Cost/benefit analysis in the implementation of sustainable construction principles in a residential building

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ABSTRACT: The construction sector is one of the major contributors for the increase of pollution and environmental degradation. The uncontrolled increase on the consumption of natural resources, the way they are used and the high emissions they arise, are impelling the study and implementation of policies and procedures which ensure a sustainable future for construction and for the sustainability of the planet. The objective of this paper is to present the work developed in order to assess and optimize the sustainability of a residential building at the design stage, through the application of a sustainability assessment tool, SBTool^{PT}-H. A first evaluation was done, when conventional solutions were adopted. After this, a proposal was developed with several improvements in order to create a sustainable building that corresponds to the Portuguese best practices. This case study was developed taking into account the twenty-five sustainability indicators of the SBTool^{PT}-H assessment system. Additionally, dynamic thermal simulation was used in order to support the optimization of the thermal performance and the indoor thermal comfort.

1 INTRODUCTION

The construction sector is one of the major contributors for the increase of pollution and environmental degradation. The uncontrolled increase on the consumption of natural resources, the way they are used and the high emissions they arise, are impelling the study and implementation of policies and procedures which ensure a sustainable future for construction and sustainability of the planet.

The development of building sustainability assessment and certification systems in different parts of the world is enabling the reduction of the negative impacts of the construction sector, the optimization of life-cycle costs and the development of a built environment with higher comfort patterns for occupants.

The objective of this paper is to present the work developed in order to assess and optimize the sustainability of a detached house at the design stage, through the application of a sustainability assessment tool, SBTool^{PT}-H (Martinho,2013). A first evaluation was done, when conventional solutions were adopted. After this, a proposal was developed with several improvements in order to create a sustainable building. The presented sustainable proposal was developed taking into account the twenty-five indicators that constitute the SBTool^{PT}-H assessment system (Mateus & Bragança, 2011).

Since the energy efficiency and the thermal comfort are two parameters that most influence the overall sustainability of a building, the methodology used in this research also included dynamic thermal simulation in the optimization of the sustainability of the case study.

An economic analysis is also performed to analyse the cost/benefit related to the proposed sustainability improvement measures. Thus, this work highlights the contribution of the building sustainability assessment tools in the development of more sustainable buildings, as a process to ensure the level of efficiency of buildings in relation to the consumption of natural resources, environmental protection and thermal comfort.

2 THE SBTooL^{PT}-H METHODOLOGY

The SBTool^{PT}-H is based in the adaption of the international Sustainable Building Tool (SBTool) to the Portuguese's environmental, societal and economy contexts. The scope of this methodology is to assess the sustainability of the existing or new and renovated buildings in the urban areas an especially in Portuguese context (Mateus & Bragança, 2010).

A variety of sustainability assessment tools is available on the construction market, and they are widely used to assess the environmental performance of building products. Therefore the majority of tools to be used on building level were developed in a bottom-up approach, i.e. the overall performance comes from summing up the contribution of building materials and components to the whole building performance. There are several LCA based tools available that were especially developed to address the building as whole. This issue is discussed, for example, in Forsberg A. & Malmborg von F. (2004).

In the Sustainable Building Tool (SBTool) the approach is to weight different criteria, considering weighting factors that are fixed at the national level. Each "score" results from the comparison between the studied building and national references (conventional and best practices). This scheme allows an international comparison of buildings from different countries. This methodology is intend to be a tool to support the building design in order that this achieves the most appropriate balance between the different sustainability dimensions, and that is at the same time practical, transparent and flexible enough to be easily adapted to different kind of building and technology (Mateus & Bragança, 2011). The framework of this methodology is presented in Figure 1 and is described in Mateus & Bragança (2011).

The methodology follows four steps: i) Quantification of performance of the building at the level of each indicator; ii) Normalization of parameters; iii) Aggregation of parameters; iv) Sustainable score calculation and global assessment.

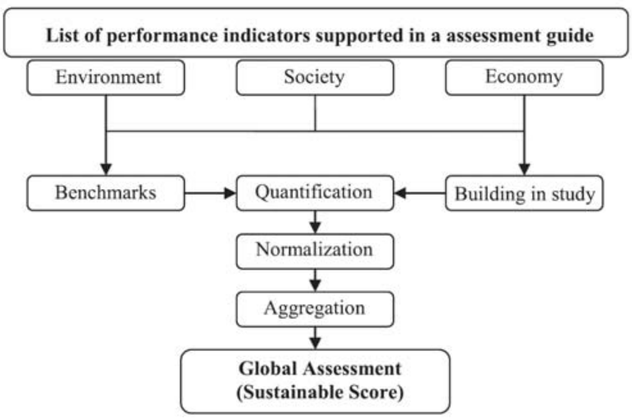

Figure 1. Framework of the SBTool^{PT}-H methodology (Mateus & Bragança, 2011).

3 PRESENTATION OF THE CASE STUDY

The case study is one residential building, for one family, with two floors (Level 0 and Level 1) and a floor for the garage (Level -1), giving a total construction area of 515.28 m^2 and a gross footprint of 245.25 m^2. The residential building is located in Casal Velho, near to the city of Pombal, in the Leiria district. The building is defined by a traditional structure, namely in reinforced concrete and the exterior and the interior walls are made of hollow brick masonry.

The land plot has 421 m^2 and is near to the urban area of Casal Velho. The buildings surrounding this case study are medium/low density, predominantly defined by residential detached buildings (for one family). The distance between the center of Castelo Velho and the city of Pombal is around 3 km. In Figure 2 to 5 are presented the plans of the building under study.

As abovementioned, the building is designed according the traditional construction techniques used in Portugal: reinforced concrete for the structure (beams and columns) and 25cm thick hollow-brick single walls in the external vertical envelope. The building uses an External Thermal Insulation Composite System (ETICS) as the basis if the thermal insulation. Interior walls are in 11cm thick hollow bick. The walls, interior and exterior, are coated with traditional Portland cement mortar.

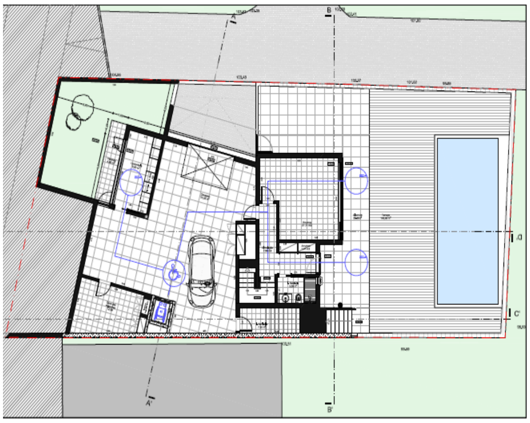

Figure 2. Plan of the Level -1

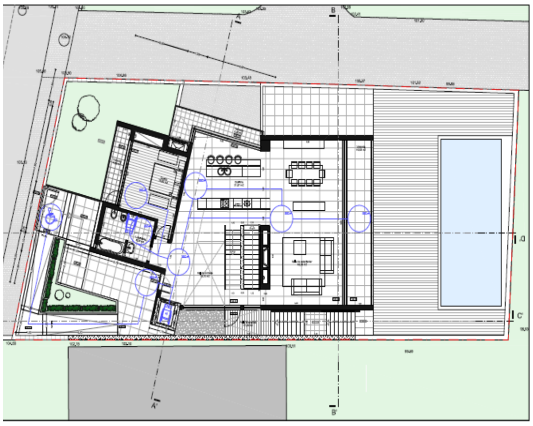

Figure 3. Plan of the Level 0

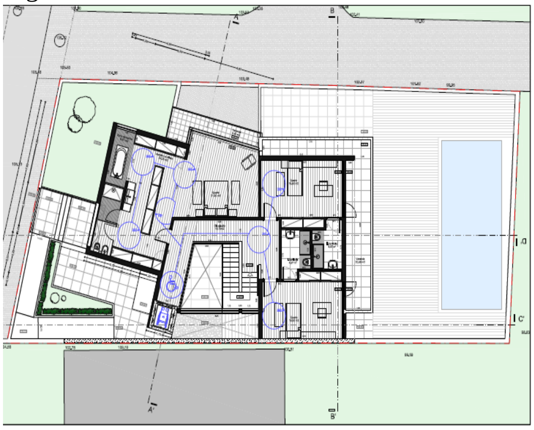

Figure 4. Plan of the Level 1

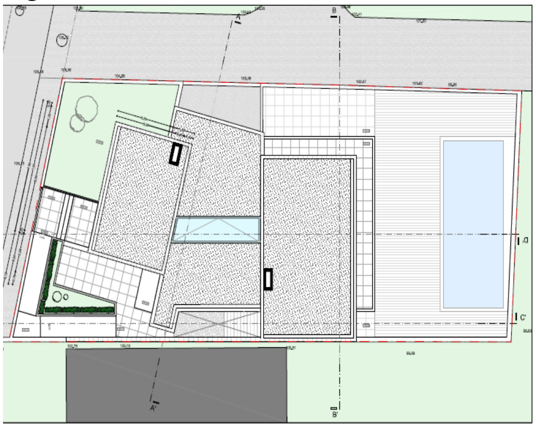

Figure 5. Plan of the Level of the roof

4 ASSESSEMENT OF THE SUSTAINABILITY

The implementation of the sustainability assessment was carried our according to the evaluation guide and the assessment procedure of the SBTool^{PT}-H methodology and follows the steps indicated in the Figure 1. To assess the environmental dimension the authors used an embedded life-cycle impact assessment (Bragança & Mateus, 2012). This database covers the most used building technologies for each building element (walls, floors, windows, doors, etc.). The physical boundary of the SBTool^{PT}-H methodology is the building site plus the level of integration of the building with other urban amenities (e.g. commercial areas and leisure areas). The time boundary it includes the whole life cycle, from cradle to grave.
The performance of the case study, assessed for the original solution and for the optimized solution, is measured against each category, sustainable dimension and global score (sustainable score)

4.1 *Original Solution*

The first step is the quantification of the performance of the original building at the level of each sustainability indicator. Table 1 lists the categories and sustainability indicators and respective results from the application of the SBTool^{PT}-H methodology to the original solution.

Table 1. Sustainability assessment of the original building

Dimension	Categories	Sustainability indicators	Original solutions	Score level
Environmental	**C1** - Climate change and outdoor environment quality	**P1** - Construction materials embodied environmental impact	Exterior walls: Single 25 cm ceramic thermal hollow brick wall. The thermal insulation is complemented with an ETICS(6cm polystyrene and polyethylene net); Interior walls: 11cm thick hollow brick masonry wall; Structure: reinforced concrete columns and beams and reinforced concrete slabs; Finishing: i) walls – Portland cement mortar (indoor and outdoor); ii) floors – ceramic tiles and insulation in level -1 and humid areas and wooden floating floor in the other areas; iii) ceilings – suspended plasterboard ceilings with rock wool in the air gap.	A (0.75)
	C2 – Land use and biodiversity	**P2** – Urban density	Total gross construction area of 515.28 m^2; a footprint of 245.25 m^2. The land plot has 421 m^2.	A^+ (1.18)
		P3 – Water permeability of the development	Traditional flat roof. The exterior land, surrounding the building, is permeable.	D (0.05)
		P4 – Use of pre-developed land;	Virgin land without any contamination and previous construction.	D (0.00)
		P5 – Use of local plants	There are 41.0 m^2 for green spaces and no local flora is used.	E (-0.20)
		P6 – Heat-island effect	There is a lake(water mirror) to reduce the heat island effect, but most of the surface is paved.	E (-0.20)
	C3 – Energy efficiency	**P7** – Primary energy	The architecture takes advantage from passive solar strategies with shading elements and a favourable solar orientation.	A (0.95)
		P8 – In situ energy production from renewable sources	It is planned the application of solar panels for water heating.	A^+ (1.20)
	C4 – Materials and waste management	**P9** – Reused materials and products	It isn't planned the use of reused materials in the construction.	D (0.00)
		P10 – Use of materials with recycled content	The used materials have a conventional recycled content.	D (0.00)
		P11 – Use of certified organic materials	No certified materials are used.	D (0.00)
		P12 – Use of cement substitutes in concrete	Concrete with 6.2% of fly ashes.	A^+ (1.16)
		P13 – Waste management during operation	Point of collection and separation of waste (recycling center public) between 50 and 500 meters; Lack of domestic ecopoints.	D (0.0)
	C5 – Water efficiency	**P14** – Fresh water consumption	Conventional taps and equipment's are used.	C (0.167)
		P15 – Reuse of grey and rainwater	There is no rainwater harvesting system.	D (0.00)
Societal	**C6** – Occupant's health and comfort	**P16** – Natural ventilation efficiency	Openings with large are allowing efficient natural cross ventilation.	A^+ (1.20)
		P17 – Toxicity of finishing	Applied materials with low COV content.	A^+ (1.11)
		P18 – Thermal comfort	Not considered in the assessment, since there was no data from dynamic thermal simulation in the original project.	
		P19 – Lighting comfort	Proper solar orientation. There are no obstructions in the openings.	A^+ (1.20)
		P20 – Acoustic comfort	Double glazed windows Large openings. External walls in thermal hollow brick and external finished with an ETICS.	A (0.82)
	C7 – Accessibilities	**P21** – Accessibility to public transportation	The plot is served by 9 lines of Bus.	A (0.70)
		P22 – Accessibility to urban amenities	The main urban amenities are within a maximum radius of 2500 m.	A^+ (1.13)
	C8 – Education and awareness of sustainability	**P23** – Education of occupants	There is not a user manual.	E (-0.20)
Ec	**C9** – Life-cycle-costs	**P24** – Capital Cost	The cost per m^2 of initial investment is 851.38 €.	E (-0.20)
		P25 – Operation Cost	Lifecycle cost with Euribor tax 10.31 € per m^2 and year.	C (0.26)

Global score	B (0.53)

Each building element used in this case study is described. The performance of each sustainable indicator was obtained after the normalization and aggregation and is presented inTable 1.

The results obtained for the categories are: C1 - Climate change and outdoor environment quality: A (0.75); C2 – Land use and biodiversity: C (0.35); C3 – Energy efficiency: A+ (1.08); C4 – Materials and waste management: C (0.21); C5 – water efficiency: C (0.11); C6 – Occupant's health and comfort: A+ (1.08); C7 – Accessibilities: A (0.90); C8 – Education and awareness: E (-0.20); C9 – Life-cycle-costs: D (0.03).

The score obtained for each dimension is: Environment: B (0.63); Society: A (0.90); Economy: D (0.03). These results lead to a final score of B (0.53). Analysing this results it is possible to conclude that this building is level B due to its high initial investment and due to the low performance at the level of the sustainability indicators in the environmental dimension.

4.2 *Optimization of sustainability*

To optimize the sustainability of the building the methodology SBTool^{PT}-H was used and the most important indicators were considered. Therefore the implemented design alternatives were bases in the purpose of improving the most unfavourable indicators. At the end it was possible to archive an overall level of sustainability of A. The implemented actions are described in Table 2.

Table 2. Sustainability assessment of the optimized building

Categories	Sustainability indicators	Optimized solutions	Score level Optimized building
C1 - Climate change and outdoor environment quality	**P1** - Construction materials embodied environmental impact	Use of green space near the pool instead of deck floor; application of a green roof; Replacement of aluminum shutters by shutters PVC; Replacement of geotextile provided by the TERBOND brand; Replacement of T61 and C31 of Amorim, lightweight concrete; Replacement of thermal isolation Roofmate SL-40, by Greycicle Key Boards; Elimination of the ceramic coating, existing in the exterior at the garage access, considering a green space.	A^+ (1.07)
C2 – Land use and biodiversity	**P3** – Water permeability of the development	Use of green space near the pool instead of deck floor. Application of s green. Elimination of the ceramic coating and use of permeable flooring in the access to the garage.	B (0.56)
	P5 – Use of local plants	Use of green space near the pool instead of deck floor; Application of a green roof using native plants; Elimination of the ceramic coating and use of permeable flooring in the access to the garage, using native plants.	A^+ (1.06)
	P6 – Heat-island effect	Use of green space near the pool instead of deck floor; Application of a green roof using native plants; Elimination of the ceramic coating and use of permeable flooring in the access to the garage, using native plants.. Application of materials with a color reflectance greater than 60%.	A^+ (1.13)
C3 – Energy efficiency	**P7** – Primary energy	Implementation of high performance glazed areas; Implementation of a pellets boiler; Application of photovoltaic panels.	A^+ (1.77)
C4 – Materials and waste management	**P13** – Waste management during operation	Application of containers of various categories of waste with volumes greater than 15 L. Implementation of used oil and used batteries containers.	A (1.00)
C5 – water efficiency	**P14** – Fresh water consumption	Implementation of tap with aerator; dual flush toilets of low capacity 4/2 litres; low flow showers; washing machines with low water consumption.	A^+ (1.07)
C8 – Education and awareness os sustainability	**P23** – Education of occupants	Development of a user manual that covers the main building sustainability aspects related to the operation phase.	A^+ (1.20)
C9 – Life-cycle-costs	**P25** – Operation Cost	Lower operation costs, resulting from the use of high performance equipments and building elements.	A (0.74)
Global score			A (0.75)

The results obtained for the categories are: C1 - Climate change and outdoor: A+ (1.07); C2 – Land use and biodiversity: A+ (1.03); C3 – Energy efficiency: A+ (1.19); C4 – Materials and waste management: C (0.25); C5 – water efficiency: A (0.71); C6 – Occupant's health and com fort: A+ (1.08); C7 – Accessibilities: A (0.90); C8 – Education and awareness: A+ (1.20); C9 – Life-cycle-costs: C (0.27). The score obtain for each dimension is: Environment: A (0.90); Society: A+ (1.04); Economy: C (0.27). Due to this optimized assessment, the environmental performance of the building was improved to the level A and the societal performance achieved the maximum level. In what respects to the economic performance, it was also improved, but due to the high initial investment a level C was obtained. These results lead to a final score of A (0.75), Table 2.

4.3 *Analysis of the thermal behavior of the building*

The building was analysed using the simulation tool Design Builder. The assessment was done before and after the optimization. These studies intended to analyse: the energy losses by the several materials that constitute the building envelope; the energy gains in the building; the behaviour of the internal temperatures of the building due to the variation of the external temperatures along the day and year; the energy consumption of the building, for heating and cooling the indoor environment and to maintain the thermal comfort during both the heating and cooling seasons.

Table 3 shows that the consideration of optimized solutions in the building induced a better thermal performance and a reduction of operation costs. For the dynamic analysis of the thermal behaviour of the building the comfort temperatures of 18 ºC for winter and 21 ºC for the summer were considered, taking in consideration the comfort class level III of the standard EN15251:2007. To assess the energy costs the following reference costs were considered: i) pellets - 0.24 €/Kg; electricity - 0.139 €/kWh. These were the valued in the local market in November 2012.

Table 3. Evaluation of the thermal behaviour of building and related operation costs

Compartment	Original building				Optimized building			
	Energy demands Kwh/year		Energy costs (€)		Energy demands Kwh/year		Energy costs (€)	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Living room (90,42m^2)	350	2200	28.23	305.80	600	1600	29.39	222.40
bedroom (21,60m^2)	150	450	12.10	62.55	300	350	14.69	48.65
WC (4,87m^2)	35	110	2.82	15.29	35	110	1.71	15.29
All building (245,25m^2)	1950	5450	157.30	757.55	1800	4350	88.16	604.65

4.4 *Economic analysis*

In order to get a better understanding of the developed work and the achieved classification for the building, after the analysis of sustainability and the thermal behaviour an economic analysis was developed. Table 4 represents the life cycle costs of the building for the two analyzed solutions: the original and the optimized.

Analysing Table 4 it is possible to conclude that the implementation of the sustainable solutions results in a reduction of costs by 1.5 times between and the improvement of the sustainability from B to A. At the end of a life cycle of 50 years the implementation of the optimized solution has a saving of 67,827.60 €. It should be noted that these analyses do not comprehend the gains from the sale of electricity to the public system, due to the production of electricity from photovoltaic panels. According to the photovoltaic panel design, the annual energy production is about 3042 kWh/year. The energy price in the subsidized regime is 0.306 €/kWh, for the first eight years and 0.165 €/kWh for the remaining seven years. After fifteen years the values for sale and acquisition are equal. According to the main Portuguese energy supplier, in

2012 the normal energy price is 0.139 €/kWh.

From the abovementioned values it can be conclude that he use of photovoltaic panels results in a gain of 13,074.50 €, considering a period of 20 years for the life cycle of the photovoltaic panels.

The graph shown in Figure 6 reflects the evolution of total investment during the entire life cycle of the building with original solution, class B, and optimized solution, class A.

Table 4. Life cycle costs of the building attending the two solutions.

Costs	Original building (Class B)		Optimized building (Class A)	
	Initial unit value (€)	Total life cycle (€)	Initial unit value (€)	Total life cycle (€)
Maintenance				
Replacement of the floor coating each 20 years.	12,185.80	24,371.60	12,185.80	24,371.60
Painting exterior, interior walls and floors each 8 years.	3756.00	22,536.00	3756.00	22,536.00
Replacement of the glazed openings each 30 years.	6811.00	6811.00	8757.00	8757.00
Operation costs (245.25 m^2)	€/m^2.year		€/m^2.year	
Energy consumption.	2.82	34,580.30	0.93	11,404.10
water consumption, wastewater production and solid waste.	9,87	121,030.87	4.76	58,369.50
Totality of the operation costs using the Euribor tax (1.23%).	10.31	126,426.38	4.62	56,652.75
Totality of life cycle costs with Euribor tax (1.23%)	-	180,145.10	-	112,317.60

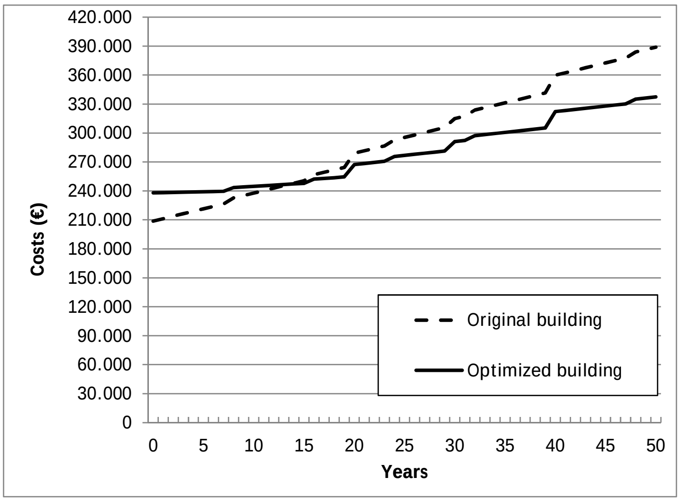

Figure 6. Evolution of the life cycle costs of the original and optimized alternatives.

It can be seen that the initial investment of 29,285.20 € in sustainability solutions are recovery at the 13th year of the life cycle of the building. At the end of the life cycle the building with Class A, has a total investment of 337,330.08 €, whereas the building with Class B has 388,946.60 €, representing a total of savings of 51,616.82€.

It can be concluded that investment in sustainability measures is profitable, with a quick return and representing significant savings at the end of life cycle.

5 CONCLUSIONS

The work presented in this paper is aimed to assess and optimize the sustainability of a residential building at the design stage, through the application of a building sustainability assessment tool, namely the SBTool^{PT}-H. A first evaluation was done, where conventional solutions were adopted. After this, a new proposal was developed with several improvements in order to create a sustainable building with a higher level of performance, corresponding to the Portuguese best practice (level A). An economic analysis is also performed to analyse the cost/benefit related to the proposed sustainability improvement measures.

As this paper highlights, the improvement of the sustainability of a building does not relies only in the preservation of the environment, but also in the consideration of social and economic aspects. The sustainability of a building depends not only on one dimension but in the harmony between the three dimensions of sustainability: environmental, societal and economic.

This research and the application of the methodology SBTool^{PT}-H allowed the development of the following conclusions to conclude that:

Sustainable building needs less extraction of raw materials and produces significantly lower greenhouse gases to the environment;

The consumption of water and energy are substantially smaller in sustainable building;

The economic analyses demonstrate a clear cost reduction from the sustainability level B to A, which would result in significant savings in life cycle of the building.

The building with sustainable level A has a much better thermal behaviour that the building with sustainable performance class B. This classification is also reflected on the energy consumption necessary to maintain the building in the range of thermal comfort.

In what respects to the contribution of the methogology SBTool^{PT}-H to the sustainable building design, it is possible to highlight that:

This methodology is a clear aid to the design of sustainable residential buildings. This framework based in the analysis twenty-five sustainability indicators covers the key points of sustainability.

It allows making improvements in the design of the residential buildings in order to ensure a better performance at the level of the three sustainability dimensions: environmental, social and economic;

It addresses the thermal comfort, giving special attention to the energy consumption and associated costs to keep the building in the range comfort.

The assessment of the sustainability of a building is an advanced vision, which shows that small options can be crucial for the environment, society and economy.

This work highlights the importance of the evaluation and certification of the sustainability of the construction, as a process to ensure a level of efficiency of buildings in relation to the consumption of natural resources, environmental protection and thermal comfort.

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