2_C15

The Influence of Balconies on the Indoor Environmental Conditions of Dwellings

Catarina Ribeiro **Pedro F. Pereira, PhD** **Nuno M. M. Ramos, PhD**

Inês Flores-Colen, PhD **Nuno Valentim, PhD**

ABSTRACT

The balcony is defined as an in-between architectural element that has the ability to intermediate the indoor and the outdoor environmental conditions. Through history, distinct balcony solutions have been used to improve the indoor environment according to their suitability to different contexts and climate conditions. The main aim of this study is to evaluate the impacts of different balconies on indoor environmental quality (IEQ) of dwellings in the mild climatic conditions of Portugal. This paper provides the results of an assessment campaign conducted in a residential building constructed at the beginning of the '60s. This existing building represents a relevant part of the housing stock that will need a deep rehabilitation intervention in the next decades. During the in-situ campaign, the indoor environmental quality was assessed in four balconies and their contiguous space: one open balcony, one glazed balcony, one eliminated balcony, and one open balcony with improved windows. The evaluated indoor environmental parameters included air temperature, relative humidity, CO_2, $PM_{2.5}$ and TVOCs concentration, illuminance level and acoustic sound pressure level. The results confirmed that different balcony solutions produce relevant impacts on the four factors that contribute to the indoor environmental quality (thermal comfort, air quality, acoustic comfort and lighting comfort). Additionally, the analysis of the interactions of the different balcony impacts highlighted the importance of finding solutions that can balance the effect on different IEQ parameters.

INTRODUCTION

The balcony is a private open-air space in dwellings defined as an in-between architectural element that has the ability to intermediate the indoor and the outdoor environmental conditions. Some studies verified that the overhang effect of balconies could reduce energy consumption in cooling (Chan and Chow 2010), and block the uncomfortable luminous glare (Xue, Mak et al. 2016). Additionally, it was confirmed that balconies increase the airflow rate in natural ventilated dwellings improving the indoor thermal conditions (Bhikhoo, Hashemi et al. 2017), and reducing the pollutant concentration (Ai and Mak 2014). Moreover, some researches indicate that balconies could act as an acoustic protection device against outdoor noise (Wang, Mao et al. 2015). The main aim of this study is to evaluate the impacts of different balconies on indoor environmental quality (IEQ) in the mild climatic conditions of Portugal.

Catarina Ribeiro is a PhD student, **Pedro F. Pereira** is a research fellow and **Nuno M. M. Ramos** is an Assistant Professor at CONSTRUCT-LFC, Faculdade de Engenharia (FEUP), Universidade do Porto. **Inês Flores-Colen** is an Associate Professor at CERIS, DECivil, Instituto Superior Técnico (IST), Universidade de Lisboa. **Nuno Valentim** is an Assistant Professor at the Faculdade de Arquitectura (FAUP), Universidade do Porto.

METHODOLOGY

The assessment campaign was conducted during the autumn season, between September 20th and October 20th of 2019, in a building constructed at the beginning of the ’60s, which represents a relevant part of the housing stock that will need a deep rehabilitation intervention in the next decades.

Case study

The studied building is located in an important street of the city of Porto. With 15 storeys, it has been systematically modified during the last decades and nowadays presents a large number of balcony types. Four south-facing balconies and their contiguous rooms (_cr), with distinct characteristics, were assessed to evaluate the impacts of different balcony types on the indoor environmental quality. As shown in Figure 1a, the monitoring was carried out on: one open balcony (OB) with the original sliding aluminium windows with simple glass; one glazed balcony (GB), in which the original window was maintained and was added a new sliding aluminium window with single glass in the outside edge of the balcony; one eliminated balcony (EB), where the wall that divides the balcony and the contiguous room was demolished, it was added a new sliding aluminium window with single glass in the outside edge of the balcony, and the former balcony was integrated into the indoor living space; and one open balcony where a double glass aluminium windows replaced the original window (OB*). The indoor spaces have low and not regular occupancy during the day and were used as offices, with the exception of the room contiguous to the glazed balcony (GB_cr), that was used as a bedroom. All the dwellings have natural ventilation, and during the monitoring period, no heating or cooling was activacted.

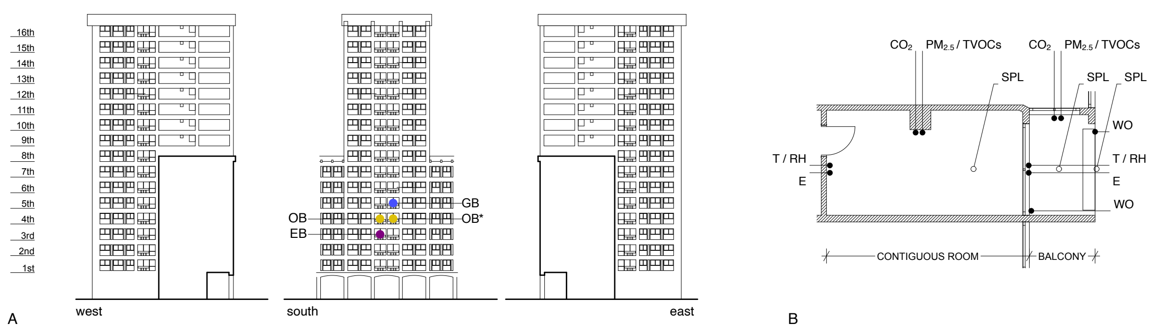

Figure 1 (a) Case study building. (b) Balcony and contiguous space plan, along with sensors location.

IEQ measurements

Air temperature (T), relative humidity (RH), carbon dioxide (CO_2), airborne Particulate Matter ($PM_{2.5}$), Total Volatile Organic Compounds (TVOCs) concentration, illuminance level (E) and the windows opening stage (WO) were monitored continuously during one month in each space, to evaluate the impact of balconies in indoor environmental quality. The measurements were done at the same place on each balcony and its contiguous room (_cr)(Figure 1b). Additionally, sound pressure level (SPL) measurements were conducted to investigate the acoustic reduction impact of the different balconies.

To evaluate the indoor air temperature and relative humidity HOBO data loggers UX100-011 were installed. The air temperature sensors have a measurement range between -20 °C and 70 °C, with an accuracy of ±0.21°C and resolution of 0.024°C, while relative humidity sensors have a range between 1% and 95%, with an accuracy of ± 2.5% and resolution of 0.05%. The hygrothermal measurements were carried out in compliance with (ISO-7726 1998) and the monitoring parameters defined in (ISO-7730 2005).

CO_2 sensors and equipment simultaneously monitoring $PM_{2.5}$ and TVOCs were installed to evaluate the indoor air quality. The CO_2 Telaire T6713-5K sensors have a recording range from 0 to 5000 ppm, an accuracy of ±25 ppm or ±3% (between 400 – 2000 ppm) and of ±30 ppm or ±3% (between 2000–5000 ppm); the $PM_{2.5}$ Sharp GP2Y1010AU0F sensors have a sensibility particulate size 0.3 µm to 2.5 µm, and range from 0 to 1 300 µg/m³, with a precision of ±4µg or ±20%; while TVOCs AMS iAQ-CORE-C sensors have a measurement range between 125–1000 ppb, with an accuracy of ± 1.0 ppb.

The lighting conditions were monitored, according to the specified on normative (EN-12464-1 2011), to assess the impact of the different balconies on the natural lighting performance of the contiguous room. Lux meter HOBO UA-002-64 Data Loggers were used to measure the vertical illuminance values, with a range from 0 to 320,000 lux.

The acoustic experimental campaign was carried out using a sound pressure level meter (Brüel & Kjæ Type 2260) with a measurement linear operating range of 80dB, adjustable to give full-scale readings from 80dB to 130dB in 10dB steps. Sound pressure levels were recorded during 15 min, between 15:00 and the 18:00, on three spaces per balcony: on the outdoor balcony limit pointed outward, in the middle of the balcony space and inside the contiguous room with the windows closed.

During the in-situ campaign a HOBO data logger (UX90-001) was installed on each window to register the periods in which it was open and closed, with a time accuracy of ±1 minute per month. Additionally, environmental data were obtained from the weather station of the municipality of Porto (Vantage Pro 2 Plus – Davis), located less than 1200 m from the case study (DMPC 2019).

RESULTS AND DISCUSSION

This section presents the most relevant results of the measurement campaign of each indoor environmental quality factor: thermal comfort, indoor air quality, visual comfort and acoustic comfort.

Thermal comfort

As verified on the recorded air temperature and relative humidity profiles, presented in **Erro! A origem da referência não foi encontrada.**, during the campaign period, all the balcony spaces registered slightly high air temperature values and low relative humidity than those measured outside. The mean air temperature in the open balcony (OB) remained on average 3.0°C above the mean outdoor temperature. Although, this phenomenon is the most obvious on the glazed balcony (GB), in which the mean temperature remained on average 6ºC above the mean outdoor temperature. These results were identical to previous studies that observed that the air temperature inside the balconies remains higher than outdoors during all seasons (respectively on average 2 ºC in open balconies and 5ºC in glazed balconies) (Hilliaho, Kolio et al. 2016).

Erro! A origem da referência não foi encontrada. presents the minimum, maximum, mean and standard derivation of air temperature and relative humidity recorded in each balcony and its contiguous spaces, within the percentage of time the windows were opened ("WO", 100% - always open, 0% - never open). To evaluate the impact of the distinct balcony spaces on the indoor contiguous room both the mean of air temperature difference (defined as the difference between indoor and outdoor air temperature, $\Delta T = Ti - To$) and the mean of water vapor pressure difference (defined as the difference between indoor and outdoor vapor pressure, $\Delta p = p_i - p_e$) were calculated.

Considering the spaces contiguous to the balconies, the mean air indoor temperature in the room contiguous to the open balcony (OB_cr) remained 5°C above the mean outside temperature. This difference was almost 2°C higher in the rooms contiguous to the glazed balcony (GB_cr) and the balcony with double glazing windows (OB*_cr). However, as observed in previous studies carried out during the winter (Song and Choi 2012), the indoor air temperature inside the space where the balcony was eliminated (EB) was slightly lower than the rooms with balconies.

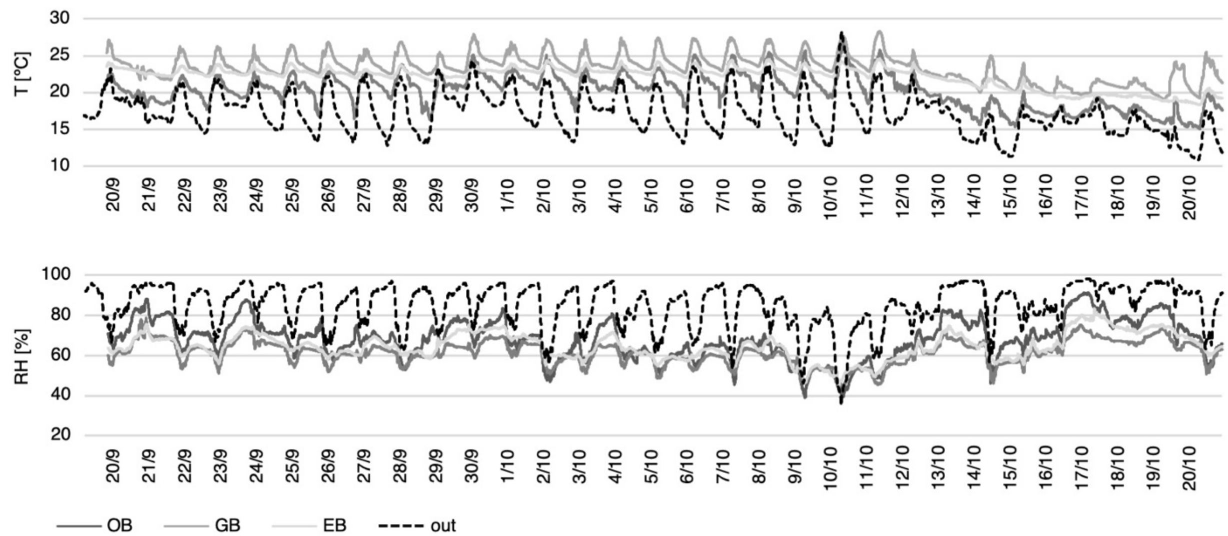

Figure 2 Air temperature and relative humidity profiles.

Additionally, the percentage of time in which the indoor air temperature (T) and water vapor pressure difference (Δp) were above threshold values was calculated, in order to evaluate the impact of balconies on the overheating of the contiguous rooms. The critical temperature value was defined daily according to the normative (EN-15251 2007), and range from 26.4 ºC to 27.9ºC ; and the water vapor pressure upper limit (Δp) value was established at as 135 Pa, as indicated in the normative (ISO-13788 2001).

No overheating problems were registered in both balconies and their contiguous spaces during the measurement period. Although, probably due to a more regular occupancy, the glazed balcony (GB) and its contiguous room were the space that overlapped more time the vapor pressure excess limit (respectively 47% and 50%).

Table 1. Means of measured temperature and relative humidity values

	T_{min} (◦C)	T_{max} (◦C)	T_{mean} (◦C)	ΔT_{mean} (◦C)	$T>_{lim}$ (%)	RH_{min} (%)	RH_{max} (%)	RH_{mean} (%)	$\Delta p>_{lim}$ (%)	WO (%)
OB	11.6	27.1	20.0	3.1	0	38.9	91.3	67.2	1	
OB_cr	19.7	23.5	22.1	5.2	0	50.4	72.7	61.8	24	100
GB	19.1	28.3	23.3	6.5	0	44.6	78.8	60.9	47	41
GB_cr	21.5	25.7	23.7	6.9	0	46.5	70.8	60.6	50	94
EB	18.3	24.6	21.9	5.0	0	42.3	83.2	63.9	30	0
OB*	11.9	29.6	19.9	3.0	0	32.0	87.9	67.8	0	
OB*_cr	23.8	25.6	24.5	6.4	0	54.3	66.9	60.1	26	1
OutT	8.8	28.3	16.9			35.0	98.0	85.0		

Indoor air quality

The indoor air pollution levels were monitored during the experimental period inside the balconies and their contiguous rooms. The measured CO2, PM2.5 and TVOCs concentrations, along with the respective limit of exposure are shown in Figure 3. A threshold of 1000 ppm for the exposure to indoor CO_2 was adopted, according to (ASHRAE 2001) and to (ASTM 2012). For particles smaller than 2.5 µm ($PM_{2.5}$) the World Health Organization proposed 25 $\mu g/m^3$ as the daily mean guideline limit to human exposure (WHO 2006). The value of 300 ppb was used for TVOCs as the threshold, considering the guidelines of the equipment manufacturer.

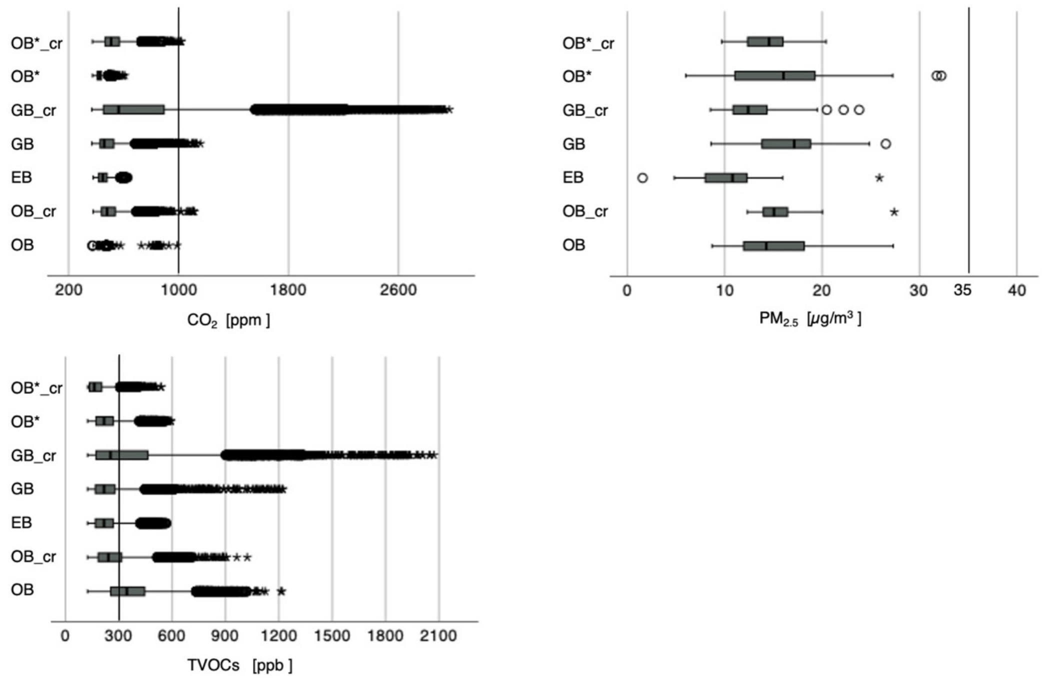

Figure 3. Boxplots of CO_2, TVOCs values, and $PM_{2.5}$ daily mean and within each balcony and contiguous rooms, along with the respective limit of exposure.

Air quality in the studied spaces was generally good, with low levels of CO_2, $PM_{2.5}$, only presenting values above the recommended limits for TVOCs measurements. CO_2 concentration is a good indicator of occupancy (Wolf, Møller et al. 2019, Pereira and Ramos 2021). Concentrations of CO_2 were low during the experimental period and did not exceed the respective exposure limit, probably due to the low occupation rate of some contiguous rooms. Although, the contiguous room to the glazed balcony (GB_cr), used as a bedroom with a regular night occupation, was an exception. The CO_2 concentration exceeded the limit during 21% of the whole measurement period and 68% of the night occupied period, with a mean concentration of 1500 ppm.

The measured values of $PM_{2.5}$ within balconies and their contiguous spaces registered low concentration levels with insignificant differences. $PM_{2.5}$ is brought in from the outdoor environment by ventilation airflow or produced by internal sources (Martins and Carrilho da Graça 2018). In this case, the limit of exposure was exceeded only on the open balconies, where there is no defined physical boundary with the outside. Due to some peaks associated to internal sources it was not possible to relate the indoor $PM_{2.5}$ to the permeability of the different balcony solution.

In turn, the TVOCs concentrations overlapped the threshold in all balconies and contiguous rooms. The presence of TVOCs is mainly associated to the chemical products applied inside the houses, and the external contribution of VOCs is considered unusual (Agüera, Amarillo et al. 2019). Therefore, the ventilation is considered a contribution to the dilution of the indoor TVOCs. However, in this study, this parameter is distorted by the distinct indoor emission rates, and it was not possible to verify any relation of the concertation of pollutants and the air permeability of the distinct balcony types.

The space where the balcony (EB) was eliminated was the only space that had the windows closed throughout all the measured period. However, due to the distinct occupancy patterns, a significant increase of pollutants in this space was not verified, as previous studies suggested (Ai and Mak 2014).

Lighting results

The lighting conditions were examined by monitoring the illuminance values (E) inside balconies and their contiguous spaces during the in-situ campaign. For this analysis, a range of vertical illuminance acceptability between 300 lux and 750 lux was established, according to the normative (EN-12464-1 2011) and some authors (Shin, Kim et al. 2013).

The lighting performance profiles were analysed in the contiguous spaces under two different sky conditions: in clear day and an overcast day (Figure 4). On this analysis, significant differences were identified in illuminance levels: the range of illuminance in the contiguous room to the balcony and glazed balcony (OB_cr and GB_cr) were more time inside the identified thresholds, respectively 31% and 30%. In turn, the room where the balcony had been eliminated (EB), was only 20% inside the identified threshold and reached illuminance values that, according to some authors, could originate visual discomfort (Shin, Kim et al. 2013).

Identical to the results of previous studies (Wilson, Jorgensen et al. 2000), it was observed that addition glazing at the edge of the balcony (GB) reduced the mean illuminance level up to 64%. In contrast, the elimination of the balcony (EB) originated an increase of the mean illuminance values of 136%. Therefore, it was verified that the shading effect of the balcony overhang creates adequate natural light for different activities, without side effects like excessive glare and blinding. On the overcast day, all the spaces presented a similar lighting profiles, and the values were identical during all day.

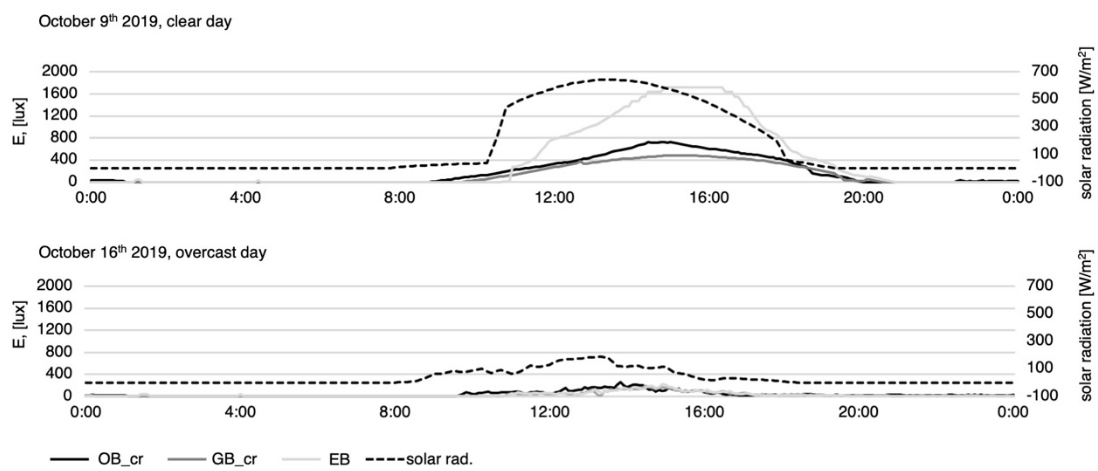

Figure 4. Illuminance profiles of balconies contiguous spaces, compared to the external solar radiation.

Acoustic results

The Sound Pressure Levels (SPL) per each studied space are shown in Table 2. These values were registered simultaneously at the outside limit of the balcony and inside the contiguous room. The table also presents the noise reduction generated by each balcony space (ΔSPL). The open balcony (OB) registered a noise reduction of 7 dBa higher compared with the rooms where the former balcony had been eliminated (EB). In turn, the addition of a glass to the edge of the balcony (GB) improved the noise reduction effect approximately 8 dBa. The space contiguous to the open balcony with new windows (OBs*) presented an intermediate outdoor noise reduction, up to 5 dBa higher than the original balcony (OB), but lower 3 dBa lower than the glazed balcony (GB)

Table 2 also presents the percentage of time that each space had the window opened (WO) during the monitoring campaign. The space in which the balcony had been eliminated (EB) had the windows closed during all the measurement period, which highlights that the acoustic noise reduction created by balconies influences the percentage of time that windows were opened in each contiguous space. This result is in line with previous studies that verified that the noise reduction provoked by balconies enhances opening the widows more regularly (Kennedy, Buys et al. 2015).

Table 2. Sound pressure level in each balcony and room contiguous

	SPL outdoor (dBa)	SPL cr (dBa)	ΔSPL (out-cr) (dBa)	WO (%)
OB	68.8	43.5	25.3	100
GB	67.1	33.8	33.3	41; 94
EB	58.9	40.9	18.0	0
OB*	69.0	39.2	29.8	100

CONCLUSION

The results proved that the different balconies analysed provoked relevant impacts on the overall indoor environmental quality during the in-situ campaign. It was verified that the open balcony (OB) acted as a buffer space, mediating the outdoor and the indoor conditions. Compared with the space where the balcony was eliminated (EB), it was observed that the room contiguous to the open balcony (OB_cr): registered slight hight indoor air temperatures; was more time inside the established range of illuminance acceptability during daylight; and presented a noise reduction up to 7 dBa higher. It was also verified that the adaptation of a balcony to a glazed balcony (GB) modified these impacts. Compared with the room contiguous to the open balcony (OB_cr), the room contiguous to the glazed balcony (GB_cr): registered almost 2°C higher indoor air temperatures; had a reduction of the mean illuminance level up to 64%; and had an increase of the noise reduction effect of approximately 8 dBa.

An early research concluded that the impacts created by balconies were interconnected and suggested that the acoustic noise reduction effect of the balcony enhances the inhabitants to open the windows more regularly, contributing to improve the indoor air quality of the contiguous room (Ribeiro, Ramos et al. 2020). In fact, in this study, the space where the balcony was eliminated had the lowest noise reduction and was the only space with the windows closed all the campaign period. Although, contrarily to the results of previous studies (Ai and Mak 2014), it was not verified a significant improvement of the indoor air quality in the room contiguous to the open balcony. In this study, the indoor air quality parameters were demonstrated to be more conditioned by the occupancy patterns and occupants' behaviour than by the balcony typology. Nevertheless, the interconnection between the balcony impacts on the noise acoustic reduction and the percentage of time the windows are opened could have particular relevance in warmer conditions. In the mild climate conditions of the north of Portugal, in which the improvement of the natural ventilation during summer can reduce the indoor air temperature and relative humidity, a balcony could contribute to reduce the overheating problems. For that reason, it seems essential to consider the complexity of the relation between the different IEQ parameters to optimize the balcony design to each climate condition and context.

This paper is an early investigation of a more comprehensive study that explores the impact of balcony spaces on the IEQ during cooling and heating periods. A winter and summer measurement campaign and an analysis of the relationship between the balcony impacts on IEQ parameters are under development.

ACKNOWLEDGMENTS

The first author would like to acknowledge the support of FCT - Fundação para a Ciência e a Tecnologia, the funding of the Doctoral Grant PD/BD/135164/2017, through the Doctoral Programme EcoCoRe. This work was financially supported by: Base Funding - UIDB/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC). The authors want to thank the Municipal Department of Civil Protection - Porto for the outdoor weather data.

NOMENCLATURE

T = air temperature
RH = relative humidity
CO_2 = carbon dioxide

TVOCs = total volatile organic compounds
$PM_{2.5}$ = particulate matter smaller than 2.5 μm
E = illuminance level
SPL = sound pressure level

REFERENCES

Agüera, J. F., S. D. Amarillo, M. Fornaciari and F. Orlandi (2019). "TVOCs and PM 2.5 in Naturally Ventilated Homes: Three Case Studies in a Mild Climate." Sustainability **11**(22).

Ai, Z. T. and C. M. Mak (2014). "A study of interunit dispersion around multistory buildings with single-sided ventilation under different wind directions." Atmospheric Environment **88**: 1-13.

ASHRAE (2001). Ventilation for acceptable Indoor Air Quality. ANSI- ASHRAE-62. ASHRAE. Atlanta, GA.

ASTM (2012). Standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation. ASTM-D6245. A. S. f. T. a. Materials. West Conshohocken, PA, USA.

Bhikhoo, N., A. Hashemi and H. Cruickshank (2017). "Improving thermal comfort of low-income housing in Thailand through passive design strategies." Sustainability (Switzerland) **9**(8).

Chan, A. L. S. and T. T. Chow (2010). "Investigation on energy performance and energy payback period of application of balcony for residential apartment in Hong Kong." Energy and Buildings **42**(12): 2400-2405.

DMPC. (2019). "Meteorological station of Porto." Retrieved 2019, from https://www.wunderground.com/personal-weather-station/dashboard?ID=IPORTOPO9.

EN-12464-1 (2011). Light and lighting - Lighting of work places - Part 1: Indoor work places. EN-124264-1. E. C. f. Standardization. Brussels, Belgium.

EN-15251 (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. EN-15251. E. C. f. S. CEN. Brussels, Belgium.

Hilliaho, K., A. Kolio, T. Pakkala, J. Landensivu and J. Vinha (2016). "Effects of added glazing on Balcony indoor temperatures: Field measurements." Energy and Buildings **128**: 458-472.

ISO-7726 (1998). Ergonomics of the Thermal Environment-Instruments for Measuring Physical Quantities EN-7726. I. O. f. Standardization. Geneva, Switzerland

ISO-7730 (2005). 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. ISO-7730. I. O. f. Standardization. Geneva, Switzerland.

ISO-13788 (2001). Hygrothermal performance of building components and building elements-Internal surface temperature to avoid critical surface humidity and interstitial condensation-Calculation methods. ISO 13788. I. O. f. Standardization. Brussels, Belgium.

Kennedy, R., L. Buys and E. Miller (2015). "Residents' experiences of privacy and comfort in multi-storey apartment dwellings in subtropical Brisbane." Sustainability (Switzerland) **7**(6): 7741-7761.

Martins, N. R. and G. Carrilho da Graça (2018). "Impact of PM2.5 in indoor urban environments: A review." Sustainable Cities and Society **42**: 259-275.

Pereira, P. F. and N. M. M. Ramos (2021). "The impact of mechanical ventilation operation strategies on indoor CO2 concentration and air exchange rates in residential buildings." Indoor and Built Environment **30**(9): 1516-1530.

Ribeiro, C., N. M. M. Ramos and I. Flores-Colen (2020). "A Review of Balcony Impacts on the Indoor Environmental Quality of Dwellings." Sustainability: 1-19.

Shin, H. Y., G. Kim and J. T. Kim (2013). "Effect of Occupants' Behaviour of Daylight Controls on Residential Visual Environment." Indoor and Built Environment **22**(1): 191-202.

Song, D. and Y.-J. Choi (2012). "Effect of building regulation on energy consumption in residential buildings in Korea." Renewable and Sustainable Energy Reviews **16**(1): 1074-1081.

Wang, X., D. Mao, W. Yu and Z. Jiang (2015). "Acoustic performance of balconies having inhomogeneous ceiling surfaces on a roadside building facade." Building and Environment **93**(P2): 1-8.

WHO (2006). Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. W. H. Organization.

Wilson, M. P., O. B. Jorgensen and G. Johannesen (2000). "Daylighting, energy and glazed balconies: A study of a refurbishment project in Engelsby, near Flensberg, Germany." Lighting Research & Technology **32**(3): 127-132.

Wolf, S., J. K. Møller, M. A. Bitsch, J. Krogstie and H. Madsen (2019). "A Markov-Switching model for building occupant activity estimation." Energy and Buildings **183**: 672-683.

Xue, P., C. M. Mak, H. D. Cheung and J. Chao (2016). "Post-occupancy evaluation of sunshades and balconies' effects on luminous comfort through a questionnaire survey." Building Services Engineering Research and Technology **37**(1): 51-65.