CONSIDERING ENERGY, MATERIALS AND HEALTH FACTORS IN ARCHITECTURAL DESIGN

Two renovation strategies for the Portuguese building stock

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Abstract. According to the Intergovernmental Panel on Climate Change, the built environment has a significant share in global final energy use, greenhouse gases emission, land-system change, and biodiversity loss to list some indicators. In Europe, the biggest challenge is to regenerate existing building stock to create a positive impact on Nature. The Portuguese housing stock is old: 56% is more than 30 years old, and it has a low level of thermal comfort and energy efficiency. The first thermal regulations appeared in 1990 and therefore most of the houses need urgent renovation to meet EU decarbonization goals, and to improve energy efficiency, as well as well-being and comfort of residents. This paper presents a method that aims to verify existing solutions known from vernacular architecture as complementary to existing strategies. It employs digital simulation to verify whether they could be used for renovation, measuring their impact on human and planetary health. The paper shows that there is a wide spectrum of parameters that influence the renovation process and that it is possible to enhance building performance using vernacular knowledge.

Keywords. Building Energy Modelling; Life Cycle Assessment; Occupant Health; Energy Renovation; Vernacular Mimicry; SDG 3; SDG 11; SDG 13.

1. Introduction

According to the Renovation Wave directive, 75% of the existing building stock in Europe needs to be renovated (European Commission, 2020). Particularly in Portugal, the 2011 National Census (Instituto Nacional Estatística, 2011) shows that 65% of the housing was built before the introduction of energy-efficient regulations in 1990.

Energy inefficient buildings are negatively impacting the residents and the environment. In Europe, buildings are responsible for about 40% of total energy consumption, and for 36% of greenhouse gas emissions (GHG) (European Commission & Joint Research Centre., 2019). A study shows that operational energy

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consumption in buildings can be reduced by 50% with the adoption of energy-efficiency methods (Magalhães et al., 2016). New buildings must meet the Energy Performance of Building Directive, therefore new buildings' negative impact on the environment in the operational phase must be significantly lower. This essentially means that to cut the GHG emission by 55%, renovation actions must be prioritised.

Today, in Portugal, research on renovation focuses mostly on engineering solutions (Almeida et al., 2014), (Sousa et al., 2013) and (Bragança et al., 2007), typically adding an HVAC system, placing insulation or changing windows. The same approach is taken by the National Agency for Energy in its recommendations (ADENE, 2016). Similarly, ´part 13´ of the Recovery and Resilience Plan covers energy efficiency and focuses on engineering and material solutions. Simultaneously, there is a wide range of bioclimatic solutions present in vernacular architecture in Portugal (Fernandes, 2020), that in the last decades have been neglected.

Europeans spend almost 90% of their time in interior spaces (European Commission, 2002), therefore it is important to evaluate the impact of architecture on health. Comfort is an immediate expression of the human body condition and is related to health (Ortiz et al., 2017). In the study, thermal and visual comfort will be used as metrics of health.

In this context, the current paper wants to evaluate renovation strategies from the context of energy, materials and health for Portuguese housing. With that goal, it presents a study exploring the concept of patterns, first presented in the book ‘A pattern language: towns, buildings, construction’ (Alexander, 1977) that connected geometrical features of architectural components with human cognition, behaviour, and relationships

The paper also looks to contribute to the local discussion on the opportunities connected to regional solutions to enhance energy efficiency and resident comfort. The study simulates the impact of a vernacular pattern following the notions of the Age of

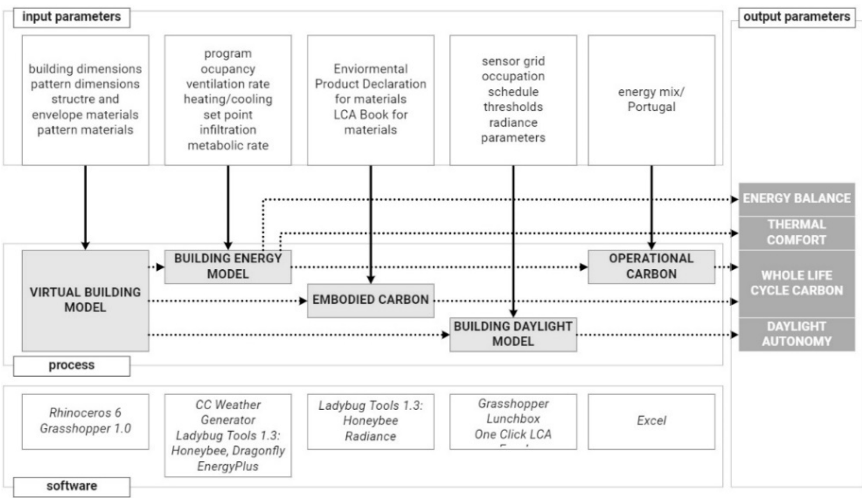

Figure 1 Workflow

Data, not the rule of thumb which has been done multiple times before (Moholy-Nagy, 1957). This article is an answer to Susane Roaf's studies (Roaf, 2020) on traditional architecture in Yazd and her suggestion to review solutions because they might not be accurate.

2. Methodology

2.1. WORKFLOW

The study is organised in two parts: (1) research and selection of patterns, and (2) analysis of the impact of the selected pattern on the environment and resident comfort, as per 'Figure 1'. The research of patterns is conducted through a literature review and on-site observation of vernacular patterns in Portugal and northern Spain.

Figure 2 Balcony in Távira (Portugal)

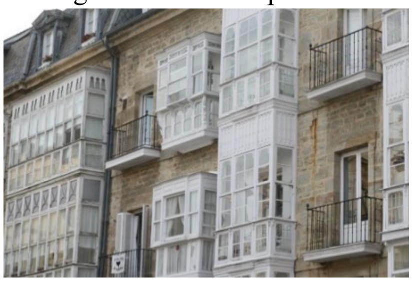

Figure 3 Balcony in Vitoria (Spain)

2.2. SELECTING THE PATTERN

Among multiple vernacular solutions that could be listed in traditional architecture in the selected region is a balcony. A survey of popular architecture in Portugal run in the 1950s has already observed balconies across the north as a pattern to protect from the summer heat (open) or cold (glazed) in the winter (SNA, 1961). So far there has been no comprehensive study measuring the impact of a balcony on the environment and resident comfort (Huang & Liu, 2020) In the scope of this study, two types of balconies (Figure 2, 3) are examined:

- Open, protected with a balustrade, of three different depths (1.0m, 2.0m, 3.0m)
- Closed/Operable, of three different depths (1.0m, 2.0m, 3.0m)

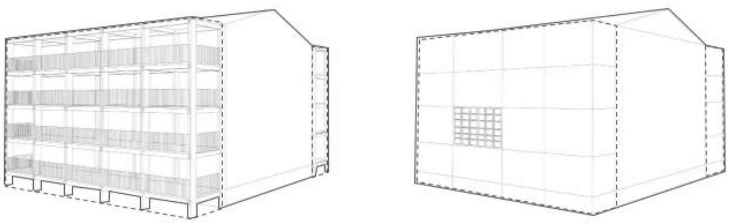

Figure 4 Renovation options: open balcony (left), closed balcony (right)

2.3. SELECTING AND MODELLING THE VIRTUAL BUILDING

Each balcony will be an addition to the Virtual Building (VB). A Virtual Building is a digital 3D model of a building based on a typical housing building in Porto from the fifties and sixties (Ramos et al., 2009).

The Virtual Building is a 4 storey collective housing, with four apartments on each floor (Figure 4). Each apartment is divided into 4 or 5 rooms, two of which were selected: South facing Room [SR] and North facing Room [NR], with Window-to-Wall Ratios of 0.2 (south) and 0.3 (north).

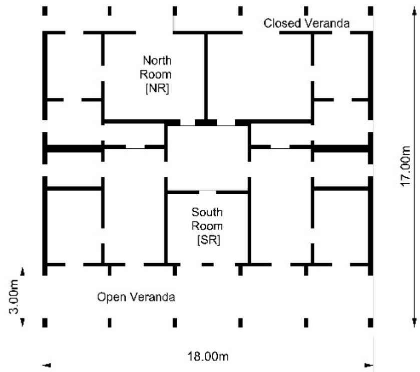

Figure 5 Typical floor plan

In the modelling phase of the Virtual Building, the author used typical materials of the 1950s and 1960s which can be listed as:

- columns and slabs: reinforced concrete,
- envelope an (uninsulated) cavity brick wall (U-value=2.08 W/m2K) of 27.5 cm,
- single glazed windows (3.50 W/m2K),
- concrete roof (uninsulated) with bituminous waterproofing (1.10 W/m2K).

To renovate, two types of balconies are used with two renovation strategies, as per Table 1: conventional (following typical constructive solutions available in the market)and regenerative (using materials aiming to reduce the environmental impact).

While the open balcony is an addition to the building without requiring demolition works or significant changes to the existing structure, the closed balcony needs the removal of the exterior wall to connect with the additional space.

The material's properties (including embodied carbon) come from One Click LCA database. Table 1 shows the materials used in the simulations and calculations: The data on the embodied carbon used in the study is heterogeneous (e.g. different sources of certificates, different countries) and reflect only the cradle-to-gate part of the life cycle. Also, the difference between the estimated size of structure causes differences lower than 0.005%. Therefore, for a more in-depth, detailed structural study is needed, which includes sizing.

	open balcony		closed balcony	
	Conventional (C)	Regenerative (R)	Conventional	Regenerative
Columns, Purlins, Beams, Slabs	Reinforced Concrete	CLT	Reinforced Concrete	CLT
Balustrade	Galvanised Steel	CLT	no balustrade	no balustrade
Windows	no windows	no windows	Aluminium	Wooden

Figure 6 Materials used for building components

2.4. SETTING UP THE ENERGY MODEL

To simulate the operation of the VB, a Building Energy Model is created and parametrized in Ladybug and Honeybee plugins (connected to EnergyPlus) for Grasshopper for Rhinoceros 6 (Figure 01). To simulate the observed climate, data from the closest weather station (PORTO 85450) are used. To generate future climate scenarios, based on the Intergovernmental Panel on Climate Change Third Assessment Report model, the CCWorldWeatherGen (Jentsch et al., 2013) tool is used It is a climate data morpher developed by the University of Southampton. For the existing building, further parameters were defined to reflect the local conditions, namely:

- energy zones are considered as conditioned,
- typical occupancy schedule for Portugal (Barbosa et al., 2016),
- no central heating or cooling system, mechanical ventilation (Vilhena et al., 2013),
- a typical gas unit heater, with the setpoint at 15°C,
- high infiltration rate: 0.004m3/s/m2 (due to the age of the VB),
- a series of metabolic rates and clothing level for different kind of activities in domestic space (American Society of Heating, 1992),

For the closed balcony, all parameters are kept and a lower infiltration rate is used (0.002m3/s/m2) due to the placement of a new exterior, sealed facade system.

2.5. SETTING UP THE DAYLIGHT MODEL

To simulate visual comfort, a Daylight Model is created and parametrized in Ladybug and Honeybee plugins (connected to Radiance) for Grasshopper for Rhinoceros 6 (Figure 01). The test plane was generated at a height of 0.7m, with sensors distributed on a grid with unit squares of 0.5m by 0.5m. There are no interior elements (partition walls, furniture, etc.). The Radiance parameters are set up to obtain a mid-quality simulation. The glass' visible transmittance is set to 0.6, and the solar heat gains coefficient to 0.25.

2.6. SIMULATING

To compare the different solutions, 10 simulations for the SR and 10 for the NR were performed for the observed and future climate (2050) for Porto, in total 40 simuations.This article will foucus on the future climate results only. The simulation started with 15°C and the open balcony options. 15°C is selected as a benchmark temperature, lower than the recommendation of the World Health Organisation (World Health Organization et al., 2018) or Portuguese building code (Presidência da República, 2013), but the prevalent indoor temperature in the north of Portugal (Magalhães et al., 2016).

Simulation name	Group	Subtype	Comfort
baseline		baseline	setpt=15°C
option 01	open balcony	1.00	setpt=15°C
option 02		2.00	setpt=15°C
option 03		3.00	setpt=15°C
option 04	closed balcony	1.00	setpt=15°C
option 05		2.00	setpt=15°C
option 06		3.00	setpt=15°C
option 07	closed balcony	1.00	setpt=18°C
option 08		2.00	setpt=18°C
option 09		3.00	setpt=18°C

Table 1. Options legend

2.7. MEASURING THE IMPACT

This study compares a conventional with a regenerative strategy, measuring Global Warming Potential (GWP), an indicator of GHG emissions, in the life cycle of the VB following the standard ISO 14040:2006 in the perspective of 30 years considering climate change according to the IPCC scenario A2 (IPCC, 2021: Climate Change 2021). The carbon life cycle assessment includes material embodied carbon. In this study, residents' comfort is based on two elements: thermal comfort and daylight availability. Other aspects of daylight, such as glare or view out, were omitted to simplify the model. The following indicators are used to evaluate each solution:

- Embodied Carbon, EC [kg CO2 equiv/m2];
- Operational Energy, OE (heating) [kWh/year/m2], to calculate GHG emissions and to understand the impact of Solar Energy Gains on thermal comfort;
- Operational Energy, OEl (lighting) [kWh/year/m2], to calculate GHG emissions and to understand the impact of daylight on visual comfort;
- Solar Gains, SG [kWh/year/m2], heat gained through the solar radiation;
- Operational Carbon, OC [kg CO2 equiv/m2], total GHG emissions related to building operation, calculated as a product of total Operational Energy and carbon intensity of the energy sources;
- Carbon LCA [kg CO2 equiv/m2], total carbon, a sum of EC and OC;
- Thermal Comfort [%],hours that residents are comfortable;

- Spatial Daylight Autonomy, sDA [%], time of the year that for a sensor, distributed on a grid 0.5 by 0.5m on the height of 0.7 m, a threshold of 100 is achieved.

3. Results

To summarise the results of renovation of the VB with an open balcony for both the SR and the NR it is observed that:

- it decreases residents' (thermal and visual) indoor comfort and therefore is likely to have negative impact on their health,
- it brings extra Outdoor Domestic Space that could be comfortably occupied for 69% of the year (according to the simulation of the Universal Climate Thermal Index) with a good quality of visual comfort,
- the sDA is reduced significantly, meaning that there is not enough daylight to perform everyday activities, lack of daylight influences human health too [41],
- indoor temperature is below the level proposed by the WHO (18°C) ,
- the environmental cost of this solution is quite large, the Carbon LCA increases by at least 30% compared with no intervention,
- the negative impact on the thermal comfort is noticeable especially while comparing the SR and the NR, the open balcony blocks longwave radiation and does not allow to capture heat,

	Total Operational Energy (heating)	Annual Solar Gain	Spatial Daylight Autonomy	Thermal Comfort	Total Carbon
South Room	15% to 26%	-11% to -49%	-21% to -70%	-18% to -22%	47% to 65%
North Room	0% to +4%	-60% to -79%	-30% to -60%	-1% to -4%	31% to 100%

Table 2. Open balcony: rooms performance in different categories in comparison to the baseline (current state).

The closed balcony brings significantly better results. First of all it reduces energy consumption, brings more daylight, and increases thermal comfort. However, the interventions in the building come with a significant carbon cost (Table 4). The Total Carbon of the NR is significantly higher than the SR. After analysing data of simulation one can observe that:

- to achieve 15°C in the wintertime (like in Table 4), which is not considered comfortable, but common in north Portugal, at least 1.61E+02 kg CO2 equiv/m2 is needed,
- additionaly to achieve 18°C in the wintertime, carbon expenses are almost tripled. Minimising both embodied carbon and operational carbon is crucial, and thus comfort should be achieved for most of the year without using an HVAC system,

Total Operational Energy (heating)	Annual Solar Gain	Spatial Daylight Autonomy	Thermal	Total

				Comfort	Carbon
South Room	-42% to -11%	40%	4%	6% to 9%	31% to 60%
North Room	-41% to -27%	-23%	4%	11% to 16%	50% to 138%

Table 3. Closed balcony: rooms performance in different categories in comparison to the baseline (current state).

While examining the building from the point of the life cycle (Table 5) one can clearly observe that the operational carbon prevails, which aligns with other studies in Portugal (Rossi et al., 2012). It is important to mention that since the space is equipped with a gas heater, and the purpose of this study is to introduce passive solutions, the replacement of a heating system was not considered. Therefore, no energy decarbonization actions were taken into consideration. It opens a door for another research on the renovation expenses in the light of energy decarbonization. It is inevitable to question what type of renovation is actually benefiting users and the enviorment in the perspective of 30 and 50 years.

To ensure the thermal comfort of the residents, an additional study was run to verify how much more carbon would be released as per Table 5. In comparison with the same renovation solution, it is almost 2.5 times more. According to this simulation, Human Comfort (100%) would cost an additional 521 kg CO2 equiv/m2 in the perspective of 30 years. As mentioned before, the renovation calculation includes only cradle-to-gate material impact, which means that the real embodied carbon values are higher. The Operational Carbon is likely to reduce if a better performing heating system is used.

	Total Operational Carbon [kWh/m2]	Total Operational Carbon [%]	Embodied Carbon [kWh/m2]	Embodied Carbon [%]
baseline	3.47E+02	100.00%	0.00E+00	0.00%
option 02	4.22E+02	76.02%	1.33E+02	23.98%
option 05	2.75E+02	69.76%	1.19E+02	30.24%
option 08	7.96E+02	86.99%	1.19E+02	13.01%

Table 4. Emboided and operation carbon for selected options.

4. Discussion

The paper does not conclude in one best solution, as per every multiobjective problem such does not exisit. Looking from the human comfort point of view, renovating with a Closed Balcony and the set point of 18°C on the SR is the best but it brings the highest environmental costs, while the 15°C set point might represent a compromise of lowering human comfort to create less negative environmental impact. Additionally changing the heating system from the gas unit to another will bring significant savings in carbon emission. Considering creation of an extra Outdoor Domestic Space for the North Façade, the Open Balcony might be considered the best option. But, again this renovation favors human comfort over the planetary safety.

The paper does not focus on questioning modern, conventional engineering solutions, it rather looks to complement them with architectural ones and looks for alternatives known from history of architecture. This study opens the author's research to find a robust workflow to verify other vernacular patterns. Future studies would benefit from collaboration with a structural engineer who can propose detailed structural solutions. The workflow is thought to be universal and possible to test, in different locations, elements such as climate (past, current and future), material availability and modus vivendi, as they are input parameters that need to be reviewed every time.

From the planetary crisis point of view, the article follows the carbon tunnel. It is focused only on one of the aspects of the earth systems; other dimensions, like Acidification Potential, that could be found in the Environment Product Declaration were not considered. It follows European policies for renovation, decarbonisation and energy. There is a research gap to clearly connect other dimensions with the built environment. The database of materials is still limited, as many vernacular materials like straw, woodfibers, and eucalyptus timber do not have EPDs or another type of assessment. This is likely to change with the European Green Deal expressed in the New European Bauhaus initiative.

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