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Analysis of the Effect of a Rooftop Greenhouse in Building Indoor Temperature and Acclimatization Needs Using Building Energy Simulation

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1 Abstract

Building-Integrated Agriculture has the potential to offer a new dimension to our buildings, providing locally grown food that increase urban resilience. This paper relies on the Rooftop Greenhouses (RG) solution, in particular its effect in the indoor temperature and its acclimatization needs on the last floor of one Portuguese 1960s building. The analysis is based on the building energy simulation of different scenarios. The simulation of the base scenario shows that the installation of a RG results in overheating that is translated in an increase of 232% in the number of annual hours of indoor temperature above 26ºC on the building last floor. The alternative scenarios to avoid this situation considered the slab thermal insulation, night air ventilation enhancement on summer and changing the indoor temperature setpoint of the RG.

The simulation results highlight that all the scenarios proposed result in a decrease (comparing with the base scenario) of the cooling needs, being the slab insulation the most effective isolated measure. Even so, the implementation of a RG in this building typology will increase total acclimatization needs of the apartment below.

Keywords: Rooftop Greenhouse, building energy simulation, indoor temperature, acclimatization needs, scenarios evaluation

2 Introduction

Rooftop Greenhouse (RG) constitutes 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.

Nevertheless, it is from crucial relevance to understand the effect of a rooftop greenhouse on the building thermal behavior, especially of the last floor. Using a building energy simulation tool, this study analyses the effect of the greenhouse on the last floor of a low-rise multi-family dwelling located in Lisbon, with 18 apartments and 60 estimated inhabitants (Figure 1). Also different scenarios were analyzed.

While the initial focus of Building Energy Simulation (BEPS) 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 (1). Since BEPS 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.

The building simulation tool used in this paper was 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. This integrated solution provides more accurate space temperature prediction crucial for occupant comfort and occupant health calculations (2).

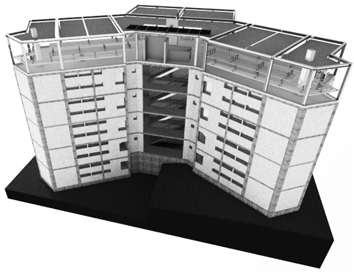

Figure 1 – BIM model of the building integrating the RG

3 Methodology

The building energy modelling allows performing an assessment of the thermal needs of the building and of the greenhouse during the operating phase and the possibility to evaluate different solutions regarding their effect in the building indoor temperatures. In this paper it was considered different alternatives for the simulation:

- Without RG –real scenario, where the building doesn't have a Rooftop Greenhouse.
- Base Scenario – building with Rooftop Greenhouse.
- Alternative Scenarios – building with Rooftop Greenhouse and improvements in the envelope, night air ventilation and greenhouse different setpoint.

The methodology used in this paper is represented in the Figure 2.

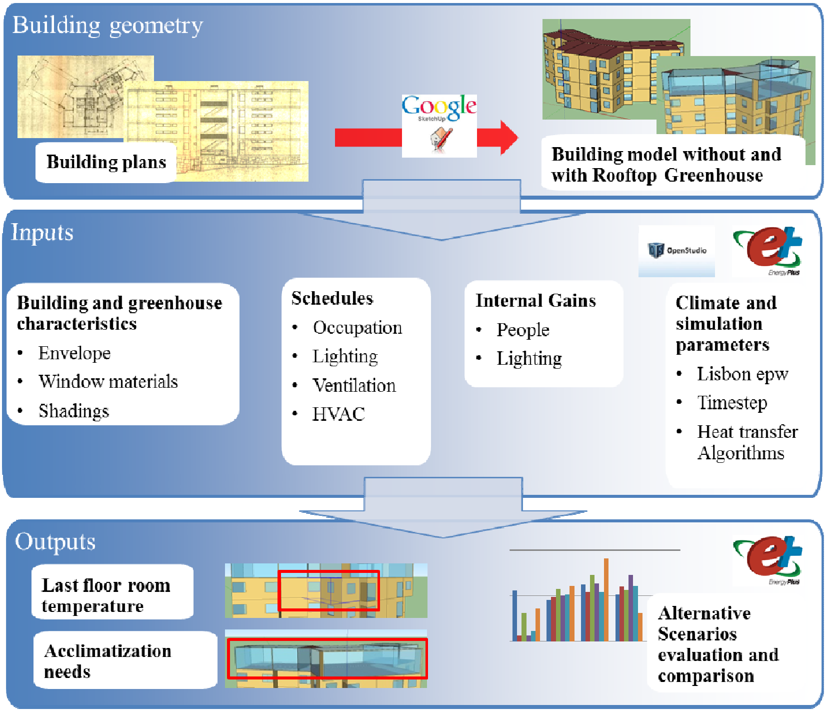

Figure 2 – Simulation methodology schematic

4 Simulation Inputs

The energy simulation of the building was performed using the software Energy Plus version 8 and the geometry was defined using Google Sketchup.

The weather file used for this simulation is the Lisbon Weather File (3). It is important to note that this simulation needs to be calibrated with in situ measurements to better represent the energy performance of the existing building. Therefore, the results presented here are a first analysis of the building and greenhouse thermal needs.

4.1 Building envelope

For this simulation, the building thermal zoning was done considering spaces with different uses (i.e. kitchen, rooms and living rooms).

The building was constructed in 1960 and the predominant constructive solutions defined for the envelope are summarized in the Table 1:

Table 1: Constructive solutions of the building envelope

Building component	Description	Thermal Conductance (W m^{-2} K^{-1})
Exterior Walls	Double brick wall with air space	1.31
Interior Ceiling	Precast concrete joist and brick panel slab	4.74

The windows defined in the simulation are constituted by a clear 6mm glass installed in an aluminium frame, with external plastic shutters.

The Table 2 presents the Window-to-Wall Ratio of one apartment.

Table 2: Window-to-wall ratio of the building

	Southwest	Northeast
Window-Wall Ratio	28%	11%

The Table 3 presents the values for the window thermal characteristics.

Table 3: Window thermal characteristics

Conductance without shade (W m^{-2} K^{-1})	Conductance with shade (W m^{-2} K^{-1})	Solar Heat Gain Coefficient (SHGC)
5.78	4.91	0.83

The Figure 3 presents the building model with and without the Rooftop Greenhouse.

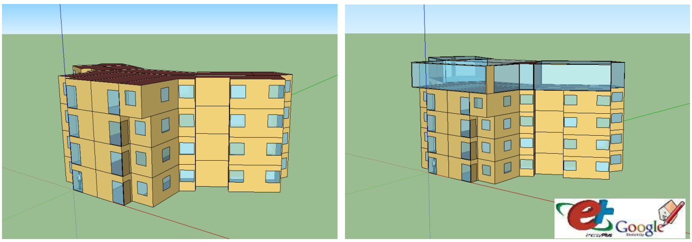

Figure 3 –Building model without RG and base scenario (southeast view)

4.2 Building internal gains

The Internal gains of the building were defined, namely occupation and lighting, considering predicted values for the building typology. Equipment heat gains were considered negligible since the analysis was focused in the bedroom temperature. The internal gains schedules and values were defined to be the most close to the real patterns and were obtained by inquiry. The Table 4 presents the values for the internal gains considered in the simulation:

Table 4: Internal gains

Internal gains	Heat gains (W)	Schedule
People	72W/person (night) (4); 100 W/person (day) (4)	Bedrooms 2 people - 8h/day Living room 2 people - 3h/day Kitchen 2 person - 2h/day
Lighting	50W/room	(4hours/day)

4.3 Building air ventilation

The building air ventilation was defined using the object "ZoneVentilation:WindandStackOpenArea"(14) with the following assumptions based on field observations:

- It was considered that the windows were opened 1/10 of its opening area during the winter and 1/2 during summer.
- It was considered that the windows were closed when the outdoor temperature is outside the range: 18-26ºC.

4.4 Bedroom Heating and Cooling needs

The heating and cooling needs for the bedroom were calculated using the "ZoneIdealLoadAirSystem" (14) considering that the HVAC system is always available and the setpoint range is 18-26 ºC.

4.5 Greenhouse

One main purpose for considering a greenhouse structure in a building rooftop is to create a controlled environment in terms of temperature and humidity for optimum growing conditions within a predictable and repeatable time schedule when compared to growing outside in a non-controlled environment. Considering the greenhouse structure, construction materials and design, it can become too warm in the summer and cold in the winter which could affect the crop production. The best indoor conditions control systems should not only be effective in providing the desired environment, but also be designed to be unobtrusive within the greenhouse system (9). Evaporative cooling is a common way to reduce indoor temperatures for greenhouses in dry climates (9) and basically consists of a process that reduces air temperature by water evaporation into the airstream. As water evaporates, it absorbs energy from the surrounding environment (greenhouse) decreasing the temperature of the air flow. Fan and pad evaporative systems consist of exhaust fans at one end of the greenhouse and a pump circulating water through and over a porous pad (Figure 4) installed at the opposite end (5, 6, 7, 8). The cooling efficiency is dependent of the pad wall material (corrugated cellulose, aspen pads or aluminium and plastic fibres) and air flow velocity and can vary between 70 to 80% (9). Additionally, the outside air conditions, namely the relative humidity and temperature, affect the cooling potential of the pad wall system (9, 10, 11).

Evaporative pad cooling system

The ventilation sizing for the evaporative pad system considered in this greenhouse was performed considering the air flow value of 2.4 m^3 min^{-1} per m^2 of floor area (8). Considering the greenhouse geometry it was considered that the system has three fans, one for each zone considered in the simulation of the greenhouse. The pad wall considered is constituted by corrugated cellulose since this is the most widely type used for evaporative pad walls (8). The pad wall was considered to be in the north façade of each zone since this is the direction of the prevailing winds in Lisbon (12), increasing the efficiency of the pad system. For heating purposes it was considered an electric baseboard equipment to heat the greenhouse. The indoor temperature setpoint defined for the greenhouse was 24- 28ºC defined by the type of crop (lettuce).

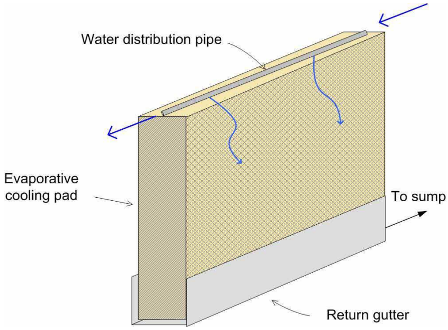

Figure 4 – Evaporative cooling pad (7)

5 Results

The simulation results address the indoor temperatures and the heating and cooling needs in one bedroom of the last floor of the building along one year.

5.1 Scenario without RG

For the scenario without the RG, the simulation results on free-floating mode (Figure 5) show significant cooling and heating needs, as the number of annual hours with indoor temperatures above 26ºC in the summer period and below 18ºC in winter period are high (considering no HVAC systems). These results were expected due to the building typology and constructive solutions. The building envelope has no thermal insulation resulting in high heat losses in the winter and in high heat gains in the summer.

5.2 Base Scenario (with RG)

The effect of the RG in the building indoor temperature can be observed in the Figure 5. Accordingly to the simulation results, the indoor temperature of the bedroom of the last floor increased with the implementation of the RG. Although this can be considered positive in the winter period, it represents a thermal comfort disadvantage in the summer period.

The indoor temperature increase is a result from a higher heat gains from the greenhouse to the last floor building considering the low thermal resistance of slab between this two levels. As the temperature of the greenhouse was defined to be between 24ºC and 28ºC during all year, it can be observed that the temperature of one bedroom in the last floor increased, being higher than 18ºC all year and reaching more than 2500 hours per year above 30ºC.

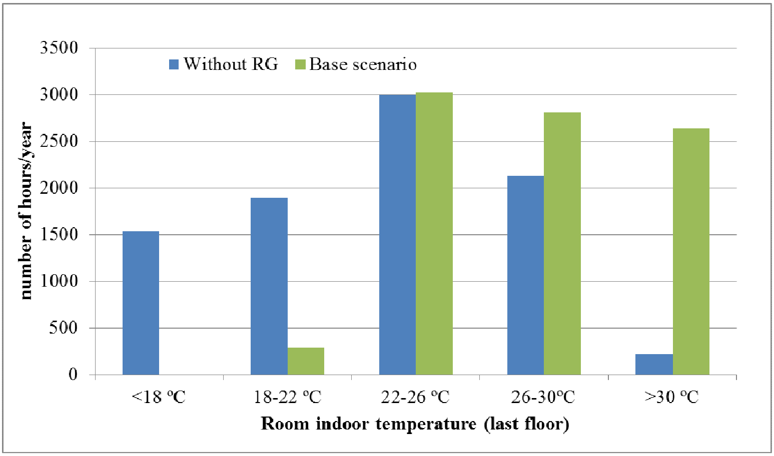

Figure 5 – Annual indoor temperature in one last floor bedroom without RG and in the base scenario (free-floating temperatures)

5.3 Alternative scenarios

The scenarios were defined considering measures that cover different construction solutions, night ventilation and equipment operation. The main goal was to reduce the room overheating related with the installation of the RG. In the following table the scenarios studied in this work are presented.

Table 5: Alternative scenarios description

	Differences from the base scenario		
Scenarios	Envelope insulation	Natural ventilation	Greenhouse setpoint
A	10cm stone wool insulation in the slab	-	-
B	-	Night ventilation in the last floor during Summer	-
C	-	-	Lower setpoint (18-24ºC)
D	10cm stone wool insulation in the slab	Night ventilation in the last floor	Lower setpoint (18-24ºC)

The insulation thickness defined for the scenario A was defined considering the Portuguese legal value for the thermal transmission coefficient of the slab (13). The thermal conductance of the interior ceiling with 10cm of stone wool is of 0.411 ($W\ m^{-2}\ K^{-1}$).

The scenario B is related with the increase of the night ventilation in the last floor. It was considered the installation of one fan with the following assumptions:

- Design flow rate of $60m^3/h$ (15)
- Fan pressure rise 60Pa
- Fan efficiency 0.9.

The scenario C consists on reducing the indoor setpoint temperature for the greenhouse considering the possibility to have different crop production. The setpoint defined for this scenario was 18 to 24ºC.

The Figure 6 presents the bedroom indoor temperature distribution along one year for the scenarios presented in the Table 5.

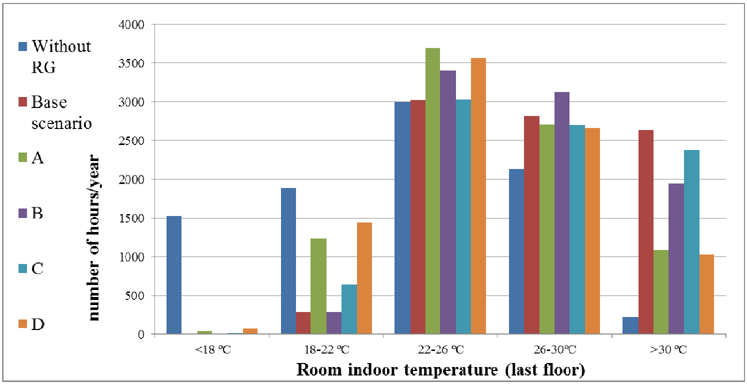

Figure 6 – Bedroom Indoor temperature annual distribution for the last floor - alternative scenarios

The results from the Figure 6 show that the application of 10cm insulation (scenario A) in the roof slab of the last floor constitutes the best isolated measure for reducing the indoor temperature in the cooling period. Nevertheless, is possible to observe that all scenarios proposed result in a decrease of the indoor temperature of the last floor when comparing with the base scenario. As it was expected the combination of all measures (scenario D) results in the higher temperature reduction. The Figure 7 shows the annual heating and cooling needs for the bedroom considering a HVAC setpoint of 18-26ºC.

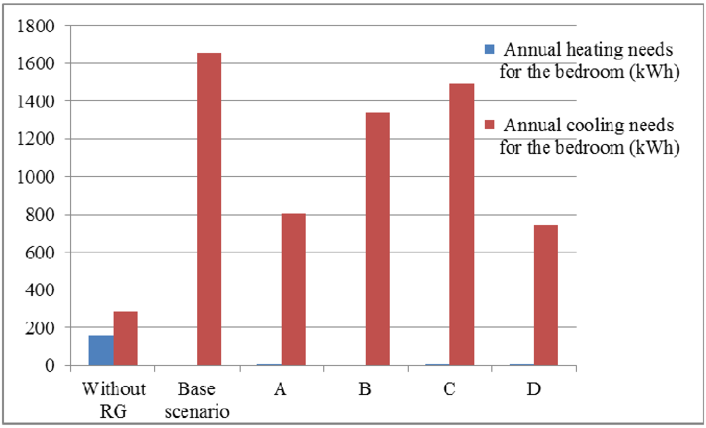

Figure 7 – Annual heating and cooling needs for the bedroom

Table 6: Cooling and total acclimatization needs variation comparing with scenario without RG

	Base scenario	A	B	C	D
Cooling	+470%	+178%	+361%	+415%	+156%
Total consumption	+269%	+81%	+199%	+234%	+66%

From the Figure 7 and the Table 6 is possible to conclude that the implementation of a RG in a residential building with low thermal insulation materials results in a significant increase of the cooling needs for the building last floor, even if considering different alternatives scenarios.

Although the RG implementation results in heating needs near zero, the total energy consumption increase in all scenarios.

This first analysis indicates that the feasibility of a RG in the building typology studied (1960s with no thermal insulation) requires the evaluation of several solutions to reduce the estimated overheating situations in the last floor.

6 Simulation Limitations

Several limitations regarding the simulation of the building and of the greenhouse can be highlighted. The calibration of the model with in situ measurements in the existing building, energy audits, detailed occupation patterns evaluation and the weather file from the building location will contribute to a more accurate building simulation (1) and a better analysis of the operative phase of the building with and without the greenhouse.

Regarding the greenhouse, is relevant to highlight the possibility of the existence of a gradient of air temperature between the pad wall and the fans (not considered in the simulation). In fact, it is expected that the temperature near the fans will be higher than on the opposite side of the greenhouse. Other relevant aspect to be analyzed is the effect of the wind on the pad evaporative system. The wind profile specific from the building location will contribute to this analysis.

7 Ongoing and Future Work

In a next step, the detailed energy modelling of the greenhouse will allow for the assessment of its heating and/or cooling energy consumptions. Also, the possibility of implementing a photovoltaic system to provide energy to the greenhouse will be considered and analyzed. Besides, the size of the greenhouse should be evaluated in order to define the most suitable solution regarding global environmental impact. The main goal is to achieve the best scenario that includes energy efficient solutions for the building as well as for the greenhouse.

Acknowledgements

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