Aplication of a Building Dynamic Simulation in the Development of Horizontal Shading Device Passive Solution in an University Canteen

Eusébio Z. E. Conceição, Mª Inês L Conceição, Mª Manuela J. R. Lúcio and Hazim B. Awbi

Abstract—In this work the application of a building dynamic simulation in the development of horizontal shading device passive solution applied in an university canteen is studied. The building dynamic simulation, that simulates simultaneously buildings or groups of buildings, with complex topologies, in transient conditions, considers the solar radiation, the HVAC system, glass radiative proprieties, radiative heat exchanges, thermal solutions, occupants' comfort and air quality, and others. In the horizontal shading devices passive solutions the numerical model, using a sun trajectory and window position, developed efficient external shading devices. The canteen considers three levels and is divided in 37 spaces. In the simulation, 100 transparent surfaces and 773 opaque surfaces are considered. Special attention is given in the students' main canteen, professors' main canteen and university bar. The simulation is made in summer conditions. A simulation without and with horizontal shading devices and without and with HVAC system on, controlled by PMV index, is considered. In the simulation, the occupation and the ventilation are considered. In accordance with the obtained results the horizontal shading derives reduce the interval air temperature and improve slightly the thermal comfort level that the occupants are subjected.

Keywords— Building simulation; Solar; Energy, Thermal comfort; Indoor air quality

Eusébio Z. E. Conceição
FCT - University of Algarve
Campus de Gambelas, 8005-139 Faro
Portugal

Mª Inês L. Conceição
Instituto Superior Técnico,
Av. Rovisco Pais, 1049-001 Lisboa
Portugal

Mª Manuela J. R. Lúcio
FCT - University of Algarve
Campus de Gambelas, 8005-139 Faro
Portugal

Hazim B. Awbi
School of Construction Management & Engineering,
University of Reading, Reading, RG6, 6AW
United Kingdom

I. Introduction

In order to evaluate the comfort, air quality, energy, and others, in buildings, the building dynamic response was applied in the last years by several authors. Examples of application of these methodologies can be seen in, Yang *et al.* [1] or Balagi *et al.* [2].

In this study a numerical software that simulates the building dynamics response is used. This software, using energy and mass integral equations, was developed by the authors in the last decades and was applied in vehicles and buildings. In vehicles, as example, in Conceição *et al.* [3] the simulation of the passengers' compartment is developed. In buildings, different works were developed. As example, some applications of the present software were made in Conceição *et al.* [4] (study of school Buildings in winter conditions); Conceição and Lúcio [5] (study of shading devices promoted by external trees in summer conditions) or in Conceição and Lúcio [6] (numerical study of a school building subjected to solar radiation with different orientations).

In the evaluation of thermal comfort that the occupants are subjected, it is an important topic which software should be used. In this study, using the indoor air temperature, indoor air velocity, indoor air relative humidity, clothing level and activity level, the software calculates the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied) indexes (see Fanger [7], ANSI/ASHRAE Standard 55 [8] and ISO 7730 [9]). In the thermal comfort, the integral or detailed evaluation can be performed.

In the integral comfort evaluation, using the building dynamic response numerical model and evaluating the comfort level that all occupants are subjected, in Conceição *et al.* [4], Conceição and Lúcio [5] or Conceição and Lúcio [6] are presented some examples.

In the detailed comfort evaluation is used the human thermal response numerical model that evaluates the comfort level that each occupant is subjected. Conceição and Lúcio [10], studied the evaluation of thermal comfort level in classroom equipped with radiant cooling systems and subjected to uniform convective Environment. Conceição e Lúcio [11], made the evaluation of thermal comfort level in students subjected to radiant system, located in front and behind, and warmed curtains. In this kind of study a coupling

of the human thermal response with a Computational Fluids Dynamics is applied in Conceição *et al.* [12].

The air quality evaluation is made using the carbon dioxide concentration, in accordance with ASHRAE 65 [13]. In this study the airflow rate of exchanging air with the external environment is made. Examples of studies that use techniques to evaluate the airflow rate can be analysed in Conceição *et al.* [14] or in Conceição *et al.* [15].

In spaces equipped with HVAC systems, the control systems should be used. These kinds of control systems can be analysed, as example, in Mathews *et al.* [16] or Mirinejad *et al.* [17]. In this control different techniques can be used: the control using preferred air temperature is showed in Conceição *et al.* [18], using thermal comfort level that the occupants are subjected is applied in Conceição *et al.* [19] and using the adaptive thermal comfort level, that the occupants are subjected, is showed in Conceição *et al.* [20].

In this study an university canteen thermal response is made. The study considers a building dynamic response software, developed by the authors, used to evaluate a passive solution applied in an university canteen. In this numerical solution the software considers a numerical model that integrates the passive solar strategies, the solar radiation, the shading devices placed above the window surface, the integral thermal comfort level and the HVAC control based in the thermal comfort that the occupants are subjected. The study is made in a summer typical day and considers, in specifying occupied spaces, the developing of special shading devices, placed above the window level, which guarantees, in specific instant, any passage of solar radiation through the window.

II. **Numerical Model**

In this work a building dynamic numerical model, developed by the authors, is used in the numerical simulation of an university canteen. The software, that is analysed and develops new passive solutions, uses energy and mass balance integral equations and uses as input data the:

- Buildings geometry (opaque, transparent and interior surfaces and interior spaces) and surfaces and spaces thermal variables;

- Building geographical information;

- External surroundings thermal variables;

- Internal HVAC systems;

- Internal ventilation;

- Occupancy information;

- Radiative and convective empirical models.

The software considers the followings numerical models:

- Building thermal response;

- Passive and active solar strategies;

- Solar radiation and window radiative proprieties;

- Shading devices placed above the window surface;

- Air quality (D.L. [21] and ASHRAE 65 [13]) and thermal comfort (ANSI/ASHRAE Standard 55 [8] and ISO 7730 [9]) levels;

- HVAC control system, based in temperature, thermal comfort, adaptive thermal comfort and surface temperature;

The output of the numerical models are:

- Incident solar radiation that each opaque and transparent surface are subjected;

- Indoor environmental variables (air temperature, relative humidity, air velocity and mean radiant temperature) inside each space;

- Internal air quality and thermal comfort level;

- Temperature of the layers of the opaque, transparent (windows glasses) and interior surfaces;

- Mass contaminants inside the spaces and in the surfaces (carbon dioxide and water vapour concentration).

More details about this Building Dynamics Software can be analysed in Conceição *et al.* [22]. Some applications can be seen in Conceição *et al.* [4], Conceição and Lúcio [5] and Conceição and Lúcio [6].

The development of a new passive solution is made in this work. The external passive solution (see in figure 1), developed in this work, considers a vertical shading device located above the window. The development of this shading device is made, it self, by the software. The software, after identifying the more uncomfortable spaces and the main windows that should be added additional shading devices, considers the window divided in two parts: The West side and the East side. In both sides, the software considers the upper and the lower window level. The dimension of the vertical shading device is calculated through the intersection of a horizontal line (with origin in the upper window level) with an oblique line (with origin in the lower window level with the direction of the sun location). In the calculation the software considers the day and hour that the shading device should guarantee that no radiation enters through the window. In this calculus the 12 hours of the 21th June were considered.

III. **Numerical Metodology**

The passive solar strategies, using numerical simulation, applied in an university canteen is made in this study. In passive strategies the university canteen is equipped with multiple vertical shading devices.

The university canteen (see figure 1) is divided in 37 spaces and considers three levels. 100 transparent surfaces and 773 opaque surfaces are considered in the simulation.

In this study two cases, without (see figure 1) and with (see figure 2) horizontal shading devices placed above the window, are analysed. In each case, without and with HVAC system with control based in PMV index, is used.

In the figure 1 the grey is associated to opaque surfaces, blue is associated to transparent surfaces (windows) and green is associated to doors. In figure 2 the The grey color is associated to opaque surfaces, blue is associated to transparent surfaces (windows), green is associated to doors and magenta is associated to shading systems.

The control of the HVAC system considers the value of PMV of 0.5 in summer conditions.

In the numerical simulation all spaces are considered. However, in the present work special attention is given to the occupation in three spaces, namely:

- the students' main canteen (room 23), with a maximum occupation with 510 occupants. However, in this simulation an occupation with 250 students was considered;

- the Professors' main canteen (room 29), with a maximum occupation with 60 occupants. However, in this simulation an occupation with 32 persons was considered;

- the university bar, with a maximum occupation with 96 persons (room 11). However, in this simulation an occupation with 60 persons was considered.

In the numerical simulation, in accordance with Conceição *et al.* [23], using experimental tests, when the space is not occupied, a natural air renovation rate of 2.42 1/h is considered, while when the space is occupied a natural air renovation rate of 5.36 1/h is used.

In Figures 1 and 2 is presented the University Canteen used in the study, respectively, without horizontal external shading devices. In this study 13 shading devices are developed:

- In room 23, located in right side of the first level of the building, are considered 2 shading devices in the space;
- In room 29, located in the central area of the second level of the building, are considered 8 shading devices in the space;
- In room 11, located in the left side of the first level of the building, are considered 3 shading devices in the windows of the space.
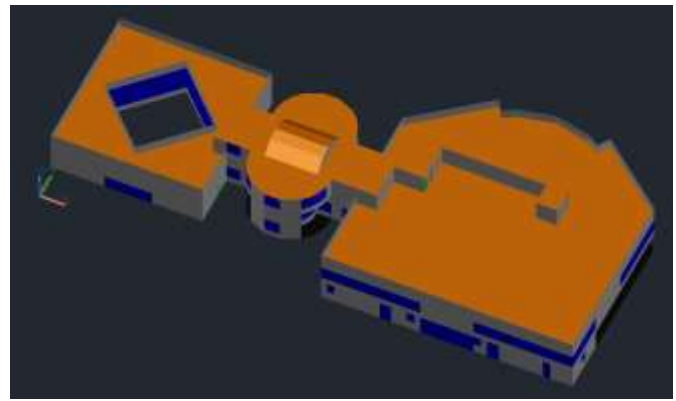

Figure 1. University Canteen used in the study (South-East view) without horizontal external shading devices. The grey color is associated to opaque surfaces, blue is associated to transparent surfaces (windows) and green is associated to doors.
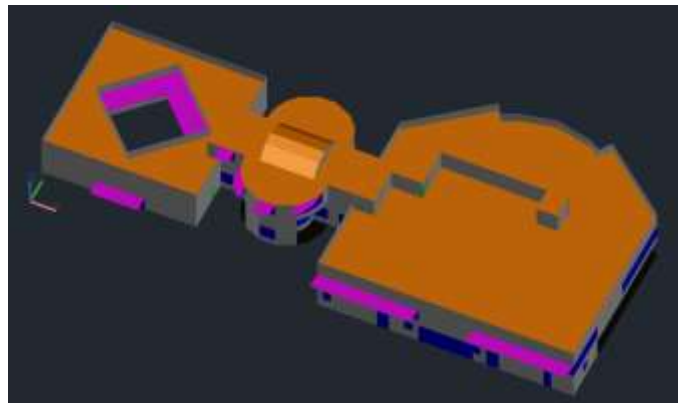

Figure 2. University Canteen used in the study (South-East view) without horizontal external shading devices. The grey color is associated to opaque surfaces, blue is associated to transparent surfaces (windows), green is associated to doors and magenta is associated to shading systems.

IV. Results and Discussion

In this section, after being presented the 3D view of the university canteen, without and with horizontal shading devices, the evolution, in a summer typical days, of the window transmittance solar radiation, air temperature and PMV index, is presented.

In Figures 1 and 2 the 3D view of the University Canteen, respectively, without and with horizontal external shading devices, is presented. In these Figures, the camera is placed in the sun location at the 12 hours of the 21th June and is possible to show the effect of the shading device in the solar radiation in the window.
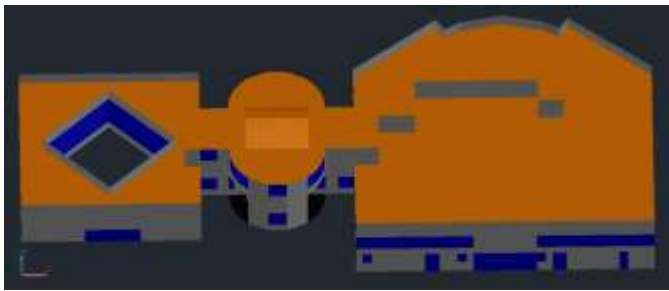
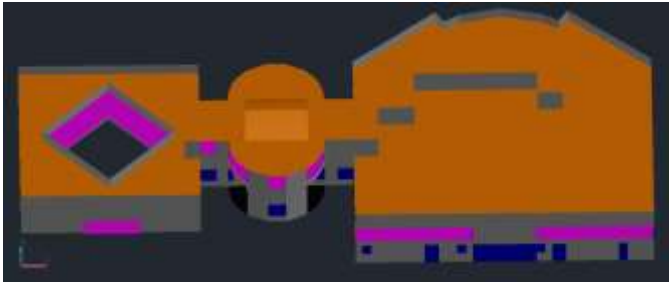Figure 3. 3D view of the University Canteen without horizontal external shading devices.

Figure 4. 3D view of the University Canteen without horizontal external shading devices.

In accordance with Figures 3 and 4 is possible to see, at 12 hours of the 21th June, the shading system guaranteeing no radiation entering through the window, because the shading device is placed exactly in the trajectory between the sun and the window.

In Figures 5 and 6, the evolution of transmitted solar radiation in windows, respectively, without and with horizontal shading devices, of the Professors' main Canteen (room 29) is presented. Red colours are associated to three windows facing East, green colours are associated to one window facing South and blue colours are associated to three windows facing West.
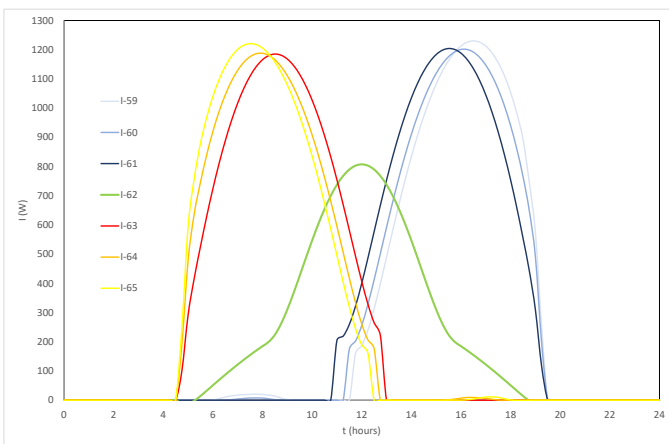

Figure 5. Evolution of transmitted solar radiation in windows, not equipped with horizontal shading devices, of the Professors' main Canteen (room 29).
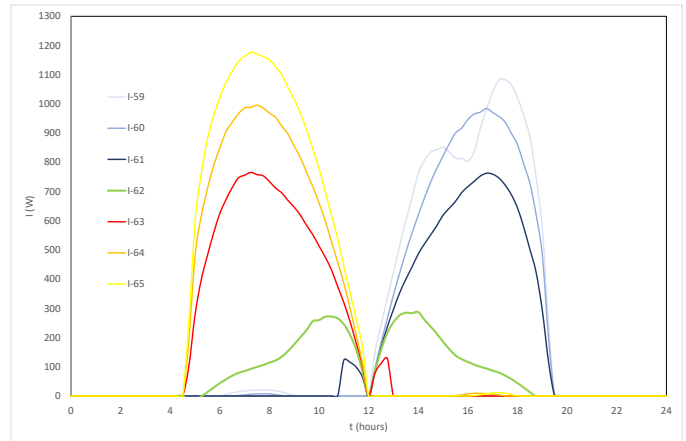

Figure 6. Evolution of transmitted solar radiation in windows, equipped with horizontal shading devices, of the Professors' main Canteen (room 29).

The shading device, in accordance with the numerical model, guarantees, at the 12 hours of 21th June, that no radiation enters through the window. However, before and after 12 hours, the shading device only reduces the transmitted solar radiation.

From Figure 5 to Figure 8 is presented the evolution of air temperature in room 11 (university bar), room 23 (students' main Canteen) and room 29 (Professors' main Canteen). In Figures 5 and 6 are not considered shading devices, while in Figures 7 and 8 are considered shading devices. In Figures 5 and 7 are not considered HVAC systems, while in Figures 6 and 8 are considered the HVAC systems.

In accordance with the obtained results, without HVAC systems, the shading devices in room 11 and in room 23 reduce around 1 ℃ the air temperature and in room 29 reduce around 0.5 ℃ the air temperature. The shading devices in the first situation reduce more the internal air temperature than in the second situation. This conclusion is associated to the fact that in the second one the windows are turned Southwest and Southeast direction and in the first one the window are mainly turn towards South.
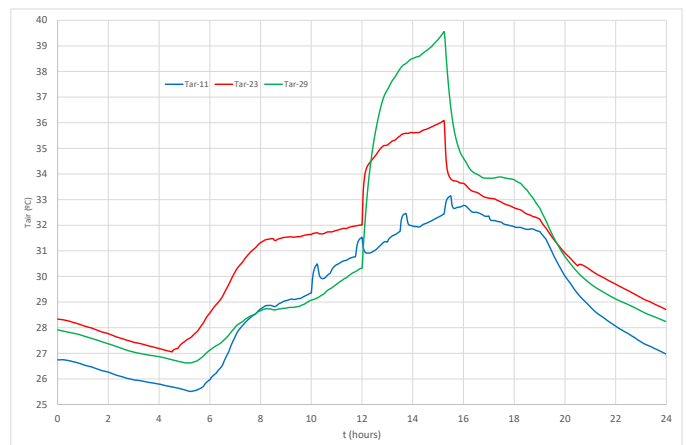

Figure 7. Evolution of air temperature in room 11 (University Bar), room 23 (Students' main Canteen) and room 29 (Professors' main Canteen), without shading devices and without HVAC system.
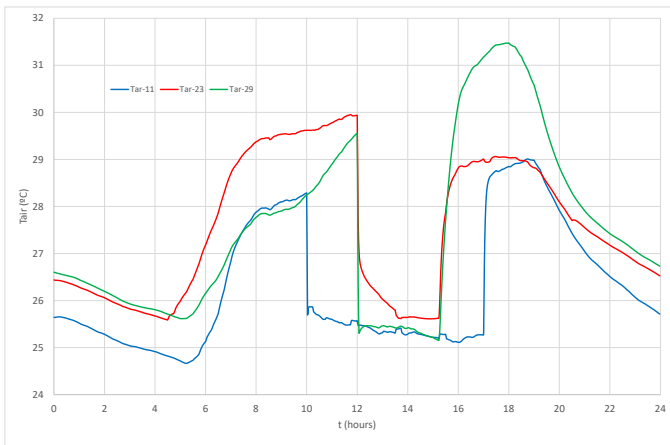
58

Figure 8. Evolution of air temperature in room 11 (University Bar), room 23 (Students' main Canteen) and room 29 (Professors' main Canteen), without shading devices and with HVAC system.

Thus, in the future is suggested the development of shading devices guaranteeing that no radiation enters through the window, except at 12 hours.
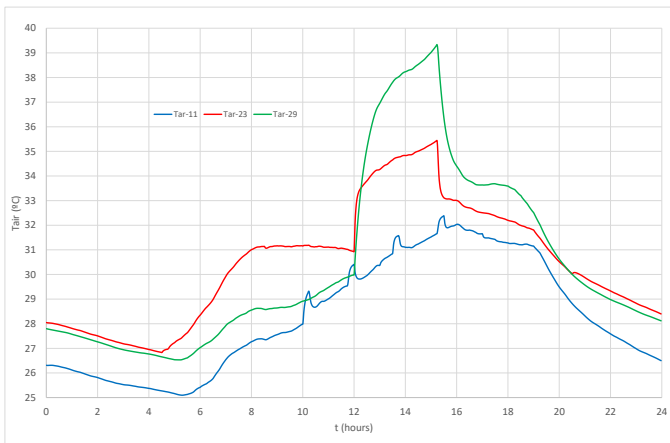

Figure 9. Evolution of air temperature in room 11 (University Bar), room 23 (Students' main Canteen) and room 29 (Professors' main Canteen), with shading devices and without HVAC system.
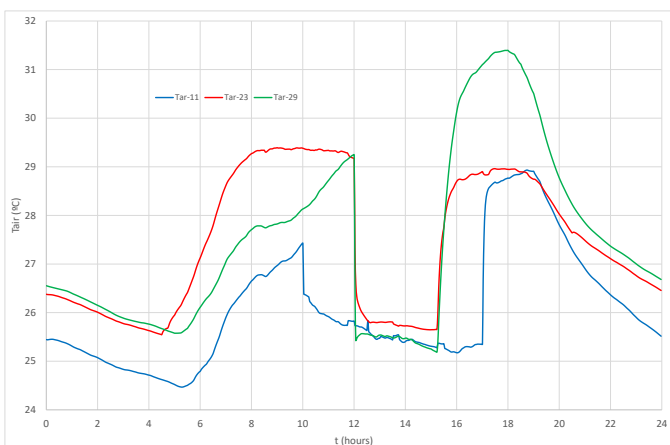

Figure 10. Evolution of air temperature in room 11 (University Bar), room 23 (Students' main Canteen) and room 29 (Professors' main Canteen), with shading devices and with HVAC system.

In accordance with the obtained results, when the spaces are occupied, in general, the HVAC system guarantees the same internal air temperature, either when shading is not considered, or when shading is considered.

The air temperature, in accordance with the Figures, when the HVAC system is on and when the spaces are occupied, inside each space, decreases slightly during the day. This fact is associated to the increase of the value of the Mean Radiant Temperature, due to the increase during the day of the surrounding opaque and transparent surfaces.

The evolution of PMV index, in the Professors' main Canteen (room 29), without and with shading devices, when the HVAC system is on, is presented in Figure 11. The HVAC control, based in PMV index, guarantees, during the occupation time, acceptable thermal comfort levels. The PMV index is in accordance with the Category B of ISO 7730 [9]
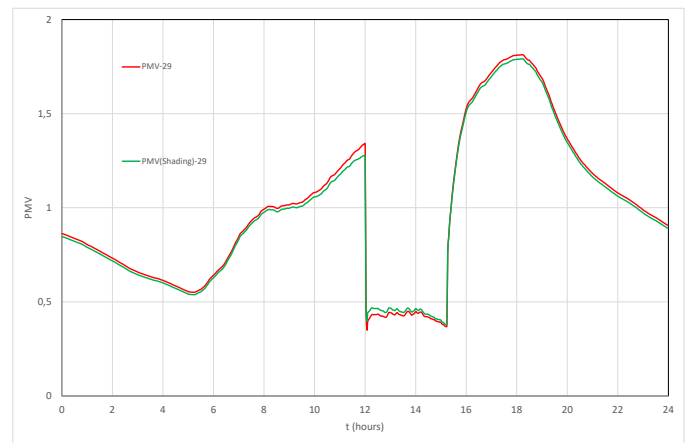

Figure 11. Evolution of PMV index in room 29 (Professors' main Canteen), without and with shading devices and with HVAC system.

In future works, in accordance with the present results, is suggested to develop new shading devices installed above the window levels, which guarantee no entrance of solar radiation after and before the 12 hours. In these shadings devices, that can be horizontal or inclined, the rectangular shape should be replaced by a trapezoidal configuration or other shape configuration.

V. Conclusions

In this work a numerical model that evaluates the buildings thermal behaviour is presented. The model was used in the thermal study of an University Canteen, with three floors, located in the South of Portugal in a typical summer day with clean sky. The shading devices system, developed in windows of three spaces, guarantee that no radiation enters through the window, at the 12 hours of 21th June.

In accordance with the virtual design of the shading devices, developed by the Building Dynamic Software, at 12 hours of the 21th June, no radiation enters through the window, because the shading devices are placed exactly in the trajectory between the sun and the window. Using the

59

evolution of solar radiation, is possible to confirm these results and verify that before and after 12 hours, the shading devices reduce the transmitted solar radiation.

Without HVAC system, the shading devices in room 11 and in room 23 reduce around 1 ºC the air temperature and in room 29 reduce around 0.5 ºC the air temperature.

The HVAC system, when the space is occupied, guarantee the same internal air temperature, either when shading is not considered, or when shading is considered. In these cases, the air temperature decreases slightly during the day, in order to the increase of the value of the Mean Radiant Temperature, due the increase during the day of the surrounding opaque and transparent surfaces.

The HVAC control, based in PMV index, guarantees, during the occupation time, acceptable thermal comfort levels, in accordance with the Category B of ISO 7730 [9]

In future works is suggested to develop new shading devices installed above the window levels, that guarantee no entrance of solar radiation after and before the 12 hours. Trapezoidal configuration or other shape configuration will be used as shading devices.

Acknowledgment

References

[1]   L. Yang, H. Yan, and J. C. Lam, "Thermal comfort and building energy consumption implications - A review," *Applied Energy*. 2014, doi: 10.1016/j.apenergy.2013.10.062.

[2]   N. C. Balaji, M. Mani, and B. V. Venkatarama Reddy, "Thermal performance of the building walls," 2013.

[3]   E. Z. E. Conceicao, M. C. G. Da Silva, J. C. S. Andre, and D. X. Viega, "Thermal behaviour simulation of the passenger compartment of vehicles," *Int. J. Veh. Des.*, vol. 24, no. 4, pp. 372–387, 2000.

[4]   E. Z. E. Conceição and M. M. J. R. Lúcio, "Thermal study of school buildings in winter conditions," *Build. Environ.*, vol. 43, no. 5, 2008, doi: 10.1016/j.buildenv.2007.01.029.

[5]   E. Z. E. Conceição and M. M. J. R. Lúcio, "Numerical study of the influence of opaque external trees with pyramidal shape on the thermal behaviour of a school building in summer conditions," *Indoor Built Environ.*, vol. 19, no. 6, 2010, doi: 10.1177/1420326X10377546.

[6]   E. Z. E. Conceição and M. M. J. R. Lúcio, "Numerical study of the thermal efficiency of a school building with complex topology for different orientations," *Indoor Built Environ.*, vol. 18, no. 1, 2009, doi: 10.1177/1420326X08099550.

[7]   P. Ole Fanger, "Thermal comfort. Analysis and applications in environmental engineering.," *Copenhagen Danish Tech. Press*, 1970.

[8]   ASHRAE-55, "Thermal environmental conditions for human occupancy," *ANSI/ASHRAE Stand. - 55*, 2017.

[9]   ISO, "ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria," *Management*, 2005, doi: 10.1016/j.soildyn.2004.11.005.

[10]   E. Z. E. Conceição and M. M. J. R. Lúcio, "Evaluation of thermal comfort conditions in a classroom equipped with radiant cooling systems and subjected to uniform convective environment," *Appl. Math. Model.*, vol. 35, no. 3, 2011, doi: 10.1016/j.apm.2010.09.006.

[11]   E. Z. E. Conceição and M. M. J. R. Lúcio, "Evaluation of thermal comfort conditions in a localized radiant system placed in front and behind two students seated nearby warmed curtains," *Build. Environ.*, vol. 45, no. 10, 2010, doi: 10.1016/j.buildenv.2010.03.006.

[12]   E. Z. E. Conceição, V. D. S. R. Vicente, and M. M. J. R. Lúcio, "Airflow inside school building office compartments with moderate environments," *HVAC R Res.*, vol. 14, no. 2, 2008, doi: 10.1080/10789669.2008.10391003.

[13]   ASHRAE, "Ventilation for Acceptable Indoor Air Quality," *J. Phys. A Math. Theor.*, 2016, doi: 10.1088/1751-8113/44/8/085201.

[14]   E. Z. Conceicao, M. C. Silva, and D. X. Viegas, "Air quality inside the passenger compartment of a bus.," *J. Expo. Anal. Environ. Epidemiol.*, vol. 7, no. 4, pp. 521–534, 1997.

[15]   E. Z. E. Conceição, J. P. Farinho, and M. M. J. R. Lúcio, "Evaluation of indoor air quality in classrooms equipped with cross-flow ventilation," *Int. J. Vent.*, vol. 11, no. 1, 2012.

[16]   E. H. Mathews, C. P. Botha, D. C. Arndt, and A. Malan, "HVAC control strategies to enhance comfort and minimise energy usage," *Energy Build.*, 2001, doi: 10.1016/S0378-7788(01)00075-5.

[17]   H. Mirinejad, S. H. Sadati, M. Ghasemian, and H. Torab, "Control Techniques in heating, ventilating and air conditioning systems," *Journal of Computer Science*. 2008, doi: 10.3844/jcssp.2008.777.783.

[18]   E. Z. E. Conceição, M. M. J. R. Lúcio, A. E. B. Ruano, and E. M. Crispim, "Development of a temperature control model used in HVAC systems in school spaces in Mediterranean climate," *Build. Environ.*, vol. 44, no. 5, 2009, doi: 10.1016/j.buildenv.2008.06.015.

[19]   E. Z. E. Conceição, J. M. M. Gomes, and A. E. Ruano, "Application of HVAC Systems with Control Based on PMV Index in University Buildings with Complex Topology," *IFAC-PapersOnLine*, vol. 51, no. 10, 2018, doi: 10.1016/j.ifacol.2018.06.230.

[20]   E. Z. E. Conceição, A. R. L. Nunes, J. M. M. Gomes, and M. J. R. Lúcio, "Application of a school building thermal response numerical model in the evolution of the adaptive thermal comfort level in the Mediterranean environment," *Int. J. Vent.*, vol. 9, no. 3, 2010, doi: 10.1080/14733315.2010.11683887.

[21]   Ministério das Obras Públicas, "O Regulamento dos Sistemas Energéticos de Climatização em Edifícios (RSECE)-Decreto-Lei n.o 79/2006," *Diário da República*, 2006.

[22]   E. Z. E. Conceição and M. M. J. R. Lúcio, "Numerical simulation of passive and active solar strategies in buildings with complex topology," *Build. Simul.*, vol. 3, no. 3, 2010, doi: 10.1007/s12273-010-0010-7.

[23]   E. Z. E. Conceição, M. M. J. R. Lúcio, V. D. S. R. Vicente, and V. C. T. Rosão, "Evaluation of local thermal discomfort in a classroom equipped with cross flow ventilation," *Int. J. Vent.*, 2008, doi: 10.1080/14733315.2008.11683817.

About first Author:

Eusébio Conceição is an Assistant Professor at Sciences and Technology Faculty of University of Algarve (Portugal).
Concluded his Ph. D. in 1996 in the University of Coimbra (Portugal).
The Areas of research interests are the energy, thermal comfort, air quality, building and occupant's thermal simulation and computational fluids dynamics.