Proceedings of the 10th International Workshop on Simulation for Energy, Sustainable Development & Environment (SESDE), 003
19th International Multidisciplinary Modeling & Simulation Multiconference

2724-0061 © 2022 The Authors.
doi: 10.46354/i3m.2022.sesde.003

A comparative numerical simulation study for outdoor comfort indexes in courtyards

Victoria Patricia López-Cabeza[1*], Eduardo Diz-Mellado[1], Carlos Rivera-Gómez[1] and Carmen Galán-Marín[1]

[1]Departamento de Construcciones Arquitectónicas 1, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Avda. Reina Mercedes, 2, Seville, 41012, Spain

[*]Corresponding author. Email address: vlopez7@us.es

Abstract

Outdoor comfort is becoming an important parameter to consider in the design of spaces given the growing concern about how the urban heat island effect increases heat stress in cities. Calculating the different comfort indexes involves the quantification of several parameters in relation to the meteorological and user conditions. There are different tools that allow comfort calculations, although the way they consider meteorological data varies, and this can alter the comfort results. This paper aims to provide a comparison between three of these tools (Rayman, ENVI-met, and Ladybug Tools) simulating three common outdoor comfort indexes (PET, SET, and UTCI) using a courtyard under hot summer conditions as a case study. The results show variations among the comfort indexes between the different tools, due to the methods that each uses to obtain the parameters needed. We conclude that the available monitored data will determine the use of the most suitable tool.

Keywords: Simulation Tools; Courtyard; Outdoor Comfort

1. Introduction

The increasing temperatures produced by climate change, urban development, and population growth are worsening the urban heat island effect (Mat Santamouris, 2001). As a mitigation strategy, urban design is known to produce microclimates that can help to make urban spaces more livable and reduce harmful urban heat island (UHI) effects. Considering specific outdoor microclimates in building simulation can enable additional passive cooling strategies to mitigate climate risks in buildings and cities, improving their resilience capacity under extreme heat events (Lizana et al., 2021). One of these strategies to create beneficial microclimates is the use of inner courtyards. These traditional spaces common in many cultures of warm climates have the ability to mitigate extreme outdoor temperatures (Rivera-Gómez et al., 2019). The performance of the courtyards depends on many variables: geometry, orientation, surface materials, vegetation, shading, etc. One way to evaluate their performance is by considering the outdoor thermal comfort in the courtyard (Diz-Mellado et al., 2021). However, the characteristic of the courtyards (they are a transitional space between the indoor and the outdoor) could make the variables considered in comfort indexes have a different weight than in more exposed environments.

As a measure of outdoor design suitability, outdoor thermal comfort is a parameter that researchers are increasingly using to measure how well designed the space is (Mauree et al., 2019). ASHRAE defines thermal comfort as the conditions of the mind that express satisfaction with the outdoor thermal environment

(*ASHRAE Climatic Design Conditions 2009/2013/2017*, n.d.). There are many variables affecting thermal comfort, including air temperature (Ta), relative humidity (RH), wind speed (W), and mean radiant temperature (MRT), as well as other variables about user conditions. To obtain all the variables, simulation tools are used, given the difficulty of directly measuring some of them. Simulation is also needed in the design process to optimize performance. Different tools have different ways to estimate these variables, and this may affect the accuracy of the results or can make them suitable depending on the available data. This research aims to conduct a comparative study on the comfort results according to the SET, PET, and UTCI indices using three of the most widely used tools, Rayman, ENVI-met, and Ladybug tools, and analyze the methodology followed by each one.

2. State of the art

2.1. Outdoor comfort indexes

In recent years, different outdoor thermal indexes have been developed. Outdoor thermal comfort has been studied using different approaches, most notably numerical simulation (Berkovic et al., 2012), assessment through surveys or measurements, and analysis of new models (Coccolo et al., 2016). Outdoor thermal comfort indices are indicators that assess the outdoor thermal environment in relation to the occupants of these spaces. Although more than a hundred thermal comfort indices have been developed for indoor and outdoor spaces, only a few are currently used. Complexity, completeness, and adaptation to different climatic scenarios have reduced the number of outdoor comfort indices in use (Potchter et al., 2018). The three most common ones are (Kumar & Sharma, 2020):

- Standard Equivalent Temperature (SET*): is an index derived from the '2-Node' model, and represents the thermal stress experienced by a standard person in a standardized environment. Being an index with a very quantitative approach, it has very little capacity to adapt to different climatic regions and people with different behavioral parameters. SET is defined as the temperature of the hypothetical environment at 50 % RH, the air velocity should be less than 0.1 m/s, and air temperature equal to MRT, where the heat loss of the user's skin at 1.0 met and 0.6 clo is equal to a respondent in a real environment wearing real clothes and performing real activity (ASHRAE-55, 2017). It is suitable for moderate and warm climates (Gagge et al., 1986). SET has been used in different studies but is the least used due to its limitations in terms of climate zones and environmental conditions.

- Physiological Equivalent Temperature (PET): comfort index derived from the human energy balance that does not use behavioral components (Assis et al., 2013). It is considered a real climatic index that evaluates the thermal environment from a thermophysiological point of view. The comfort thermal range varies according to the climatic zone evaluated. The neutral PET range, that is, 18-23 °C, may not be comfortable in all climate zones. The PET range demonstrates the feeling of thermal comfort in an environment with specific conditions. PET aims to assess the perception of thermal comfort conditions (from very cold to very hot) in urban outdoor spaces (Andreas Matzarakis et al., 1999). Recent research, taking into account adaptation, has established different PET scales for different climatic zones, highlighting the thermal increase for different sensations (Cohen et al., 2013).

- Universal Thermal Climate Index (UTCI): defined by a comparison of meteorological conditions with a reference environment with 50% RH, still air, and MRT equal to Ta (*UTCI - Universal Thermal Climate Index*, n.d.). In this index, physiological parameters cannot be adjusted. It is an index with high complexity of calculation, approximated with an abbreviated regression equation, but with a small range of input parameters. It is based on the multinodal thermal regulation model that takes into account the total heat balance of the human body and the physiological response (Fiala et al., 2012). This model predicts the thermal effect on the entire body and on individual parts of the body. UTCI has been developed by the International Society for Biometeorology, with the consensus of multidisciplinary experts (thermophysiology, occupational medicine, physics, meteorology, biometeorology, and environmental sciences). The other variables such as metabolic rate met and thermal properties of clothing clo are of great importance.

2.2. Comfort simulation tools

The development of tools to predict outdoor environment allows the calculation of the comfort indices described above. However, the different assumptions and capabilities of the tools may lead to differences in the results and the applicability of the methodology depends on the inputs available. Some of the most common tools for calculating outdoor comfort indexes are:

- Rayman (A. Matzarakis & Rutz, 2007) is a microscale model that has been used and validated to calculate radiation fluxes in urban environments. This tool allows the calculation of the MRT, a parameter used by most comfort indices. Rayman allows using monitored data to perform comfort calculations with or without modeling of the obstacle environment.

- ENVI-met (*ENVI-Met*, n.d.): It is widely used and validated to simulate the evolution of urban microclimate using Computational Fluid Dynamics (CFD). It accounts for the interactions between soil, air, water, vegetation, and buildings. ENVI-met requires the modelization of the geometry of the urban setting and the input of meteorological boundary conditions. It also requires a great deal of computational power for the simulation of large models.

- Ladybug Tools (*Ladybug Tools | Home Page*, n.d.): It is a set of plugins for Grasshopper that link different background simulation engines to perform environmental and energy performance analysis. It also requires a geometry model to perform the analysis. The meteorological conditions from an .epw file are required inputs for the simulations.

Previous studies have analyzed how these tools calculate the specific parameter of mean radiant temperature (Evola et al., 2020; Gál & Kántor, 2020), wind flow, and temperature. Although these parameters separately affect thermal comfort, there are not many studies that compare the results of the comfort indexes of the different tools and analyze the applicability of each of them in the specific case of courtyards. This study aims to make this comparison by applying these tools to a case study of outdoor thermal comfort in a courtyard in the summer of the Mediterranean climate.

3. Materials and Methods

3.1. Case study

A residential building with an inner courtyard has been selected as a case study, located in the city center of Cordoba, in the south of Spain, in a hot and dry area of the Mediterranean climate, classified as Csa in the Koppen classification (Kottek et al., 2006). The geometry of the courtyard is defined in Table 1. The building is a traditional house with a courtyard that has recently been refurbished, with the rooms organized around the courtyard, which serves as lighting, ventilation and outdoor living space of the house. An image of the courtyard is shown in Figure 1. The walls of the courtyard are coated in white painting and there are some windows, the larger ones on the ground floor.

Table 1. Courtyard's geometry.

Location	Width (m)	Length (m)	Height (m)	Aspect Ratio (AR)
(37.88, -4.77)	4.5	4.5	7.0	1.5

AR: Relation between the height and the width of the courtyard (AR=height/width)

Figure 1. Image of the case study courtyard

3.2. Monitoring campaigns

A monitoring campaign was carried out during the summer of 2017 to record input data for the simulations. The variables recorded were air temperature (Ta), relative humidity (RH), and wind speed outdoors (W) using a PCE-FWS 20 weather station located on the roof of the building. The air temperature and relative humidity inside the courtyard were recorded using TESTO 174H dataloggers. The hottest day was selected to perform the analysis. The technical information of the measuring instruments is given in Table 2.

Table 2. Technical data of the measurement instruments

Sensor	Variable	Accuracy	Resolution
TESTO 174H	Dry bulb temperature	±0.5 °C	0.1 °C
	RH	±0.1%	2%
PCE-FWS 20	Dry bulb temperature	±1 °C	0.1°C
	RH	±5%	1%
	Wind	±1 m/s	-

3.3. Simulation tools

Monitoring data were used as input for the different tools used to simulate the comfort indexes. This section describes how each tool manages the meteorological information provided and its outputs. For the condition of the person, the same parameters are used in all calculations, a male of 35 years, dressed in 0.9 clo and a metabolic rate of 80W.

Rayman uses the monitoring values inside the courtyard for the calculation of the different comfort indices. It needs the monitoring data inside the courtyard because it cannot calculate the thermodynamic effects that occurs inside it. The input climate values are Ta, RH, W and global solar radiation (G) inside the courtyard, needed to calculate the MRT and the outdoor comfort indices. It also allows for the introduction of a model for the MRT calculation, although in this case, it is not used given that G is provided by Ladybug, which uses information from an .epw file and is already accounting for the surroundings.

ENVI-met takes the geometry model of the building and the meteorological data from the monitoring campaign, which is used as boundary conditions of the simulation. The ENVI-met CFD simulation is then used to obtain the comfort variables required for each index inside the courtyard (Ta, RH, W, and MRT).

In Ladybug Tools, the monitored data outside the courtyard is used to modify an .epw file that is used as input, together with the geometry model in Rhinoceros, to perform the simulation. Ladybug combines the Honeybee plugin that performs energy analysis to obtain MRT with the Butterfly plugin that performs CFD to obtain Ta and W inside the courtyard. The RH is not simulated by this tool and is obtained directly from the monitored data.

4. Results

4.1. Monitoring results

Figure 2 shows the results of the monitoring campaign for the selected day (August 19th, 2017). It shows a day of extreme heat, with a peak of 45ºC at 17 hours and a minimum temperature of 25ºC in the early morning. The tempering potential of the courtyard is significant, generating a microclimate that peaks at 37ºC during the day, which means a thermal delta of 8ºC with the outdoors. However, during the night, the courtyard is slightly overheated. In terms of relative humidity, the maximum value was 55% during the night and the minimum was 10% coinciding with the time of higher temperatures. The wind was low during this day, with maximum values of 1.7 m/s, which is common in this densely built area.

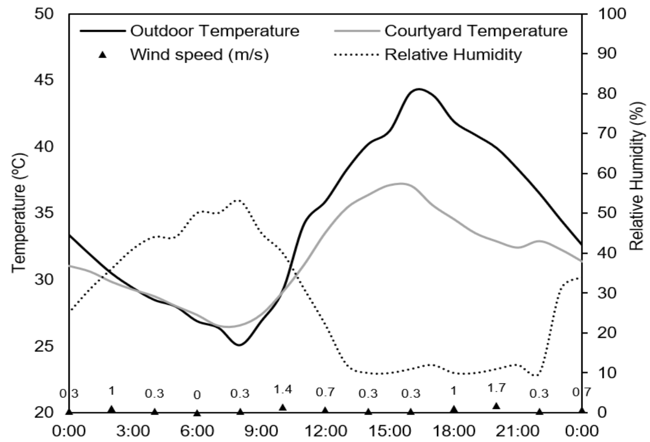

Figure 2. Monitoring data recorded on 19th august 2017.

4.2. Comfort indexes results

Figure 3 shows the results of the simulation of each comfort index obtained with the three tools. In general, ENVI-met results are the highest values, followed by Ladybug tools and Rayman. Per comfort index, PET results are generally the highest during daylight hours and the lowest during the night. It is also interesting to see that differences between the indexes are higher in ENVI-met results than in the other tools, and Rayman provides the lowest differences between indexes.

To understand the differences in the results in Figure 3, the input variables of the comfort index are also compared. Figure 4 shows the air temperature input in each tool. It can be seen that the ENVI-met temperature is the highest, followed by Ladybug Tools and Rayman. This correlates with the results in the comfort indexes. Note that the air temperatures of ENVI-met and Ladybug Tools inside the courtyard are calculated by CDF engines, while Rayman inputs are monitored. The lowest accuracy of ENVI-met and the improved accuracy of Ladybug Tools in reproducing temperatures inside a courtyard has been previously analyzed (V. P. López-Cabeza et al., 2018; Victoria Patricia López-Cabeza et al., 2022).

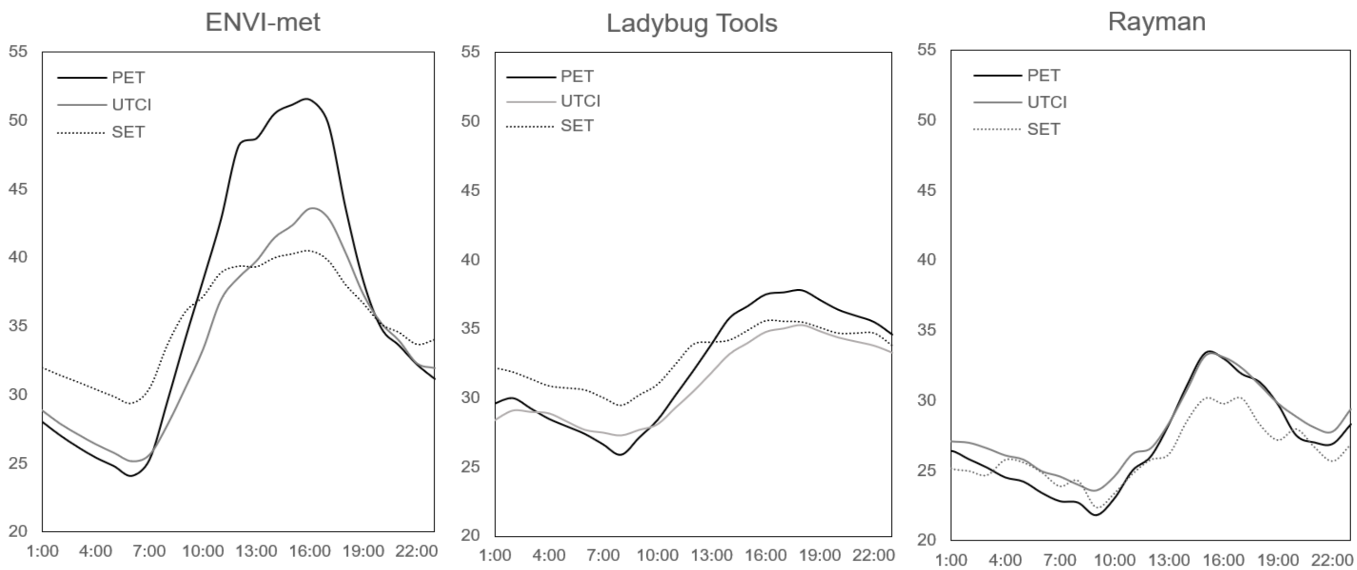

Figure 3. Case study comfort indexes results per simulation tool.

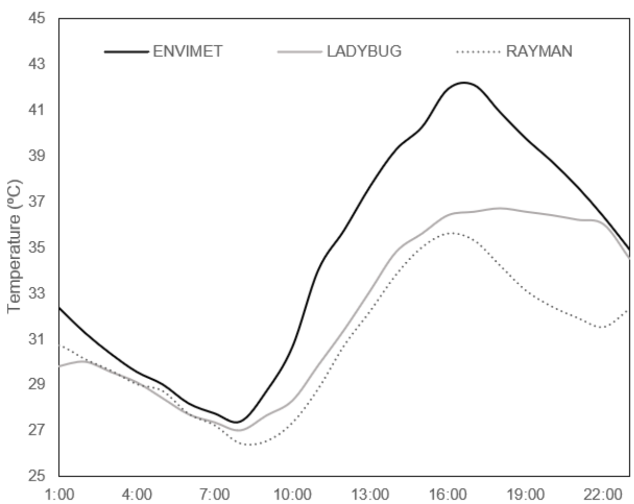

Figure 4. Air temperature inputs for comfort calculation in the different tools.

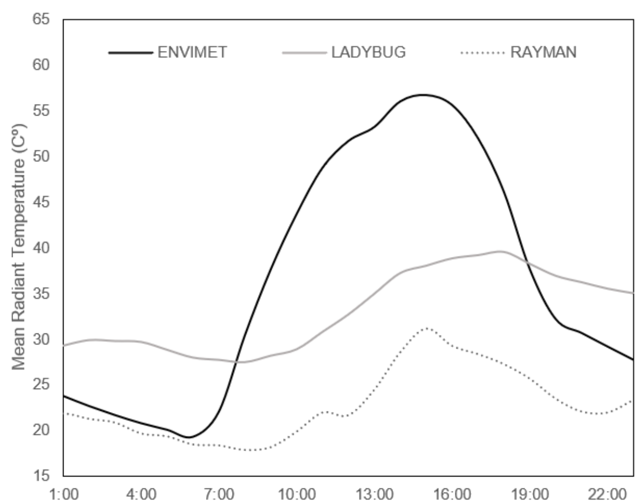

Figure 5. Mean Radiant Temperature inputs for the comfort calculation in the different tools.

The mean radiant temperature is represented in Figure 5. Here all the inputs are calculated by the software. Again, the values provided by ENVI-met are higher during the day than the other tools, with a peak in 55ºC, and Rayman provides the lowest. During the night, Ladybug Tools which provides the highest MRT values, exceeding 30ºC. This is correlated with the comfort results in both tools. Thus, MRT can be considered an important parameter that affects comfort indexes in this case. The higher difference between indexes provided by ENVI-met also shows that some of them could be more affected by MRT than others.

The relative humidity values (Figure 6) are very similar in all tools. Considering that RH form ENVI-met is calculated, from Rayman is monitored inside the courtyard and from Ladybug Tool is monitored on the roof of the building (extracted from the .epw file), differences in the values are negligible and all the methods can be considered equivalent if RH is not high. However, ENVI-met is the only suitable tool if higher values of humidity are possible, or if vegetation is present, being the only tools capable of simulating the evapotranspiration effects of vegetation.

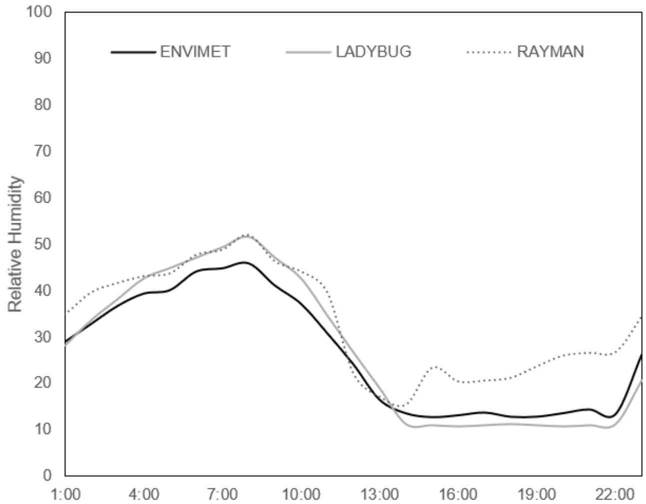

Figure 6. Relative Humidity (%) inputs for the comfort calculation in the different tools.

The differences in wind speed input between software are also important (Figure 7). Both tools that use CFD (ENVI-met and Ladybug Tools) provide lower values of wind speed than the Rayman tool, which uses monitored data altered by the logarithmic calculation of wind speed reduction with height. This means that inside the courtyard, in this case a small and deep courtyard, wind speed is reduced by the built environment, and CFD is needed to ensure the accuracy of the data. Contrasting Figure 3 (Rayman) and Figure 7, it is noted that SET is the Comfort index that is more affected by wind variations, producing a curve with small peaks when wind speed changes.

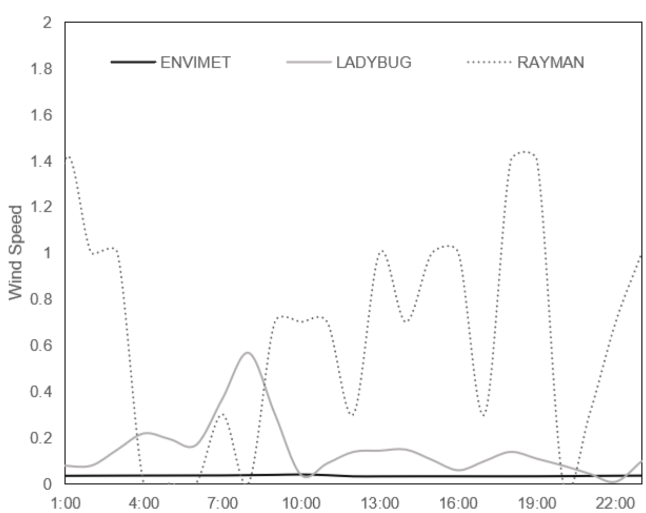

Figure 7. Wind Speed (m/s) inputs for the comfort calculation in the different tools.

5. Discussion

The results show that the accuracy of the inputs for the calculation of the different comfort indexes is the key to provide reliable data. In the case study analyzed, air temperature and MRT are the two variables that affect the comfort indexes most, as the RH values are not extremely high and the wind speed is low, except for the Rayman wind values. For this reason, the way of obtaining these data needs to be considered. In this case study, Rayman comfort indexes are considered the most accurate since they are calculated using monitored data. However, this information is not always available (i.e., at the design stage, or when monitoring cannot be an option). In these cases, the accuracy of the simulation tool must be considered and CFD tools are needed to account for the microclimate of courtyards. As commented before, Ladybug Tools is more accurate than ENVI-met at simulating air temperature inside the courtyards. Furthermore, previous studies report that ENVI-met tends to provide higher MRT than Ladybug Tools in summer conditions (Naboni et al., 2017). With this information, we consider that ENVI-met could be overestimating the comfort indexes.

Another factor to consider is the simulation time required. In this sense, ENVI-met is the tool with the longer simulation time and computational power requirements. Ladybug also required a long simulation time if CFD is used, but in this case, it is a steady state solver that can be used to calculate shorter periods thus reducing the simulation time.

Finally, the only software capable of simulating the evapotranspiration effect of vegetation is ENVI-met, thus if humidity is important (in contrast to this case), ENVI-met needs to be used to account for it.

6. Conclusions

This paper illustrates the importance of an accurate selection of inputs and simulation tool to calculate outdoor comfort indexes. It also provides a recommendation on the suitable tool to be used according to the specific data available. In this case, Ladybug Tools has been selected as the best tools for simulation of the comfort indexes if no monitored data are available and Rayman if the data is available. However, if the outdoor space is very influenced by vegetation and RH can be high, ENVI-met is then the only option.

The results of this work imply that differences in simulating the comfort indexes can be important regarding the simulation tool used. The accuracy of the four parameters that intervene is key to provide accurate data, especially the air temperature and the MRT for the specific case of courtyards in summer conditions of the Mediterranean climate (when wind speed and relative humidity are not high).

The results are limited to the specific case of small inner courtyards in the summer conditions of the Mediterranean climate. More analysis needs to be done if humid or windy climates are considered, since these variables are not important in the case study specific conditions. Other types of outdoor spaces should also be analyzed.

Funding

This work was supported by the grant RTI2018-093521-B-C33 funded by MCIN/AEI/ 10.13039/501100011033 and by "ERDF A way of making Europe" and the Ministry of Education, Culture and Sports Spain via a pre-doctoral contract granted to V.P. L-C. [FPU17/05036] and E. D-M [FPU18/04783].

Acknowledgments

Special thanks to the association "Patios de la Axerquía (PAX)" of Cordoba for his help in letting us visit the building, it would have been impossible to carry out the monitoring campaigns.

References

ASHRAE-55. (2017). Thermal environmental conditions for human occupancy. *ANSI/ASHRAE Standard - 55*, *7*, 6.

ASHRAE climatic design conditions 2009/2013/2017. (n.d.). Retrieved November 16, 2019, from http://ashrae-meteo.info/

Assis, E. S. De, Sirqueira, C. a De, Bamberg, A. M., Sustentável, P., Khalid Setaih, Neveen Hamza, T. T., Monam, A., Rückert, K., Matzarakis, A., Amelung, B., Robitu, M., Musy, M., Inard, C., Groleau, D., Ali-Toudert, F., Mayer, H., & Jorg Spangenberg, Paula Shinzato, Erik Johansson, D. D. (2013). Assessment of Outdoor Thermal Comfort in Urban. *Solar Energy*, *4*, 1–19. http://linkinghub.elsevier.com/retrieve/pii/S0038092X06002623%5Cnhttp://linkinghub.elsevier.com/retrieve/pii/S0038092X05002574

Berkovic, S., Yezioro, A., & Bitan, A. (2012). Study of thermal comfort in courtyards in a hot arid climate. *Solar Energy*, *86*, 1173–1186. https://doi.org/10.1016/j.solener.2012.01.010

Coccolo, S., Kämpf, J., Scartezzini, J. L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. *Urban Climate*, *18*, 33–57. https://doi.org/10.1016/j.uclim.2016.08.004

Cohen, P., Potchter, O., & Matzarakis, A. (2013). Human thermal perception of Coastal Mediterranean outdoor urban environments. *Applied Geography*, *37*(1), 1–10. https://doi.org/10.1016/j.apgeog.2012.11.001

Diz-Mellado, E., López-Cabeza, V. P., Rivera-Gómez, C., Galán-Marín, C., Rojas-Fernández, J., & Nikolopoulou, M. (2021). Extending the adaptive thermal comfort models for courtyards. *Building and Environment*, *203*, 108094. https://doi.org/10.1016/j.buildenv.2021.108094

ENVI-met. (n.d.). Retrieved October 28, 2019, from https://www.envi-met.com/

Evola, G., Costanzo, V., Magrì, C., Margani, G., Marletta, L., & Naboni, E. (2020). A novel comprehensive workflow for modelling outdoor thermal comfort and energy demand in urban canyons: Results and critical issues. *Energy and Buildings*, *216*, 109946. https://doi.org/10.1016/j.enbuild.2020.109946

Fiala, D., Havenith, G., Bröde, P., Kampmann, B., & Jendritzky, G. (2012). UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *International Journal of Biometeorology*, *56*(3), 429–441. https://doi.org/10.1007/s00484-011-0424-7

Gagge, A. P., Fobelets, A. P., & Berglund, L. G. (1986). A standard predictive Index of human reponse to thermal enviroment. - OceanRep. *Transactions / American Society of Heating, Refrigerating and Air-Conditioning Engineers*, *92*, 709–731. https://oceanrep.geomar.de/42985/

Gál, C. V., & Kántor, N. (2020). Modeling mean radiant temperature in outdoor spaces, A comparative numerical simulation and validation study. *Urban Climate*, *32*, 100571. https://doi.org/10.1016/j.uclim.2019.100571

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., & Markus Kottek, Jürgen Grieser, Christoph Beck, B. R. and F. R. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Kumar, P., & Sharma, A. (2020). Study on importance, procedure, and scope of outdoor thermal comfort –A review. *Sustainable Cities and Society*, *61*, 102297. https://doi.org/10.1016/j.scs.2020.102297

Ladybug Tools | Home Page. (n.d.). Retrieved September 4, 2020, from https://www.ladybug.tools/

Lizana, J., L, V. P., Renaldi, R., Diz-mellado, E., Rivera-g, C., & Gal, C. (2021). Integrating courtyard microclimate in building performance simulation to mitigate extreme urban heat impacts. *Sustainable Cities and Society*, 103590. https://doi.org/10.1016/j.scs.2021.103590

López-Cabeza, V. P., Galán-Marín, C., Rivera-Gómez, C., & Roa-Fernández, J. (2018). Courtyard microclimate ENVI-met outputs deviation from the experimental data. *Building and Environment*, *144*(August), 129–141. https://doi.org/10.1016/j.buildenv.2018.08.013

López-Cabeza, Victoria Patricia, Diz-Mellado, E., Rivera-Gómez, C., Galán-Marín, C., & Samuelson, H. W. (2022). Thermal comfort modelling and empirical validation of predicted air temperature in hot-summer Mediterranean courtyards. *Journal of Building Performance Simulation*, *15*(1), 39–61. https://doi.org/10.1080/19401493.2021.2001571

Matzarakis, A., & Rutz, F. (2007). Rayman: A tool for tourism and applied climatology. *3rd International Workshop on Climate, Tourism and Recreat, January 2007*, 129–138.

Matzarakis, Andreas, Mayer, H., & Iziomon, M. G. (1999). Applications of a universal thermal index: Physiological equivalent temperature. *International Journal of Biometeorology*, *43*(2), 76–84. https://doi.org/10.1007/s004840050119

Mauree, D., Naboni, E., Coccolo, S., Perera, A. T. D., Nik, V. M., & Scartezzini, J.-L. (2019). A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities. *Renewable and*

Sustainable Energy Reviews, *112*, 733–746. https://doi.org/10.1016/J.RSER.2019.06.005

Naboni, E., Meloni, M., Coccolo, S., Kaempf, J., & Scartezzini, J. L. (2017). An overview of simulation tools for predicting the mean radiant temperature in an outdoor space. *Energy Procedia*, *122*, 1111–1116. https://doi.org/10.1016/j.egypro.2017.07.471

Potchter, O., Cohen, P., Lin, T. P., & Matzarakis, A. (2018). Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification. In *Science of the Total Environment* (Vols. 631–632, pp. 390–406). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2018.02.276

Rivera-Gómez, C., Diz-Mellado, E., Galán-Marín, C., & López-Cabeza, V. (2019). Tempering potential-based evaluation of the courtyard microclimate as a combined function of aspect ratio and outdoor temperature. *Sustainable Cities and Society*, *51*(July), 101740. https://doi.org/10.1016/j.scs.2019.101740

Santamouris, Mat. (2001). *Energy and Climate in the Urban Built Environment* (M. Santamouris (Ed.)). Routledge.

UTCI - Universal Thermal Climate Index. (n.d.). Retrieved June 3, 2020, from http://www.utci.org/