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BUILDING SIMULATION ANALYSIS OF THE EFFECT OF A ROOFTOP GREENHOUSE LOCATED ON A LISBON URBAN MARKET.

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Abstract *The Rooftop Greenhouses (RG) are one example of Building-Integrated Agriculture, offering a new dimension to our buildings, providing locally grown food that increase urban resilience. This paper relies on the analysis of a Rooftop Greenhouse, which is planned to be installed on an existing urban market, in particular its effect in the market indoor temperature during the summer period. The analysis is based on the building simulation of the real scenario and with the RG. A measurement campaign was performed to assess the thermal behaviour of the market shops and calibrate the model. According to the simulation results, the RG causes a reduction of the number of hours of overheating and thermal discomfort in the Shops when they are occupied.*

1 Introduction

Rooftop Greenhouses (RG) constitute a solution that can improve the locally grown food increasing urban resilience and reducing carbon emissions related to food transport. Other advantages can be highlighted such as improving well-being of the urban citizens giving them the opportunity to produce vegetables and fruits close to their home (Gomes, Benis, Santos Silva, & Vicente, 2016).

Nevertheless, it is from crucial relevance to understand the effect of a rooftop greenhouse on the indoor temperature of the building below. This study analyses, using a building energy simulation tool, the effect of a RG in a Lisbon Market (Figure 1~~Figure 1~~).

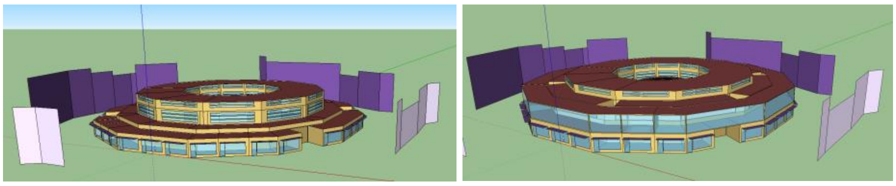

Figure 1 –Model of the building wituout and with the RG (southeast view)

While the initial focus of Building Energy Simulation (BES) tools was primarily on the design phase, simulation is now becoming increasingly relevant in post-construction phases of the building life-cycle, such as commissioning and operational management and control (Coakley, Raftery, & Keane, 2014). Since BES models are based on physical reality rather than arbitrary mathematical or statistical formulations, they have a number of inherent advantages. One of the primary benefits of detailed simulation models is their ability to predict system behaviour given previously unobserved conditions. This allows for analysts to make alterations to the building design or operation, while simultaneously monitoring the impact on system behaviour and performance (Coakley D. , 2014).

This paper considers the use of a building simulation tool to evaluate the effect of a RG in the market indoor temperature.

2 Case Study

The case study of this paper is an urban Market located in Arroios, Lisbon (Figure 2~~Figure 2~~). This building has a dodecagonal geometry, its major area is on the ground floor and has a smaller underground floor.

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Figure 2 – Arroios Market (source: GoogleEarth, 2016)

The outside area is divided in different shops that have access to the street surrounding the market. The market was divided as the following figure suggest.

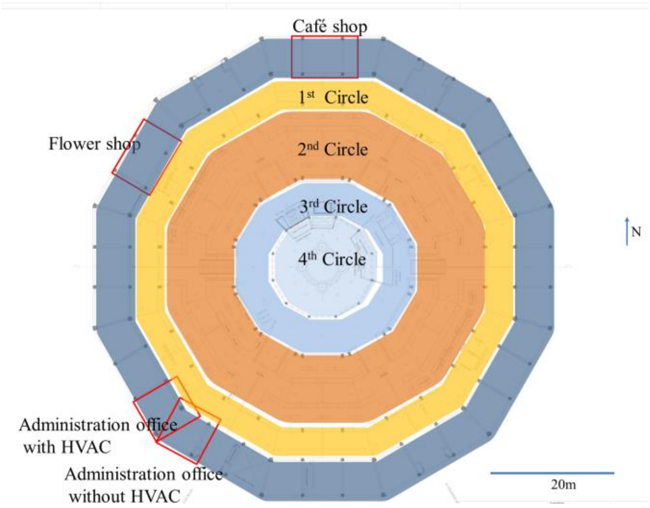

Figure 3 – Market areas (schematic)

The 1st circle is a corridor along the market, where people can access the shops. The 2nd and 3rd circles are the areas where the market stands are located. The 4th circle is a circulation area.

The following table shows some characteristics of the market shops considered in this paper.

Table 1: Shops characteristics

Shop	Area (m^2)	Percent Exterior Glazing/Orientation	HVAC use*	Regular Occupation
Administration with HVAC	33-37	30%/ SouthWest	On: 8-14h	1ocup 8-14h
Administration without HVAC		57%/ SouthWest	NA	0 ocup
Flower Shop		31%/NorthWest	NA	1ocup 8-18h
Café		57%/ North	On: occasionally	Variable: 1 to 10 ocups 8-18h

* Air-conditioning units

Rooftop Greenhouse

The implementation of the Rooftop Greenhouse (RG) is planned to happen in 2017, and it consists in installing a greenhouse above the Shops and the 1st circle (grey and yellow areas in Figure 3~~Figure 3~~). The greenhouse' height will be between 3.55m and 4.15m. The greenhouse will be constituted by panels of alveolar polycarbonate. The total area of the RG will be around 2000 m^2 (Lisbon Farmers, 2015).

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3 Methodology

In this paper a building simulation of the Market is performed, without (real case) and with the RG. To calibrate the model and to evaluate the real situation without the RG, a measuring campaign was also executed in summertime. The methodology used in this paper is briefly described in the Figure 4~~Figure 4~~.

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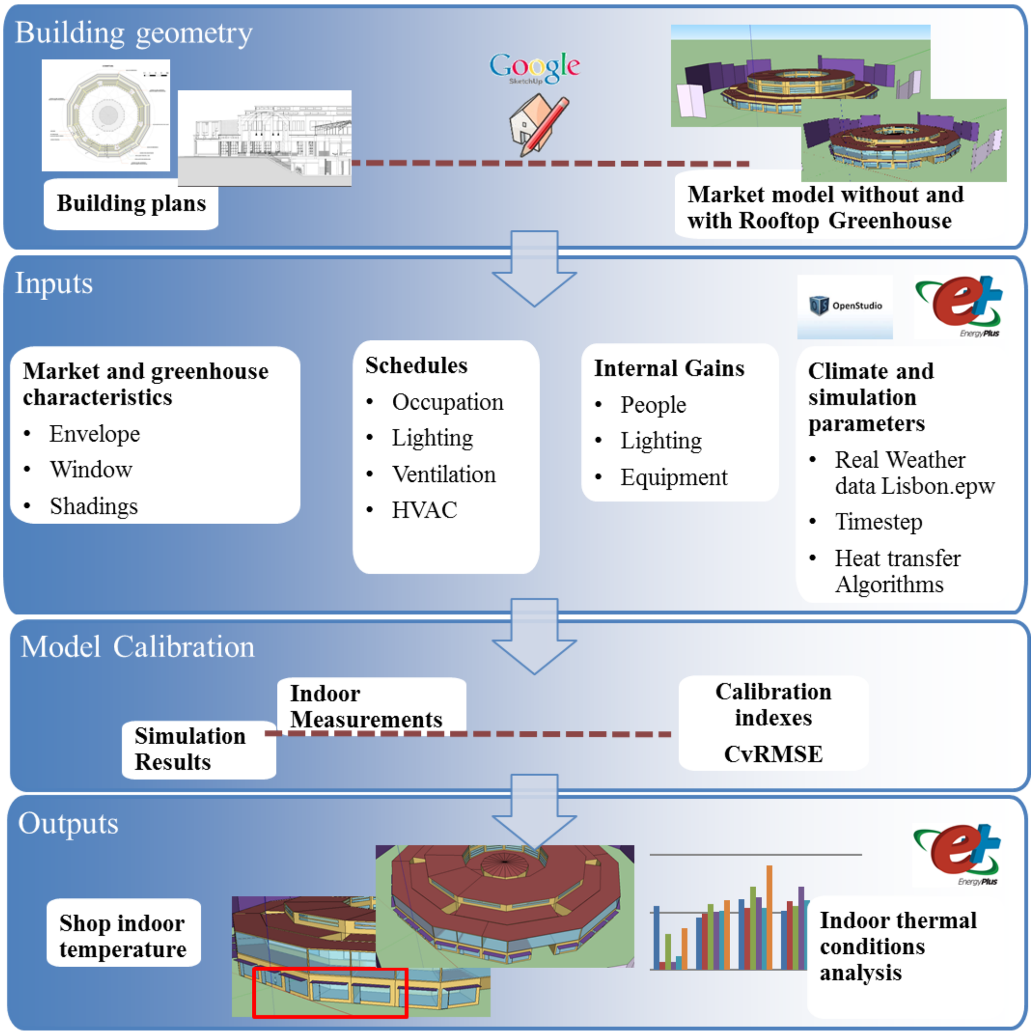

Figure 4 – Simulation methodology schematic

The building simulation tool used in this paper was the EnergyPlus, that is a modular, structured code based on the most popular features and capabilities of BLAST and DOE-2.1E. The EnergyPlus building systems simulation module, with a variable time step, calculates heating and cooling system and plant and electrical system response (US Department of Energy., 2013). This integrated solution provides more accurate space temperature prediction crucial for occupant comfort and occupant health calculations (University of Strathclyde and University of Wisconsin, 2015)

In this paper, the simulation is focused in the shops, since is predicted that the installation of a RG upon them could influence the indoor temperature. Having this in mind, a measurement campaign of indoor temperature was performed in the following areas (Figure 3~~Figure 3~~) during the Summer period.

- Administration shop with HVAC
- Administration shop without HVAC (no occupation)
- Flower shop
- Café Shop

If possible, these measurements will be repeated in the Winter period and after the implementation of the RG.

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4 Simulation inputs

As referred before, the building simulation of the building was performed using the software Energy Plus (version 6) and the geometry was defined using Google Sketchup. The model was calibrated with the shops' indoor temperature measurements collected during the campaign.

For this simulation, the building thermal zoning was done considering spaces with different uses (Shops, Circulation areas, underground floor, rooftop greenhouse).

Constructive solutions of the building envelope

The market building was constructed in the 1920s and renovated in the 1940s. The predominant constructive solutions (Lisbon Farmers, 2015) defined for the envelope are summarized in the Table 2~~Table 2~~:

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Table 2: Constructive solutions of the building envelope

Building component	**Description**	**U - Thermal Conductance with film (W m^{-2} K^{-1})**	**U - Thermal Conductance without film (W m^{-2} K^{-1})**
Exterior Walls	Plaster, 20cm brick, plaster	2.63	4.34
Exterior Roof/Slabs	waterproof layer, 20cm concrete, plaster (inside)	2.39	4.34

The windows defined in the simulation are constituted by a clear 6mm glass installed in an aluminium frame, with internal shade (curtains). Internal gains of the building were defined, namely occupation, lighting and equipment, considering predicted values for the building typology and with a survey during the measurement campaign.

Building internal gains

The internal heat gains considered for this simulation are related with people, equipment and lighting. The internal gains schedules and values were defined to be the closest to the real patterns as presented before in Table 1~~Table 1~~. The activity level was defined as 108W by person ((US Department of Energy., 2013)

Zones air renovation

The air renovation is one simulation parameter that influence greatly the thermal behaviour of a building model (Villi, Peretti, & Graci, 2012). This parameter is influenced by different factors such as the wind, the windows, frames and outdoor openings, the material air permeability and the indoor temperature (Silva & Pinto, 2011). This parameter was not estimated during the measuring campaign. Consequently, the infiltration considered in this paper was calculated using two different approaches. For the shops without outdoor door the method used was given by the application created by the National Laboratory for Civil Engineering within the scope of the Portuguese Ordinance 349-B (ADENE, 2013). This method considered the permeability of the frame, the window area, and the surroundings obstacles. For the shops with outdoor doors, it was considered the method (ASHRAE, 2009) defined by the following equations:

$$Q = \frac{A_L}{1000}\sqrt{C_s \Delta t + C_w U^2} \quad (1)$$

Where:
Q = airflow rate, m^3/s
A_L = effective air leakage area, cm^2
C_s = stack coefficient, $(L/s)^2/(cm^4 \cdot K)$
Δt = average indoor-outdoor temperature difference for time interval of calculation, K
C_w = wind coefficient, $(L/s)^2/[cm^4 \cdot (m/s)^2]$
U = average wind speed measured at local weather station for time interval of calculation, m/s

The air renovation estimations for the different shops are presented in the following table:

Table 3: Air Renovation values

Zone	Air renovation per hour	Calculation Method
Café Shop	Occup. Time (4.84) Non occupied time (0.1)	ASHRAE*
Flower Shop	Occup. Time (4.84) Non occupied time (0.1)	ASHRAE*
Administrations Shops	0.1	LNEC**

* American Society of Heating, Refrigerating and Air-Conditioning

** National Laboratory for Civil Engineering

Simulation inputs for the greenhouse

As the main goal of this paper is to evaluate the effect of the RG in the market thermal behaviour, the RG HVAC system was not simulated in detail. It was considered the RG geometry and constructive solutions. The RG thermal needs were achieved by using an ideal air load system, that allowed the RG temperature to be between a defined set point interval (20-25ºC). This set point was suggested by the market project team (Lisbon Farmers, 2015), but may vary depending on the agriculture production chosen,

5 Measurement campaign

The measurement campaign occurred during the period of July 27 to September 9 of 2016. The indoor temperatures of four shops were measured every 15 minutes. The results of the measurement campaign are presented in the following figures (overall campaign and one week).

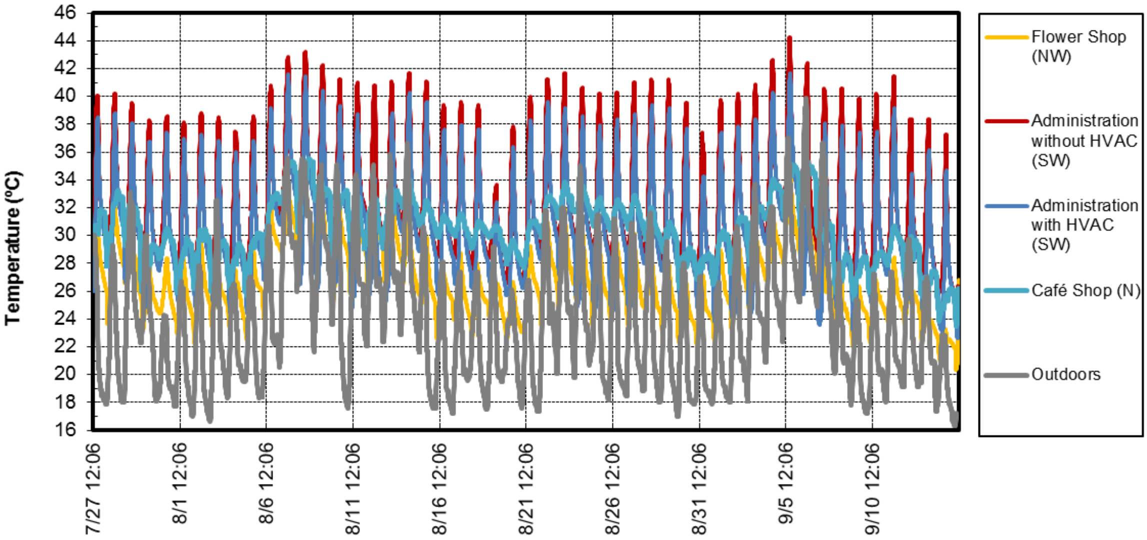

Figure 5 – Shops indoor temperature and outdoor temperature – measurement campaign (7/27 to 9/10)

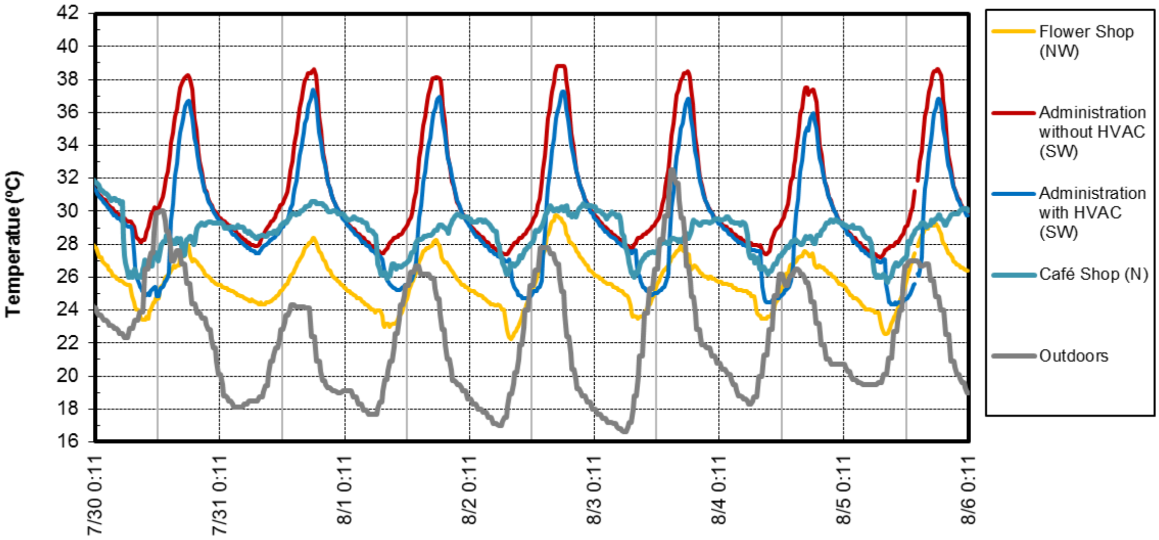

Figure 6 – Shops' indoor temperature and outdoor temperature (7/30 to 8/6)

As we can see in the overall graphic (Figure 5~~Figure 5~~) the indoor temperature during the measuring campaign was always above 20ºC in the studied shops, even when the outdoors temperatures decrease, during the night, down to nearly 16ºC. This fact is related with the high building inertia and with the low infiltration rates during the night (shops' doors closed).

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The highest temperatures were registered in the shops facing SW, such as the Administration shops. In these locations, the indoor temperature reached frequently temperatures higher than 38ºC.

As it was expected the shops facing the north-quadrant had registered lower temperatures comparing with other shops. This is mainly result of less direct solar radiation incidence.

Analysing one week campaign (Figure 6~~Figure 6~~) is possible to confirm that the HVAC was always in the On mode during the occupation of the Administration Office. When the HVAC systems is turned Off, the indoor temperature rises and during the night is almost the same comparing with the Administration office without HVAC system.

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Comparing the two shops in the north-quadrant (Flower and Café shops) the temperature is higher in the Café. The higher temperatures of the Café are related with higher indoor internal gains (equipment and occupation).

Considering only the occupation period (8:00 a.m. to 18:00 p.m.), Table 4~~Table 4~~ presents minimum, maximum and mean temperatures measured. Table also shows the percentage of occupied hours where indoor temperature was higher than 27ºC (thermal discomfort).

Table 4: Shops' indoor temperature and hours' percentage of thermal discomfort

Shop	Tmax (ºC)	Tmean (ºC)	Tmin (ºC)	Thermal discomfort (% occupied hours)
Administration without HVAC	37.6	30.0	24.2	95
Administration with HVAC	34.5	26.6	22.6	32
Flower shop	~~32.3~~35.1	~~25.5~~26.8	~~20.3~~20.3	~~24~~43
Café	~~34.3~~35.4	~~29.4~~30.0	~~23.6~~23.6	~~82~~87

The data analysis of the two administration rooms shows that with the use of HVAC, there is a reduction of about 4ºC of mean indoor temperature and about two thirds of the period of thermal discomfort (Ta>27 ºC).

The results achieved in the Café evidence the high internal gains (equipment and occupation) and an almost non-existent use of HVAC, which causes a significantly high percentage of discomfort time.

6 Model Calibration

In order to consider the simulation results it is necessary to calibrate the model with real measurements. During the calibration process two main sets of data are needed and compared: the simulation data set, from the building model created, and the metered data set, from the real building monitoring. Due to the lack of detailed energy consumption data, the calibration process was performed considering the indoor temperature. The weather file considered information from a weather station located nearby (less than one kilometer).

As any building simulation model, the data set is composed of large quantity of data, among which, the most influencing parameters have to be selected in order to find a matching between simulated and measured energy consumption. Different indices are commonly used for evaluate the data matching and quantify the accuracy of the validation of the model. These criteria determine how well simulated indoor temperature matches the measured data at the selected time interval. They do not constitute a methodology for calibrating buildings models, but rather a measure of the goodness-of-fit of the building model. Statistical indices have become the international reference criteria for the validation of calibrated models (Fabrizio & Monetti, 2015) (Yang & Becerik-Gerber, 2014) (Karlsson, Rohdina, & Persson, 2007). They have been recommended by three main international bodies in the following documents:

- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guidelines 14;
- International Performance Measurements and Verification protocol (IPMVP);
- M&V guidelines for FEMP.

Commonly the Mean Bias Error (MBE) and the Coefficient of variation of the Root Mean Square Error (Cv(RMSE)) are the two statistical indices used. The consideration of both indices allows preventing any calibration error due to errors compensation.

$$MBE\ (\%) = \frac{\sum_{Period}\ (S-M)_{interval}}{\sum_{Period} M_{interval}} \times 100\% \quad (2)$$

$$RMSE_{period} = \sqrt{\frac{\sum (S-M)^2_{interval}}{N_{interval}}} \quad (3)$$

$$A_{period} = \frac{\sum_{Period}\ M_{interval}}{N_{interval}} \quad (4)$$

$$Cv(RMSE)_{period} = \frac{RMSE_{period}}{A_{period}} \times 100\% \quad (5)$$

Where: M is the measured data point during the time interval; S is the simulated data point during the same time interval; NInterval is the number of time intervals considered for the monitored period.

MBE measures how closely simulated data corresponds to monitored data. It is an overall measure of how biased the data are. MBE is calculated, as reported in Equation (2), as the total sum of the difference between measured and simulated energy consumption at the calculation time intervals (e.g., month) of the considered period. The difference is then divided by the sum of the measured energy consumption. Due to a compensation effect (positive and negative values contribute to reduce MBE final value), MBE usually is not a “stand-alone” index, but it is assessed together with the Cv(RMSE). The Root Mean Squared Error (RMSE) is a measure of the sample deviation of the differences between the measured values and the values predicted by the model. The Cv(RMSE), as reported in Equation (5), is the Coefficient of Variation of RMSE and is either a normalized measure of the variability between measured and simulated data and a measure of the goodness-of-fit of the model. It specifies the overall uncertainty in the prediction of the building energy consumption, reflecting the errors size and the amount of scatter. It is always positive. Lower Cv(RMSE) values bring to better calibration (Fabrizio & Monetti, 2015).

In order to consider a model calibrated, a threshold limit of the MBE and the Cv(RMSE) must be respected. In compliance with the requirements of the Standard/Protocol considered, the limit threshold is subjected to slight differences, as reported in Table 5~~Table 5~~.

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Table 5: Calibration indexes limit values (Fabrizio & Monetti, 2015).

	Hourly Calibration	
	IPMVP*	**FEMP****
MBE (%)	± 5	± 10
Cv(RMSE) (%)	20	30

*International performance measurement and verification protocol
** Federal Energy Management Program

If a model is calibrated in compliance with these limits, “it is sufficiently close to the physical reality that it is intended to simulate”. However, these thresholds represent a first guidance for the energy building calibration and should not be taken as definite values. The presented statistical indices are related only to the shops’ indoor temperature. The compliance with the thresholds can also be achieved with different models, as the solution is not unique and may not guarantee that all the model input data are correctly tuned. Calibration is an underdetermined problem. Moreover, it is important to note that this validation approach does not take into account uncertainties in the model and takes no notice of other influent parameters, such as building energy consumption and occupancy.

The calibration indexes calculated within the simulation process are presented in the following table:

Table 6: Calibration indexes values.

	overall	**Administration without AVAC**	**Administration with AVAC**	**Café**	**Flower Shop**
MBE	4.35%	10.00%	7.61%	5.43%	-7.34%
Cv(RMSE)	11.29%	12.68%	11.22%	10.47%	10.10%

The overall values calculated for the calibration indexes are below the limits suggested in Table 5~~Table 5~~ for the Cv(RMSE) index and for the index MBE considering the limits proposed by the FEMP. The fact that the model calibration isn’t totally satisfactory considering the limits proposed in the Table 5~~Table 5~~ confirms that the model calibration can and should be improved for a more accurate analysis.

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7 Simulation Results

The following graphs show the indoor temperature results for the Shops, without and with the RG for one summer week.

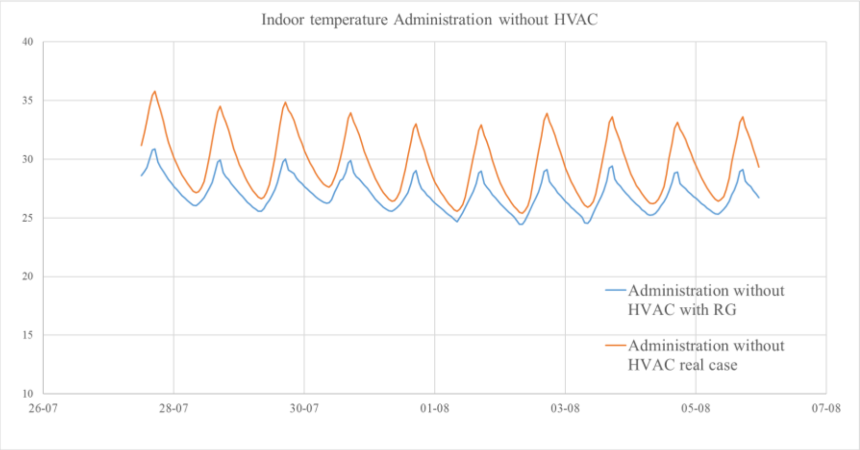

Figure 7 – Administration without HVAC shop indoor temperature and outdoor temperature (7/30 to 8/6)

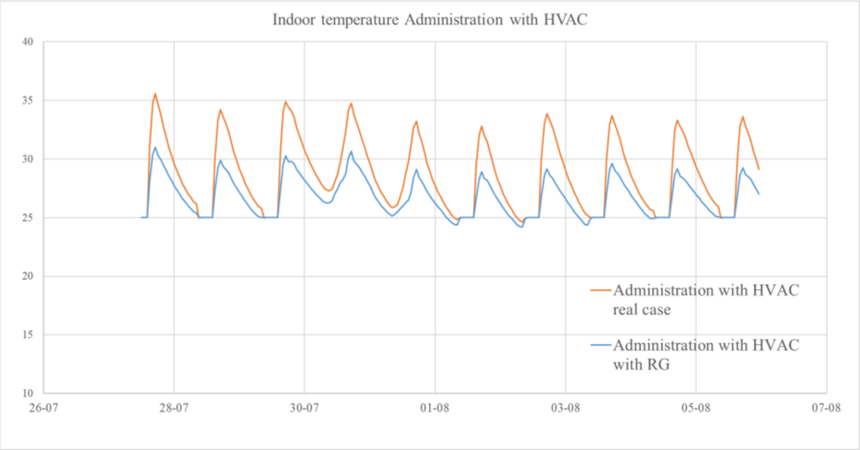

Figure 8 – Administration with HVAC shop indoor temperature and outdoor temperature (7/30 to 8/6)

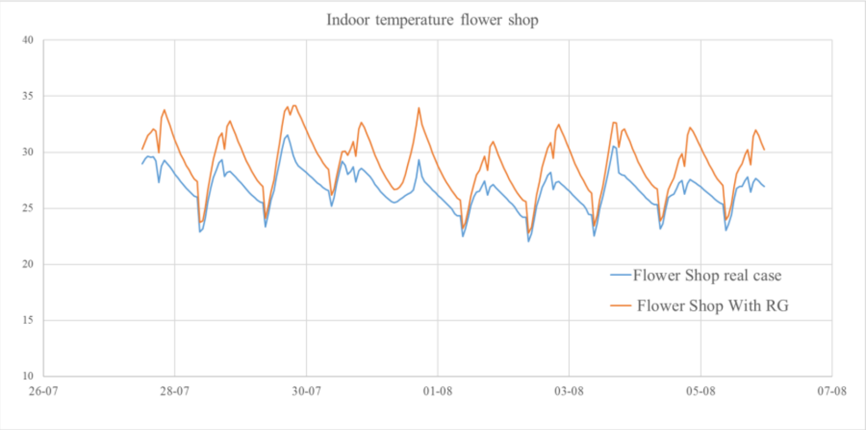

Figure 9 – Flower shop indoor temperature and outdoor temperature (7/30 to 8/6)

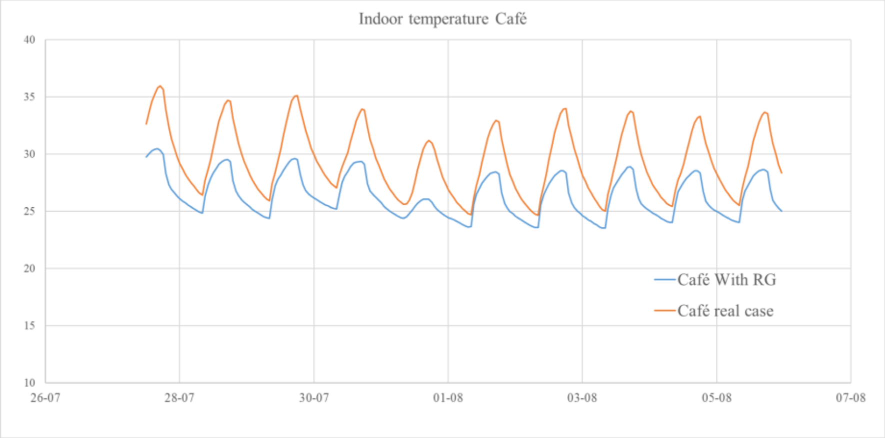

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Figure 10 – Café indoor temperature and outdoor temperature (7/30 to 8/6)

The simulation results show an overall indoor temperature reduction in all shops during the occupation time. The results show that the RG will perform as a thermal buffer and reduce the heat gains from the slab to the shops. The explanation for the lower indoor temperatures in the shops with the RG, during the occupied time, is related with the fact that the RG avoids direct solar radiation in the shops' roof and also reduces the heat transfer by the slab thermal conduction, since the indoor temperature of the RG during the day is lower than the outdoors temperature. Even when considering that the installation of the RG will reduce air renovation in the contiguous inner circles, that therefore should get warmer, the number of hours of thermal discomfort in the shops is lower when comparing with real case.

The following table presents the results obtained regarding thermal discomfort (considered only for the occupied and without HVAC shops).

Table 7: Simulation results for indoor temperature shops and thermal discomfort.

Shop	**Thermal discomfort (% ocuppied hours) without RG (real case)**	**Thermal discomfort (% ocuppied hours) with RG (real case)**
Flower shop	18%	12%
Café	35%	21%

In what concerns to thermal discomfort in the Shops, without and with the RG, the simulation results show that the number of hours of discomfort related with overheating (Tint>27ºC) decreased.

8 Future Work

The future work will rely on performing a Winter Campaign in order to assess the indoor temperature and the thermal behavior of the market shops during this period. Also, air infiltration measurements will be performed to better characterize this parameter in the simulation model. The simulation of different market areas, such as the 1st circle and 2nd circle, will also be executed and analysed in detail, and the influence of the RG in the indoor temperatures of these areas will be addressed. It is expected that these areas will have an indoor temperature increase due to lower ventilation rates.

After the installation of the RG, it is also planned a new measurement campaign to evaluate the indoor conditions and its real effect in the thermal behavior of the market. The simulation parameters will be better characterized and more accurate analisys will be executed. The calibration process will also be improved with more detailed data and a more detailed analyis is planned.

It is relevant to highlight that the simulation relied on the indoor temperature of the shops and not in the indoor temperature of the inner circles where the market banks are located. This work will be developed and it will be assessed the impact of the RG in the thermal behaviour of these areas. A particular relevant aspect related with the influence of a RG in these areas is its influence in the estimation of the air renovation in the inner circles (1st, 2nd, 3rd and 4th circles) without and with the RG. It is expected that the RG will reduce the air renovation in these zones, since its implementation will reduce the outdoor windows number and area.

The energy consumption related with HVAC equipment in the market, will also be addressed in future works.

9 Conclusions

The simulation results show that the installation of a rooftop greenhouse reduces the number of hours of thermal discomfort related with overheating in the shops during the occupied hours. The RG will reduce the direct solar gains in the rooftop, and also, considering the greenhouse set point of 20-25ºC, reduce the heat transfer to the shop trough the slab. Further work will help to confirm these results and analyse in detail the thermal behaviour of different areas in the market.

10 Acknowledgements

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11 References

Fabrizio , E., & Monetti, V. (2015). *Methodologies and Advancements in the Calibration of Building. energies.*

(IPMVP), I. P. (2003). *Concepts and Option for Determining Energy Savings in New Construction.* IPMVP New Construction Subcommittee.

ADENE. (2013). Portaria n.º349-B. Portugal.

ASHRAE. (2009). *Handbook: Fundamentals;2009, p16, Ventilation and Infiltration.*

Coakley, D. (2014). *Calibration of Detailed Building Energy Simulation Models to Measured Data using Uncertainty Analysis, PhD Thesis.*

Coakley, D., Raftery, P., & Keane, M. (2014). A review of methods to match building energy simulation models. *Renewable and Sustainable Energy Reviews*.

Gomes, R., Benis, K., Santos Silva, C., & Vicente, R. (2016). Analysis of the Effect of a Rooftop Greenhouse in Building Indoor Temperature and Acclimatization Needs Using Building Energy Simulation. *Clima 2016.* Aalborg.

Karlsson, Rohdina, P., & Persson, M.-L. (2007). Measured and predicted energy demand of a low energy building: important aspects when using Building Energy Simulation. *Building Serv. Eng. Res. Technol.*, 14.

Lisbon Farmers. (2015). *Estudo Prévio Mercado de Arroios.* Lisbon.

Silva, F., & Pinto, A. (2011). Avaliação experimental da permeabilidade ao ar da envolvente e do sistema de ventilação. Edifício "Gaioleiro" (1880). *Contributos para uma reabilitação sustentável. ". Sustentabilidade na Reabilitação Urbana: o novo paradigma do mercado da construção*.

University of Strathclyde and University of Wisconsin. (2015). *Contrasting the capabilities of Building Energy Performance Simulation Programs.* United States Department of Energy.

US Department of Energy. (2013). *Input Output Reference, The Encyclopedic Reference to EnergyPlus Input and Output.*

Villi, G., Peretti, C., & Graci, S. (2012). Building leakage analysis and infiltration modelling for an Italian multi-family building. *Journal of Building Performance Simulation*.

Yang, Z., & Becerik-Gerber, B. (2014). A model calibration framework for simultaneous multi-level building. *Applied Energy, 149*, 415-431.