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Optimization of the Sustainability during the Refurbishment design phase of a Residential Building Using SBTool^{pt}-H

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ABSTRACT

As it has been observed along the years, the unsustainability of the built environment is due to the high resources consumption and low indoor air quality of the existing building stock.

In order to support the sustainable refurbishment design of buildings, and to meet European goal to achieve nearly zero-energy consumption standards in buildings in 2020, it is urgent to define guidelines that can be implemented since the earlier stages of the design.

This paper defines guidelines to optimize the sustainability of a residential building and presents the process of sustainable building refurbishment, applied to a case study. To achieve this goal, the definition and evaluation of a group of procedures to be implemented, and a cost-benefit analysis applied to a case study was performed.

1. INTRODUCTION

1.1.Context

In Portugal several programs were implemented to support the refurbishment of buildings, such as REHABITA, RECRIA, RECRIPH, SOLARH and JESSICA that give incentives through tax benefits (PH, 2012), but it is necessary to go beyond and perform the refurbishment according to the sustainability guidelines.

The first steps towards sustainability in Portugal were given with the implementation of the building thermal regulation and with the development of some guidelines and manuals related to the energy refurbishment of buildings. However, it is necessary to optimize the buildings not only in terms of energy and water consumption, but also at the level of functional adequacy to up-to-date comfort standards, daylight, adequacy of the interior spaces areas, preservation of the existing materials, and use of more sustainable materials.

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This work aims at analysing and discussing the complexity of the architectural activities, in the context of the rehabilitation and optimization of the sustainability of a residential building located in a historic city centre.

1.2.Aims

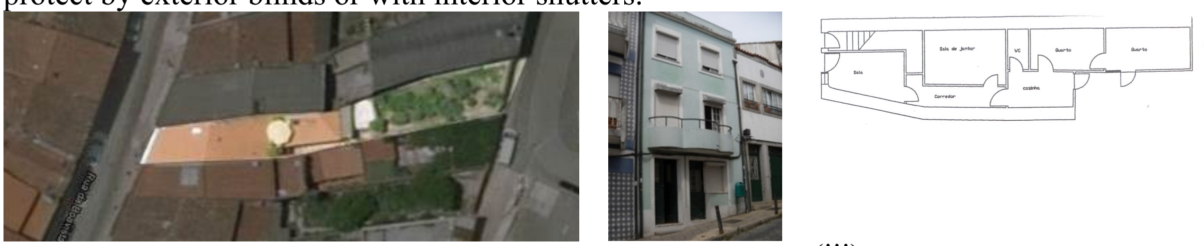
The main goal of this study is to define building and spatial solutions, together with the use of renewable energy to optimize the sustainability of the residential buildings. This goal is applied in the rehabilitation of a real case study, where the optimization of the following aspects were taken into consideration during the design phase: i) solar gains (e.g. daylight and solar thermal and photovoltaic panels); ii) water resources use efficiency (e.g. collect the rainwater, re-use of the grey water, and the implementation of systems that minimize the water usage); iii) preservation and re-use of existing materials; iv) minimization of the production of waste; v) maximization of the use of sustainable materials, with low embodied energy, with recycled context and with high recycling potential; vi) optimization of the thermal comfort conditions (e.g. improvement of thermal insulation of the building envelop, walls, windows and roof, installation of efficient acclimatization systems); vii) optimization of the natural ventilation and natural lighting; viii) implementation of shading devices; ix) development of a cost-benefit analysis of the previous mentioned approaches.

The abovementioned solutions are implemented on the refurbishment project of a residential building located in the Historic Center of Braga.

2. CASE STUDY

2.1.Building Description

The residential building (Figure 1) is from the XVIII Century and it is located in Rua da Boavista in Braga. The case study is integrated in the Urban Critical Area of Rehabilitation and Redevelopment of Braga. The building has three floors with three different independent dwellings, one per floor. The building main façade is south oriented. The main entrances are located at ground floor level. There are two entrances: one that serves the ground floor dwelling and one that serves, through a common staircase, the first and second floors dwellings. The lot has a total area of 180 m^2, the outdoor area has 111.2 m^2 and the building has a total area of 192.6 m^2. The exterior walls are of stone masonry, plastered and painted in white, the pavements are made of wood and supported by a wood structure, with the exception of the ground floor that is covered in parquet placed over a cement structure. The interior walls are in *taipa* (rammed earth). The windows have a wood frame with single glass, protect by exterior blinds or with interior shutters.



(i) (ii) (iii)

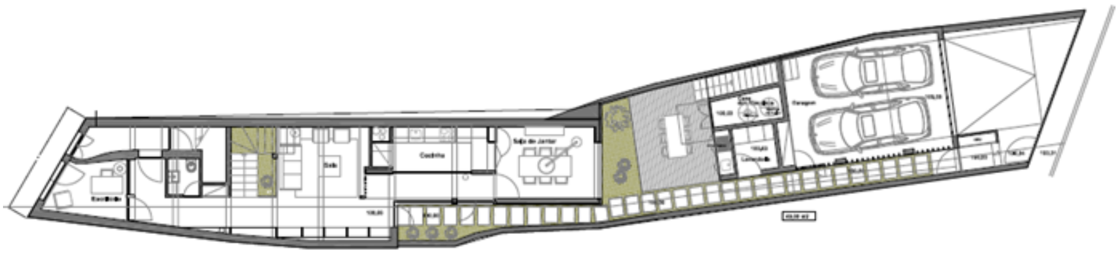
Figure 1 – Satellite view (i); view of the façade (ii); plan of the existing ground floor (iii).

2.2.Intervention Proposed

The aim of the project is to transform the three independent dwellings in only two, the first dwelling (dwelling I) will occupy the ground and first floors and the second dwelling (dwelling II) the second floor.

Since the building is very narrow and some bedrooms do not have access to daylight, it is intended to reorganize the interior spaces in order to improve the daylight and natural ventilation conditions in both dwellings (Figure 2). To overcome this goal a skylight and new windows will be opened or widened. The skylight will be located over the staircase that connects the ground and first floors, and will have lateral adjustable air vents, to ventilate the interior spaces. A window frame with thermal cut, double glass, and tight adjustable air vents, to prevent high internal gains in the summer and losses during the winter was selected.

In order to promote daylight in the indoor spaces, the exterior space of the lot was also redesigned. For that the terrain level was changed and a garage with a green roof was implemented (Figure 2).



(i)

(ii)

Figure 2 – Ground floor plan of the rehabilitation project (i); Cross section of the building (the red line represents the existing levels of the terrain) (ii).

3. ASSESSMENT METHODOLOGIES

The methodologies adopted in this study to assess the performance and sustainability of the different design scenarios are: the Ecotect software, to assess the predicted energy consumption for heating, cooling and hot water; the SimaPro software, to assess the life-cycle environmental impacts resulting from each design scenario; the Methodology for the Relative Sustainability Assessment of Building Technologies (MARS-SC), to support decision making towards the use of more sustainable building solutions; and the Sustainability Assessment Tool (SBTool^{PT}) to assess the overall sustainability score of the building.

3.1. Methodology for the relative sustainability assessment of building elements (MARS-SC)

The methodology used in this study to evaluate the sustainability of the several analysed building elements follows the stages of a LCA. The aggregation of indicators and the comparative analysis is supported by the Methodology for the Relative Sustainability Assessment of Building Technologies (MARS-SC) (Bragança & Mateus, 2006; Mateus et al, 2013). This methodology is based in three groups of sustainability indicators: environmental (NDA), functional (NDF) and economic (NDE). For this study was decided to use the environmental impact categories that are considered the most important according to other studies (EPA, 2000; EPA & SBA, 2000): Global Warming Potential (GWP) and the primary embodied energy (PEC). Table 1 presents the considered indicators that describe the environmental performance. To quantify the environmental parameters, this study is based in the Ecoinvent report V2.2 (Hischier et al, 2010), since the database covers the average environmental impacts of the main building materials at different regional contexts. The LCI data was converted into environmental impact categories using the following LCA methods: CML 2 baseline 2000 V2.04 and Cumulative Energy Demand V1.0. In order to facilitate the quantification process, a life-cycle analysis software (SimaPro 7.3.3) was used to assess the abovementioned life-cycle impact categories.

Table 1 – Indicators, parameters and weights considered in the application of the MARS-SC.

Dimensions						
Environmental			Functional		Economic	
Indicators	Global Warming Potencial (PAG)	0.25	Normalized air born sound insulation index ($D_{nT,w}$)	0.33	Construction Cost	1.00
	Primary Embodied Energy (PEC)	0.75	Thickness (Walls) or Normalized impact sound insulation index ($L'_{n,w}$) (floors)	0.33		
			Thermal insulation (Umed)	0.33		
0.30			0.50		0.20	

For the functional performance, this study considers three functional requirements for partition walls: normalized airborne sound insulation index ($D_{nT,w}$); thickness of the building element (m) for the walls or the normalized impact sound insulation ($L'_{n,w}$) for floors; and thermal insulation (U-value). The airborne sound insulation index was estimated using the analytical method proposed by Meisser (Meisser, 2004). The quantification of the U-value is based in the methodology of the Portuguese thermal regulation (eq. (1)).

$$U = \frac{1}{R_{si} + \sum_{j=1}^{n} R_j + R_{se}} \; (W/m^2.ºC) \quad (1)$$

Where, R_j is the thermal resistance of the layer j (m^2.ºC/W) and R_{si} and R_{se} are the internal and the external thermal resistances, respectively.

The economic performance is based in the Construction Cost (CC) and is calculated using the average market price of the building materials used and includes the workmanship and equipment costs.

The next step is the aggregation. In order to avoid scale effects in the aggregation of parameters inside each indicator and to solve the problem of some of the parameters being of the type "higher is better" and others "lower is better", normalization was done using Diaz-Balteiro equation (eq. (2)).

$$\overline{P}_i = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \forall_i \quad (2)$$

In this equation, Pi is the value of i^{th} parameter. P^*_i and P_{*i} are the best and worst value of the each sustainability indicator. In addition to making the value of the indicators considered in the assessment dimensionless, normalization converts the values between best and conventional practices into a scale bounded between 0 (worst value) and 1 (best value).

The methodology uses a complete aggregation method for each sustainability dimension (NDj) (eq. (3)).

$$ND_j = \sum_{i=1}^{n} w_i . \overline{P_i} \quad (3)$$

The indicator ND_j is the result of the weighting average of each normalized indicator inside the sustainability dimension j, w_i is the weight of the i^{th} indicator. The sum of all weights must be equal to 1. This study considered the default weights of the MARS-SC that are presented in Table 1.

The global assessment is based in the quantification of the sustainable score (*NS*). The *NS* is a single index that represents the global sustainability performance of a building element and it is evaluated using eq. (4).

$$NS = ND_A . w_A + ND_F . w_F + ND_E . w_E \quad (4)$$

Where, *NS* is the sustainability score, ND_j is the performance at the level of the dimension j and w_j is the weight of the dimension j^{th}.

According to the MARS-SC the default weight of the environmental, social and economic dimensions in the assessment of global performance is, respectively, 30%, 50% and 20%.

3.2 Methodology to assess the thermal performance

The energy performance of the refurbished building was assessed using Ecotect software. To perform the thermal performance analysis, the heating and cooling needs were calculated considering the occupation, internal gains, infiltration and equipment, according to the conditions presented in Table 2.

3.3 Methodology to assess the overall sustainability score

The assessment of the sustainability of the residential building is performed through the use of the system SBTool^{pt}-H that allows the assessment and certification of the sustainability of a building (Mateus & Bragança, 2011).

This assessment tool was used in the case study to evaluate the sustainability of the building optimized rehabilitation scenario, in order to verify if all the measures that were implemented will contribute to a good sustainable score. The evaluation includes not only the environmental dimension but also the social and the economic dimensions, in which there are a number of parameters that are evaluated. The values obtained in each parameter are normalized and converted to a scale from 0 (reference value) to 1 (best value), that are then translated in a qualitative scale bounded from E (worst) to A+ (Best).

Table 2 – Building use conditions.

Use Conditions	Dwelling I
Number of Occupants (P)	6
Occupation /Use Conditions	20h00 – 08h00 = 6 P /09h00 – 19h00 = 3P (70 W/ P – sedentary)
Clothes (clo)	1,0
Lighting and equipment	Sensible gains = 5 W/ m^2 - Latent gains = 2 W/ m^2
Comfort Temperature range	18ºC - 25ºC
Interior Relative Humidity (%)	60
Air speed	0.50 m/s – Soft breeze
Ventilation	Mix mode – Heating/Cooling - Efficiency = COP 4
Air Infiltration	0.50 exchanges/ hr (well insulated)

4. OPTIMIZATION AND ASSESSMENT OF THE SUSTAINABILITY

4.1 Construction solutions

Different construction solutions for the building envelop were chosen. The position and the external finishing's of the front facade could not be changed, due to the existing street alignments. Taking these aspects in consideration, the rehabilitation of the front façade was done by the interior and the back facades were rehabilitated from the exterior. Different building solutions were also taken in consideration for the interior walls and pavements. Analysing the different building solutions using the abovementioned method to assess the environmental performance, it was possible to define which solutions are going to be implemented in the front façade (Figure 3i), in the back façade (Figure 3ii), in the interior walls and in the pavements.

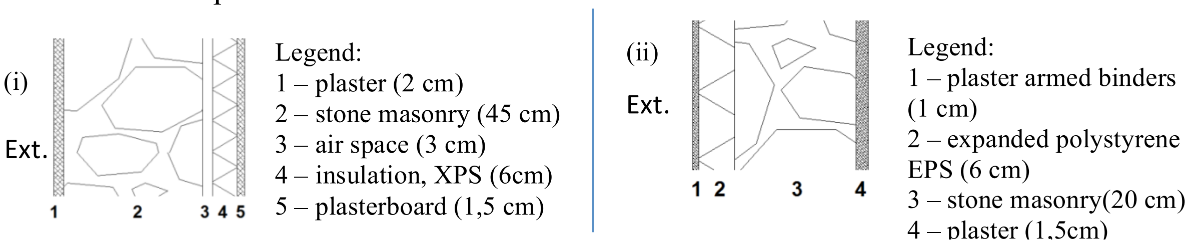


Figure 3 – Solution for the rehabilitation from interior (i); solution for the rehabilitation from the exterior (ii)

In Summary the measures implemented in the rehabilitation process were:

- Reorganization of the interior and exterior spaces to promote a better natural ventilation;
- Opening of new windows and implementation of a skylight to improve daylight conditions in the interior spaces;
- Rehabilitation of front façade with the construction of an interior wall pane in plasterboard, with XPS as insulation;
- Rehabilitation of the back façade with the application of the ETICS system with EPS insulation;
- Rehabilitation of the roof with the integration of an interior suspended ceiling in plasterboard with XPS insulation, and introduction of sub-tiles;
- Replacement of the window frames for new ones with thermal cut and double glass, similar to the existing ones;

- Rehabilitation of the ground floor, recovering the existing pavement and integrating XPS insulation, in the cases of bathrooms and kitchens the covering is in self-leveling;
- Rehabilitation of the pavements between floors through the recovering of the existing pavement and wood structure with the integration of a suspended ceiling in plasterboard with mineral wool as insulation, in the cases of bathrooms and kitchens the covering is in self-leveling;
- Integration of exterior blinds, similar the existing ones;
- Integration of a heat pump with a solar panel in dwelling I for heating and cooling and domestic hot water production;
- Integration of a solar panel with a heat recovery system in dwelling II for heating and domestic hot water production;
- Integration of a collection and treatment of rain and bath water system, that is common to both dwellings;
- The artificial illumination will be in LED bulbs adapted to the dimension of the spaces, and all the electrical equipment will be the most efficient, as possible.

4.2 Implemented Systems

4.2.1 Passive Systems

Some passive measures were implemented such as, the reorganization of the interior spaces, implementation of a skylight, and new and larger windows, to promote natural ventilation and capture more daylight and solar gains in winter to the interior spaces. The thermal insulation was improved in the walls, roof, and in the windows.

4.2.2 Active Systems

For heating, cooling and domestic hot water production, in dwelling I a heat pump connected to a solar thermal panel was chosen. For dwelling II, for heating and for domestic hot water production a solar thermal collector was installed. Additionally the ventilation of the dwelling is done through a heat recovery ventilation system. To complement the efficiency of the ventilation systems, it was installed an earth tube in the ground for pre-heat and pre-cool the air. This allows the fresh air that enters into the houses to be warmer during the winter and colder in the summer and therefore contributes for lower energy needs for heating and cooling.

A system for the collection and treatment of rain and bath water is also implemented and the recycled water will be used for sanitary discharges, irrigation and pavement cleaning.

All the artificial illumination will be in LED, and the appliances will be of A energy efficiency class, in order to reduce electricity costs.

4.3 Assessment of the Thermal Performance of the Building

Through the thermal evaluation of the building, it was verified that dwelling I had an annual energy consumption of 7.75 kWh/m^2 and dwelling II an annual energy consumption of 30.4 kWh/m^2. The consumption are higher for dwelling II than for dwelling I, because the systems that were implemented in dwelling I are more efficient, which leads to lower annual energy consumption.

4.4 Sustainability Assessment of the Building

For the sustainability assessment the SBTool[pt] - H methodology was used. Table 3 presents the results from the application of the methodology.

Table 3 – Values for the Environmental Dimension, Social and Economic Dimensions

Category	Parameters (PID)	Performance	Category evaluation [A]	Weight Category [B]	Weighted Value [A]x[B]
C1 – Climatic changes and air quality	P1 - Aggregated value of the life cycle environmental impact categories of the building for m^2 of net pavement area per year	B	0.548	12	0.066
C2 – Use of soil and biodiversity	P2 - Percentage of use of the available land use index	A+	1.080	19	0.205
	P3 - Waterproofing index	C			
	P4 - Percentage of intervention area previously contaminated or built	A			
	P5 - Percentage of green areas occupied by native plants	A+			
	P6 - Percentage of area with reflectance equal or superior of 60%	A+			
C3 – Energy efficiency	P7 - Consumption of non-renewable primary energy in the operation stage	A	0.956	39	0.373
	P8 - Quantity of energy from renewable energy sources produced in situ	A+			
C4 – Materials and residual waist	P9 - Percentage in cost of reused materials	B	0.929	22	0.204
	P10 - Percentage in weight of recycle content of the building	A+			
	P11 - Percentage in cost of organic base products that are certified	A+			
	P12 - Percentage in mass of cement substitutes in concrete	A			
	P13 - Potential of the condition building to allow separation and recycle	A			
C5 – Efficient water usage	P14 - Volume of annual water usage per capita	A	1.069	8	0.085
	P15 - Percentage of reduction of the drinking water	A+			
S= Performance in the Environmental Dimension					**0.934**
C6 – Comfort and health of occupants	P16 - Potential of natural ventilation	B	0.943	60	0.566
	P17 - Percentage in weight of low COV materials	A			
	P18 - Annual level of thermal comfort	B			
	P19 - Average factor of the light in the medium day	A+			
	P20 - Average of acoustic insulation	A			
C7 – Accessibility	P21 - Index of accessibility of public transports	B	0.536	30	0.161
	P22 - Index of accessibility to amenities	A+			
C8 – Education for sustainability	P23 - Availability of the Usage manual of the building	A	0.967	10	0.097
S= Performance in the Social Dimension					**0.823**
C9 - Life cycle cost	P24 - Initial value cost for m^2 of usage area	A+	1.20	100	1.20
	P25 - Actual value of usage cost for m^2 of area	A+			
S= Performance in the Economic Dimension					**1.20**

Analysing the results, in general all the measures implemented promoted the sustainability of the building (Table 4). The values of each Dimension were normalized and a Final Sustainable Score of 0.98 was obtained, which represents a qualitative sustainability level of “A” (Table 4) which means that the building obtained a good level of sustainability.

Table 4 – Sustainability level of the building

Dimension	Category evaluation [A]	Weight Category [B]	Weighted Value [A]x[B]
D1 - Environmental	0.934	40	0.374
D2 - Social	0.823	30	0.247
D3 - Economic	1.200	30	0.360
∑ = Sustainability Level (NS)			**0.980**

4.5 Economic Viability of the Implemented Solutions

Some of the proposed solutions that were implemented showed to have economic viability.

The system of collection and treatment of rain and bath water, with the flow controllers has a payback time of 6.8 years, which is very good taking in consideration the durability of the system that is about 20 years. Due to the 50% reduction of drinking water use, the annual saving cost it is about 457.80 €.

The heating, cooling and domestic hot water production systems implemented, in comparison to a propane system, has a payback time, for example, for the dwelling I of 6.9 years, that it is very good taking in consideration the durability of the system (Table 5).

Table 5 – Payback time of the heating, cooling and hot water system of the dwelling I

Annual Saving (€) – Heat Pump	595.16
Total cost of the system of Heat Pump (€)	9750.00
Total cost of the propane system (€)	5600.00
Payback time (years)	6.9**

**considering that the cost is the same along the years, annual tax of 0% and that there is not any cost of maintenance along the years.

Using only LED bulbs for the artificial lighting, the annual saving with electricity costs, in comparison to conventional bulbs, is about 702.83€. The payback time of the LED lighting is about 1 year.

A system of photovoltaic panels was thought to be implemented, but because of the location, orientation and surroundings of the building it would not be viable.

5. CONCLUSIONS

This work discussed and presented the importance of assessing the contribution of different design approaches for the overall performance level of a building, since the early design stages of a rehabilitation project.

At the level of the global sustainability score of a building, the use of more sustainable building solutions and systems that contribute to the reduction of energy consumption and costs led to the achievement of a good sustainable score.

Taking into account that it takes time to apply all the methodologies that were presented in this work, in order to promote a higher number of sustainable refurbishment principles it is necessary to develop a tool that integrates all the methodologies presented in this work. To be effective, this tool must be easily understood by architects and other stakeholders of the design process of a building.

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