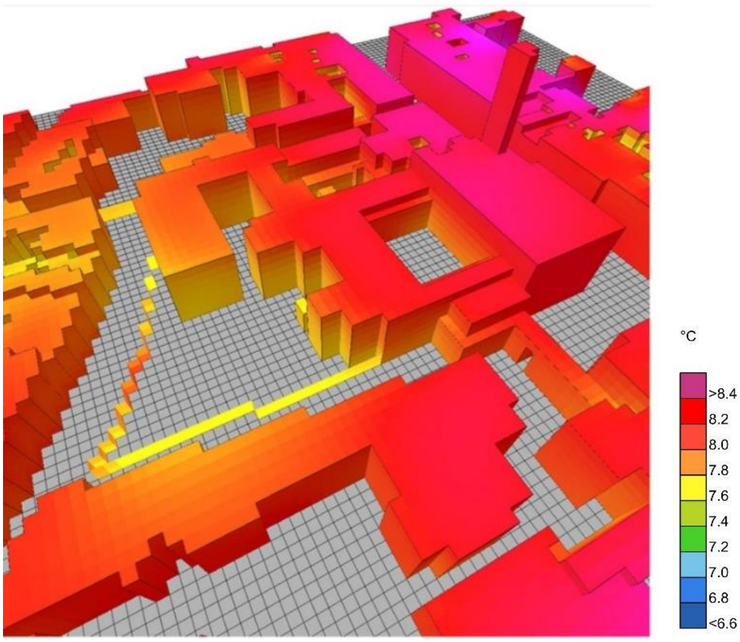

Figure 4. Change in Air temperature in front of facades between the years 2020 and 2080 for the hottest time of the year (5th of August-15:00).

Potential air temperature is expected to increase by 2080 by approximately 8 °C, with overheating of higher floor facade surfaces identified as the main issue (Fig. 4). Inside the cloister (in the center), potential air temperature during the hottest time of the year is going to change from 40 °C in 2020 to 47.6 °C in 2080. The three covered sides provide better conditions compared to the surroundings, but still the situation is critical (Fig. 5).

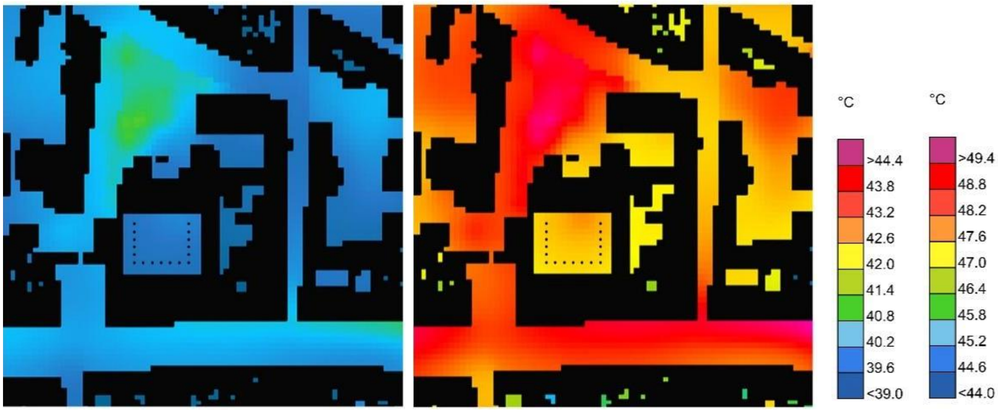

Figure 5. Potential air temperature in 1.15 m height from the ground in 2020 and 2080 for the hottest time of the year (5th of August-15:00).

3.2.4. Universal thermal climate index

In the 2020 plan map (Fig. 6 a), the value of UTCI under the arcades ranges from 35 to 38 °C (strong heat stress-SHS according to UTCI classification), whereas values from the exposed part of the cloister reach 42 °C (very strong heat stress-VSHS according to UTCI classification), similar to those of the surrounding streets. In the 2080 map (Fig. 6 b), this difference is not present, with all cloister parts (both exposed and covered) presenting a value around 43 °C (VSHS).

Lack of thermal comfort is an evident climate-related issue to be addressed. The analysis reveals that the most resilient parts of the area are those with high LAD (Leaf Area Density) vegetation, suggesting that the role of evapotranspiration is crucial to the mitigation of overheating in the urban context.

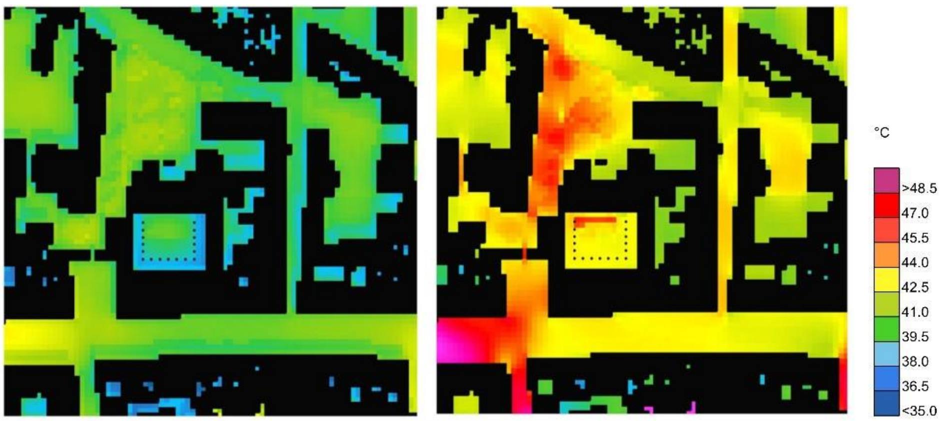

Figure 6. UTCI at 1.15 m height from the ground in 2020 and 2080 for the hottest day and hour (5th of August- 15:00)

3.3. Critical issues

The ENVI-met analysis relating to the courtyard of San Sepolcro cloister highlighted some critical issues. Thermal discomfort of the open internal area of the cloister, occurring during the summer period, is mainly due to the following causes (Fig. 7):

- excessive radiation
- high temperature

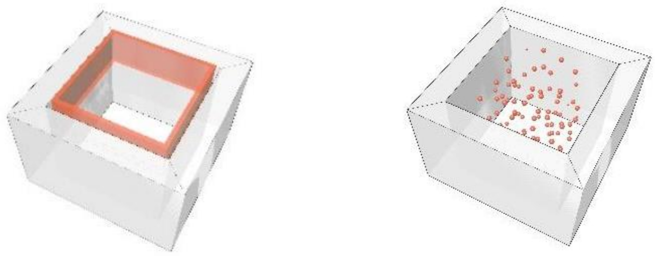

Figure 7 Critical issues identified from the analyses: excessive radiation and high temperature

3.4. The Design Strategy

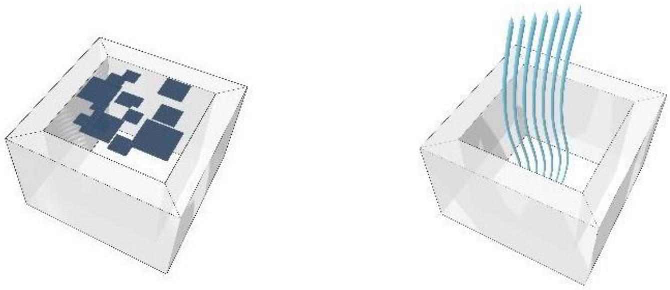

Figure 8. The two elements of the design strategy: solar protection and allows vertical ventilation

To improve the climatic comfort of the courtyard, a design strategy based on biomimicry principles was adopted. The aim was to limit the amount of solar radiation in the cloister, while at the same time to not prevent the vertical ventilation (Fig. 8) in order to produce a reduction of the air temperature and perceived temperature. The observation of biological organisms that resist high temperatures inspired the biomimicry methodology that was adopted for the development of the design solution. In accordance with the thermal discomfort described, the research is aimed at the observation of biological organisms that resist high temperatures. The cactus adopts a series of effective strategies for survival in climates of extreme heat.

The interest is directed to the Opuntia ficus-indica [32] (Fig. 9), belonging to the Opuntioideae, one of the sub-families of the Cactaceae [33]. In these succulent plants, commonly known as prickly pears cactus, the branches are made up of discs arranged vertically in various directions. The composition with vertical discs of Opuntia ficus-indica has relations with the maximization of shading and the minimization of solar radiation towards the plant body, and allows air to rise from the ground, creating vertical ventilation. The emulation of this natural strategy brings to the biomimicry imitation of the form.

Figure 9. Opuntia ficus-indica. Acatlán, Hidalgo, México,2013. Diego Delso.

A second level of biomimicry emulation is added to this first one, which involves the imitation of the generative morphogenetic biological processes in relation to the parameters of solar radiation. The imitation of the processes takes place thanks to the software tools of the generative parametric design, namely Rhino/Grasshopper and Galapagos for the morphogenesis in combination with LadybugTools for the assessment of environmental parameters. A large body of research showed that the use of optimization algorithms is an efficient method to investigate and find solutions with high environmental performance in architectural design [34].

3.5. Proposed project

The proposed project (Fig. 10) is a shading structure constituted by vertical hollow elements with a squared section descending from the roof height. A square grid with cells 3,00 x 3,00 m subdivides the cloister area, creating a set of elements with different extrusion height. The objective is the minimization of the solar radiation at ground level, setting as target value that received by the side of the cloister shadowed by the church.

Unlike many shading systems, in this project the elements are not horizontal or oblique, but vertical, thus the natural vertical ventilation is not hindered. According to the biomimicry strategy adopted, this allows the courtyard to be shaded without obstructing vertical ventilation.

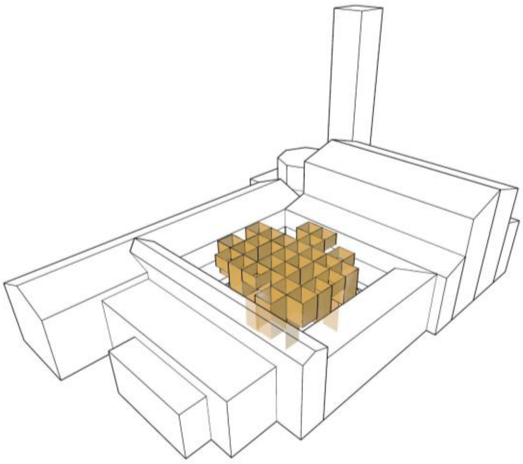

Figure 10. Proposal project. A square grid with cells 3,00 x 3,00 m subdivides the cloister area, creating a set of elements with different extrusion height

3.6. Design Morphogenesis

The method of mimicking natural morphogenesis used Rhino/Grasshopper [30] parametric design environment and the Galapagos evolutionary solver [35], for the optimization of the shading structure (Fig. 11). The relationship with the solar radiation parameters is ensured by the use of Ladybug and by the adoption of EPW data.

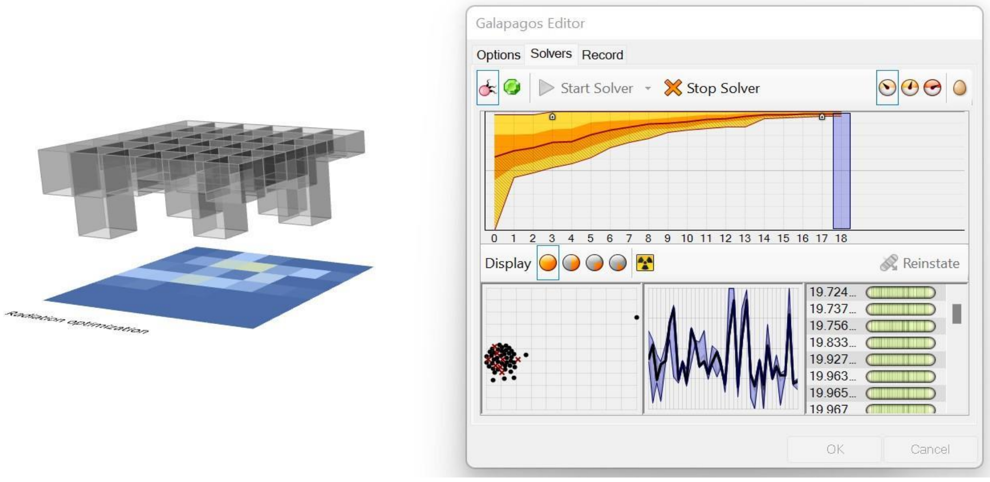

Figure 11. Rhino/Grasshopper generative software and the use of Galapagos plugin.

The parametric model allows for controlling the length of the extrusion of each squared element separately, from 0 to 7 m with increments of 1 m, which are used as the variables in the optimization process. Consequently, a fitness function is created which includes the result of the sum of direct and diffuse solar radiation simulation performed for the selected critical day and time at each iteration and the sum of the lengths of the extruded squared elements. The objective of the optimization is the minimization of the sum of the solar radiation simulated at courtyard ground level and of the cumulative extrusion length of the shading elements (Fig. 12).

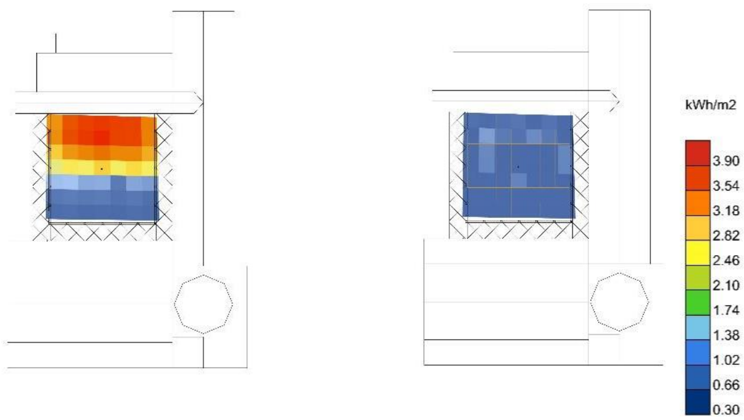

Figure 12. Radiation Analysis ante operam and post operam.

IOP Conf. Series: Earth and Environmental Science 1196 (2023) 012032 doi:10.1088/1755-1315/1196/1/012032

For the minimization of solar radiation, the target of the sum of direct and diffuse solar radiation simulated in all the area of the courtyard is the value of solar radiation simulated in the section of the courtyard shaded by San Sepolcro church. Through the fitness function it is possible to optimize the shape of the shading structure using the minimum quantity of material for the extruded elements and adapting the variable shape of the structure to the different climatic conditions inside the courtyard. At each iteration of the process, the evolutionary solver tests a different configuration of the shading and performs a direct and diffuse solar radiation simulation. After a number of generations, the optimal solution is determined.

The virtual machine [36], created through the Galapagos tool for the process definition, mimics the genetic rules of natural selection to determine the most suitable solution to the resolution of the issue. At the end of each process the most optimized solution is chosen and the process is repeated until you have a number of optimized solutions, among these you prefer the one with the best performance in relation to the amount of material used for the realization.

4. Results

4.1. Project analysis result

As the results of the project analyses (Fig. 13-14) show, at 15:00 the entire courtyard is sheltered from the direct radiation. A higher UTCI is recognizable under the arcades (sides east, south and west) due to the different materials on the floor, that are grass in the open area and granite under the porch. The structure blocks the direct radiation but at the same time reduces sky-view by a small amount. The UTCI is reduced up to 2°C in comparison with the basic configuration in the entire surface of the court.

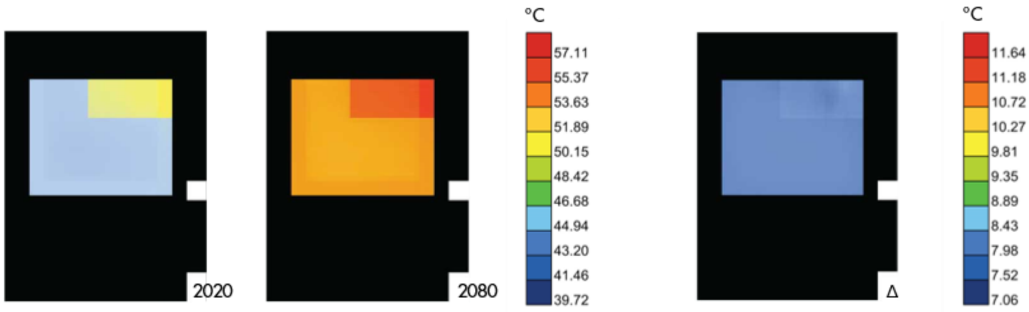

Figure 13. UTCI Simulation Results of the Cloister of San Sepolcro in the basic configuration. 2020; 2080; delta. Basic configuration.

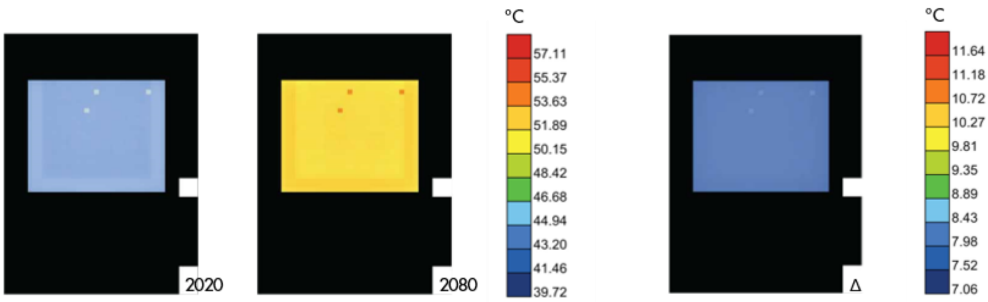

Figure 14. UTCI Simulation Results of the Cloister of San Sepolcro in the shaded configuration. 2020; 2080; delta. Project configuration.

4.2. Application and reiteration of the project

Light architecture structures, often temporary, represent an expression of our time. The courtyards are often the subject of artistic installations, which exalt some aspects of the pre-existence. This design proposal (Fig. 15) allows for the creation of a pleasant scenario with specific climate-mitigating characteristics. The design model can be adapted to other courtyards in different climatic areas, thanks to the parametric approach adopted in the methodology.

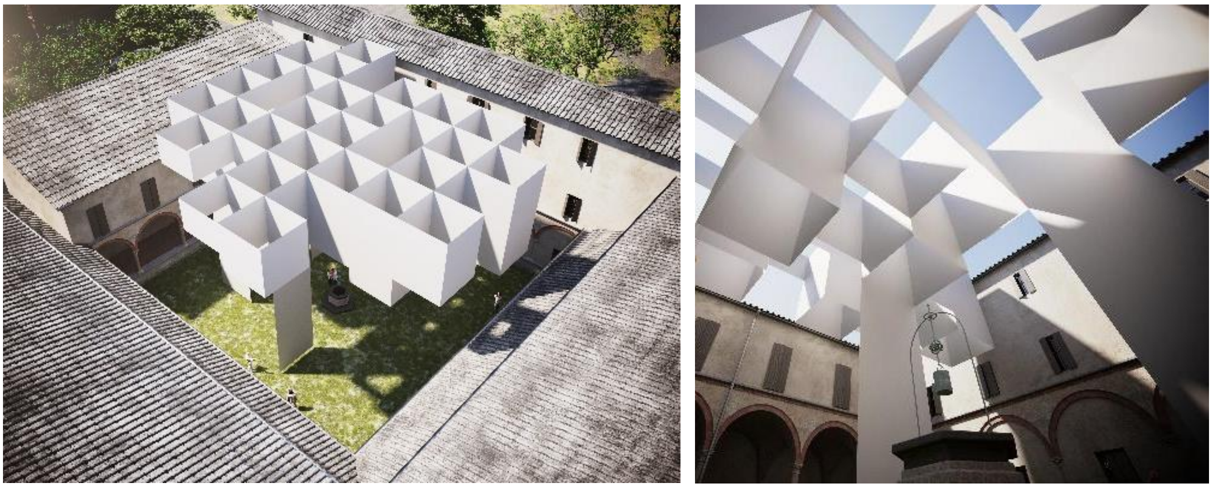

Figure 15. Photorealistic representation of the shading architectural proposal.

5. Conclusion

The microclimatic simulations show that the courtyard comfort is and will be further compromised due to increased direct solar radiation and high air temperature. The biomimicry approach combined with algorithmic morphogenesis tools has proved to be an effective and easily applicable method in various cases. The choice of a system that reduces solar radiation and at the same time does not hinder vertical ventilation can locally counteract climate change, reducing sensibly the perceived temperature.

References

[1] The Cambridge Dictionary. https://dictionary.cambridge.org

[2] Muhaisen, A.S., Gadi, M.B. 2006. *Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome*. Build. Environ. 41, 245–253. https://doi.org/10.1016/j.buildenv.2005.01.031.

[3] Taleghani, M., Tenpierik M.J., van den Dobbelsteen A. 2012. *Environmental Impact Of Courtyards—A Review And Comparison Of Residential Courtyard Buildings In Different Climates*. Journal of Green Building 7 (2012): 113-136.

[4] Aldawoud. 2008. *Thermal performance of courtyard buildings.* Energy Build. 40 (5) (2008), pp. 906-910.

[5] Almhafdy, A., Ibrahim, N., Ahmad, S. S., & Yahya, J. 2015. *Thermal Performance Analysis of Courtyards in a Hot Humid Climate Using Computational Fluid Dynamics CFD Method. Procedia* - Social and Behavioral Sciences, 170, 474-483.https://doi.org/10.1016/j.sbspro.2015.01.012

[6] Akbari, H., Cherati, S. M., Monazam, N. H., & Noguchi, M. 2021. *Effect of courtyards' geometrical parameters on climate adaptability and shading performance in hot-arid climate of Yazd (Iran)*. Sustainable Energy Technologies and Assessments, 48, 101594.

[7] Lopez-Cabeza, V. P., Alzate-Gaviria, S., Diz-Mellado, E., Rivera-Gomez, C., & Galan-Marin, C. 2022. *Albedo influence on the microclimate and thermal comfort of courtyards under*

Mediterranean hot summer climate conditions. Sustainable Cities and Society, 81, 103872. https://doi.org/10.1016/j.scs.2022.103872

[8] Diz-Mellado, E., Lopez-Cabeza, V. P., Rivera-Gomez, C., Galan-Marín, C., Rojas- Fernandez, J., & Nikolopoulou, M. 2021. *Extending the adaptive thermal comfort models for courtyards*. Building and Environment, 203, Article 108094. https://doi. org/10.1016/j.buildenv.2021.108094

[9] Soflaei, F., Shokouhian M., Abraveshdar, H., Alipour, A. 2017. *The impact of courtyard design variants on shading performance in hot- arid climates of Iran*. Energy Build;143:71–83. https://doi.org/10.1016/j.enbuild.2017.03.027.

[10] Zamani, Z., Heidari, S., & Hanachi, P. 2018. *Reviewing the thermal and microclimatic function of courtyards*. Renewable and Sustainable Energy Reviews, 93, 580-595. https://doi.org/10.1016/j.rser.2018.05.055

[11] Abass F., Ismail L. H., Solla M., 2016. *A review of courtyard house: history evolution forms and functions*. ARPN Journal of Engineering and Applied Sciences.

[12] O'Lenick, C.R, Wilhelmi, O.V., Michael, R., Haydenb, M.H., Baniassadi, A., Wiedinmyer, C., Monaghan, A.J., Crank, P-.J., Sailor, D.J., 2019. *Urban heat and air pollution: A framework for integrating population vulnerability and indoor exposure in health risk analyses.* Science of the Total Environment 660 715–723. https://doi.org/10.1016/j.scitotenv.2019.01.002

[13] EEA 2017. *Climate Change Impacts and Vulnerability in Europe - An Indicator-Based Report*. EEA Report European Environment Agency. Available online at: https://www.eea.europa.eu/publications/climate- change- impacts- and-vulnerability-2016 (accessed October 05, 2020).

[14] Alcamo, J., Olesen, J. 2012. *Life in Europe under climate change*. Wiley-Blackwell, Chichester.

[15] Kumar, P. 2021. *Climate Change and Cities: Challenges Ahead*. Front. Sustain. Cities 3:645613. doi: 10.3389/frsc.2021.645613

[16] United Nations Environment Programme 2022. *Emissions Gap Report 2022: The Closing Window — Climate crisis calls for rapid transformation of societies.* Nairobi. https://www.unep.org/emissions-gap-report-2022

[17] Poggi, C., Rogora, A., Scudo, G. 2014. *Evaluation of Environmental Control of Transitional Microclimatic Spaces in Temperate Mediterranean climate. In Passive and Low Energy Architecture* (PLEA 2014), Ahmedabad, December 16-18.

[18] Taleghani, M. 2018. *Outdoor thermal comfort by different heat mitigation strategies- A review*. Renewable and Sustainable Energy Reviews, 81, 2011–2018. https://doi.org/ 10.1016/j.rser.2017.06.010

[19] Emmanuel, R. 1993. *A Hypothetical 'Shadow Umbrella' for Thermal Comfort Enhancement in the Equatorial Urban Outdoors.* Architectural Science Review 36(4), 173-184 .

[20] DeKay, M., Brown, G.Z. 2001 *SUN, WIND & LIGHT: Architectural Design Strategies*. John Wiley and Sons Inc, New York, USA.

[21] Lechner, N. 2015. *Heating, Cooling, Lighting. Sustainable Design Methods for Architects*. Fourth, John Wiley & Sons, Hoboken (NJ), USA.

[22] Martinelli, L., Matzarakis, A., 2017. *Influence of height/width proportions on the thermal comfort of courtyard typology for Italian climate zones.* Sustainable Cities and Society, 29: p. 97-106.

[23] Gherri, B., Maiullari, D., Finizza, C., Maretto, M., & Naboni, E. 2021. *On the Thermal Resilience of Venetian Open Spaces*. Heritage, 4(4), p. 4286–4303.

[24] Muhaisen, A.S., Gadi, M.B. 2006. *Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome*. Build. Environ. 41, 245–253. https://doi.org/10.1016/j.buildenv.2005.01.031.

[25] Taleghani, M. 2014. *Dwelling on Courtyards. Exploring the Energy Efficiency and Comfort Potential of Courtyards for Dwellings in the Netherlands*. A+ BE| Architecture and the Built Environment, 4(18), 1-354.

[26] Forouzandeh A. 2018. *Numerical modeling validation for the microclimate thermal condition*

of semi-closed courtyard spaces between buildings. Sustain Cities Soc, 36 (2018), pp. 327-345, 10.1016/j.scs.2017.07.025
[27] ENVI_met, [Online], Available: https://www.envi-met.com/ [27 March 2022].
[28] Benyus, J. M. 2002. *Biomimicry. Innovation Inspired by Nature*. 2° ed Morrow, New York.
[29] Pawlyn, M. 2016. *Biomimicry in Architecture*. Riba Publishing 2016
[30] McNeel, R. & Associates, Rhinoceros, [Online], Available: https://www.rhino3d.com/ [21 September 2021].
[31] Melley, M. E., 2012. *I Chiostri negli organismi religiosi di Parma: Geometria, Proporzioni, Architettura*. Mattioli.
[32] Opuntia ficus-indica, su Enciclopedia Britannica, Encyclopædia Britannica, Inc.
[33] Anderson, E.F., 2001. *The cactus family*. Portland, Oregon, USA, Timber Press, ISBN 0-88192-498-9.
[34] Wortmann, T., & Nannicini, G. 2017. *Introduction to Architectural Design Optimization*. In City Networks - Planning for Health and Sustainability (Karakitsiou, A., Migdalas, A., Pardalos, P. M., & Rassia, S., Eds.). Springer International Publishing. doi: 10.1007/978-3-319-65338-9
[35] Rutten, D. 2010. *Evolutionary Principles applied to Problem Solving.* Available at: https://www.grasshopper3d.com/profiles/blogs/evolutionary-principles
[36] Turing, A. 1950. *Computing Machinery and Intelligence*. Mind. 49 (236): 433–460.