BUILDING SUSTAINABILITY ASSESSMENT BASED ON MATERIALS USED: CASE STUDIES IN LISBON, PORTUGAL

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ABSTRACT
Nowadays, sustainability is one of the main objectives of the world, also shared by the construction sector. However, despite the calls toward construction sustainability and its benefits, the project design decisions are often based only on the economic point of view, which is useful for the building cost but underestimates the materials' environmental impacts. The subject of this paper is the buildings' sustainability assessment, concerning the environmental impact of materials used, in two stages of the building life cycle: (i) building construction; and (ii) building occupation. In order to define the sustainability degree of the buildings, correspondence analysis as discriminant analysis was used to establish a numerical scale that allows comparing the buildings in relative terms. The buildings are scored and ranked through this scale. The Parque das Nações (Nation's Park) area, Lisbon, was chosen because it was designed to be an example of sustainable urban planning, with concerns for the preservation and conservation of resources. The methodology developed, which allows synthesizing in a single numerical value the buildings' sustainability, was tested in 30 buildings, with promising and intelligible results for non-professionals and professionals. In general, residential buildings reveal high sustainability than office buildings in the construction stage. In the occupation stage, both types of buildings reveal sustainability scores more similar.
Keywords: building sustainability, sustainable materials, barycentric discrimination, Parque das Nações.

1 INTRODUCTION

Several centuries ago, the human population was small, and the civilizations had few needs, which gave the illusion that natural resources were unlimited because the ability of nature to regenerate itself was much larger than the resources' usage rate.

Nowadays, there is awareness that natural resources are limited and that it is necessary to ensure a future for coming generations, through sustainable development [1]. In fact, at the world level, civil works and building construction consumes 60% of the raw materials extracted from the lithosphere [2]. From this volume, buildings represent 40%, or 24% of these global extractions [2]. This sector's intensive use of concrete, iron, metal alloys, plastics, and synthetic materials consumes large quantities of raw materials and energy, leading to depletion of resources and contributing to the increasing greenhouse effect [3]. The European Commission recognizes that "better construction and use of buildings in the EU would influence 42% of our final energy consumption, about 35% of our greenhouse gas emissions and more than 50% of all extracted materials; it could also help us save up to 30% water" [4].

To cope with this problem, in 1994 the Conseil International du Bâtiment (CIB) defined sustainable construction as "…creating and operating a healthy built environment based on resource efficiency and ecological design" [5]. Sustainable construction also concerns "the adoption of materials and products in buildings and construction that will require less use of natural resources and increase the reusability of such materials and products for the same or similar purpose, thereby reducing waste as well" [6]. Following the same line of thought, the

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Environmental Protection Agency (EPA) of the USA defines a green building as a building, which is designed, built operated, maintained, or reused with objectives to protect occupant's health, improve employee productivity, use wisely natural resources and reduce the environmental impacts [7].

So, sustainable construction must respect both the needs of the inhabitants and the natural resources of the Earth. It contributes significantly to environmental enhancement and quality of life improvement. Building sustainability also promotes the local economy and decreases energy consumption.

Furthermore, by choosing suitable materials, preferably durable and energy-efficient, the utilization costs decrease. This choice also contributes to increasing the buildings' life cycle, which can be, supported by maintenance procedures, extending furthermore until the building is eventually rehabilitated, avoiding the demolition waste.

However, despite the calls toward construction sustainability and its benefits, the project design decisions are often based only on the economic point of view, which is helpful for the building cost but underestimates the materials' environmental impacts.

Thus, the question arises of assessing the sustainability grade of buildings constructed in the last decades.

This paper seeks to achieve the quantification of a qualitative variable such as building sustainability, taking into account the materials that were applied. A methodology based on Correspondence Analysis as Discriminant Analysis, mathematically developed by Ribeiro [8] and Pereira et al. [9], was used to show the quantitative results for 30 buildings in Lisbon, following the research work of Barbosa [10], Ribeiro and Barbosa [11] and Barreto [12]. Thus, the aim is to obtain the sustainability grade of a particular building in relation to others with similar construction characteristics.

Another objective, more general, is consolidating the methodology to quantify the quality variability.

2 BRIEF LITERATURE REVIEW

Until recently, the only method to evaluate the sustainability of products was the life cycle assessment (LCA), which "seeks to quantify the environmental impacts over the infrastructure life cycle by identifying the costs during each phase" [13], considers the environmental impact of a given material, since the extraction through production, use, recycling and what happens to the product after it is no longer used. "However, surveys of building practitioners have shown that LCA tools are not widely used to guide design development because the analyses are time-consuming, require burdensome data collection, and are poorly integrated with the design process" [14], despite the streamlined methodologies developed by Rodrigues et al. [15] and Hester et al. [16].

Following the LCA structure, the environmental preference method (EPM), created in 1991 by Woon/Energie in the Netherlands, compares construction materials and sorts them according to environmental preference. It takes into account the life cycle, in a process called "cradle to grave", from the extraction of the raw material to the waste from demolition. The main topics considered are: the shortage of raw materials, the ecological damage caused through the extraction of raw materials, energy consumption at every stage, water consumption, noise, emissions that destroy the ozone layer, global warming, and acid rain, health aspects, risk of natural hazards, maintenance, reuse and waste from demolition [17]. The aesthetic or cost are not involved in this evaluation, and the result of this preference is not an absolute value, but a ranking based on environmental impact. The reuse and recycling of materials are always preferable [17].

As such, the selection of the materials should take into account all stages of their life, such as manufacturing, processing, transportation, construction, maintenance, demolition, and recycling, but also the influence of the material on the behaviour of the building, concerning its relationship with their users and the surrounding environment.

Thus, it was decided in this paper to distinguish the two major stages in the life of buildings, the construction stage (from raw material extraction, passing through material production, until its application), and the occupation stage (from the use of the material to the end of its life) to better understand sustainability as a whole. Although the demolition stage creates a lot of waste, this stage can be avoided in most cases with maintenance and rehabilitation, lengthening the building's lifetime.

3 METHODOLOGY

The methodology (Fig. 1) was implemented in several fields [8], [9] and can be applied to any buildings [10], [11], providing they have similar characteristics, allowing the comparison between them.

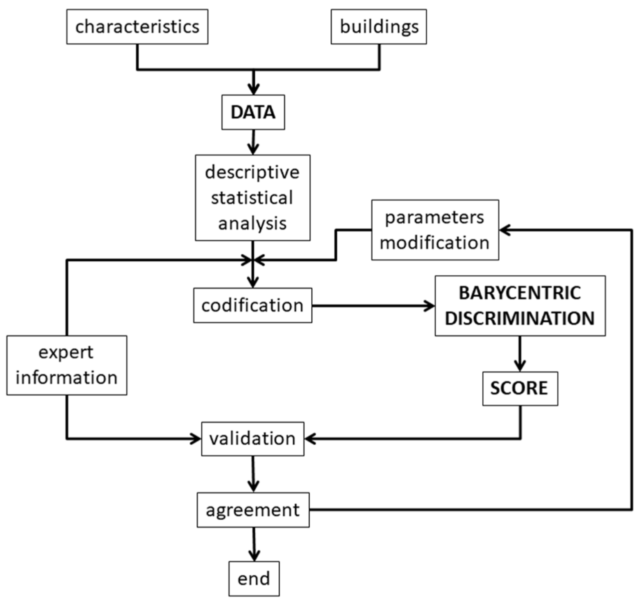

Figure 1: Schematic representation of the methodology. *(Source: Adapted from Ribeiro [8].)*

The first step is defining the characteristics (attributes, categories, or variables) that will be included in the analysis and selecting the buildings to assess. The data collection can be triggered by observation or experimentation, by surveys or other processes, providing samples vs. characteristics (variables), followed by descriptive statistical analysis.

In order to submit all the variables (quantitative and qualitative) to the algorithm, they should be codified in a disjunctive complete matrix [18].

Applying subsequently the barycentric discrimination (BD) – an adaptation of correspondence analysis (CA) to the discrimination around poles that are the centre of gravity of the starting attributes [8], [9] – to defining the extremes of the quality scale (discriminant axis), the coordinate of the individuals' projection on this scale is a quantitative representation of quality (score).

The results are compared with more information, later obtained from unknown or random individuals taken from the data set in order to modify some parameters, thus resuming the entire process until the score is calibrated, validating the approach and methodology and the consequent use of the score as an assessment tool.

4 CASE STUDY

The eastern part of Lisbon was a rural area until industrialization in the first decades of the 20th century. After the deindustrialization process, the site was contaminated, mainly on soil and water, and served as a deposit to containers and fuel tanks.

The site was therefore an area available for urban renewal, using sustainable guidelines. The location for the EXPO'98 (the 1998 Universal Exhibition) was, therefore, a consensus due to: the need to revitalize the eastern part of Lisbon; the fact that it was a large plain on a riverfront; the potential for transformation into a city's new centrality, accessible by major roads and a new bridge over the river Tagus and, finally, the potential for public transportation with the airport, train, and subway nearby. The EXPO'98 located in the area now called Parque das Nações, created challenges for sustainable urban development, and was used for experimental concepts like reducing the consumption of energy or implementing alternative energy supply, in order to minimize the economic and environmental costs. In Calixto [19] and Cabral de Mello and Almeida [20] more details and measures applied in the area could be seen.

All the innovative solutions have contributed to the Parque das Nações area being recognized as an international case study, and the largest revitalization project design held in Lisbon since the 1755 earthquake. The area is a paradigmatic case study of urban regeneration and new construction, allowing assessment of the state of recent construction in Portugal.

The buildings selected for the study are distributed along the length of the entire area of the Parque das Nações and are a representative sample of the area. Thirty buildings (twenty residential buildings and ten office buildings) were selected (Fig. 2). The data was collected through direct observation of the buildings, information found at the Municipal Archive of Lisbon, the ADENE (Portuguese Energy Agency) Buildings Energy Evaluation, and documentation published on the internet [21]. The photographs of the buildings were obtained through the feature "Street View" of the Google Earth [22] platform. In this process, there were some constraints, such as the scarcity or uncertainty of information in the documents consulted, difficult access to the interior of buildings, and the unavailability of all the information contained in the Buildings Energy Evaluation.

The fieldwork consisted in completing a form with information about the materials and assigning percentages to the amount of materials used in each building. The components defined in this form can be seen in Table 1 and were based on the evaluation performed by Appleton [23], adapted to the current building materials.

Despite the diversity of materials used in the buildings, they have, as common characteristics, the period of construction and structure type, which gives coherence to the methodology.

In order to apply the methodology, the materials used are ranked from the less to the high environmental impact (Table 1) and for both stages. This ranking is based on different principles such as: the environmental cost, the embodied energy, the material life cycle, the emissions to the atmosphere, and the damage they cause to human health or a combination of them.

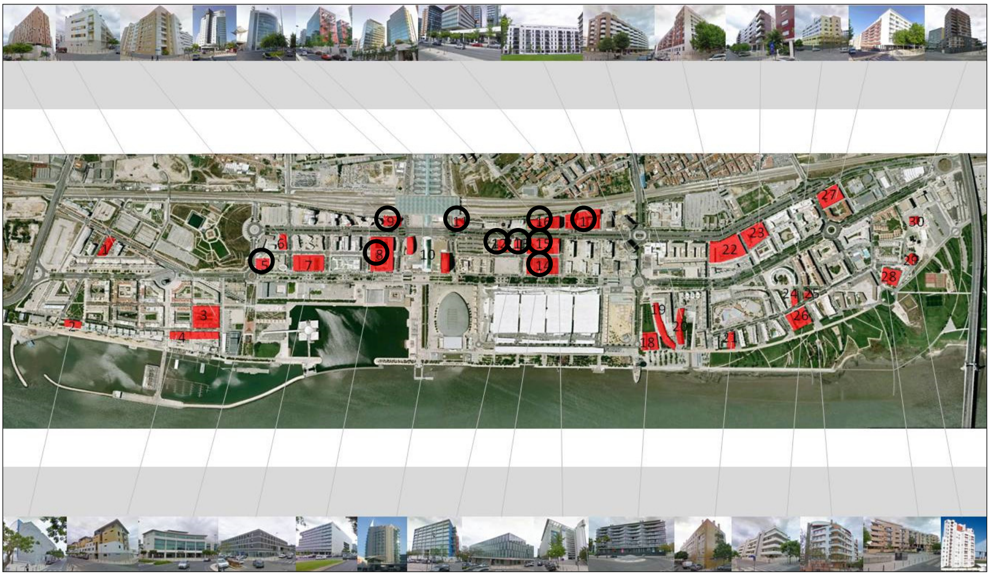

Figure 2: Location of the residential buildings (numbers in red patches) and office buildings (numbers and circles in red patches). *(Source: Adapted from Barreto [12].)*

A data matrix codified, crossing buildings versus materials, was built to synthesize the information collected (Table 2).

For each of the two sustainability assessments (concerning the construction stage, and the occupation stage), were added two lines (named CSUS and CNUS for construction stage and OSUS and ONUS for occupation stage) corresponding to the archetypes that define the extremes of the arbitrary scale of sustainability. CSUS and CNUS are, respectively, the best and worse material categories, from the sustainability point of view, for each building element at the construction stage. OSUS and ONUS have the same meaning for the occupation stage (Table 2).

Thus, these two lines of each stage (CSUS and CNUS for the construction stage and OSUS and ONUS for the occupation stage) were submitted to the barycentric discrimination algorithm [8] through software AnDad 7.12 [24] in order to create the discriminant axis, that defining the arbitrary scale of sustainability that has its extreme archetypes as CSUS and CNUS (the best and the worse possible scores, respectively) for construction stage, and OSUS and ONUS (the best and the worse possible scores, respectively) for occupation stage. The buildings from the data matrix (buildings vs. materials) are then projected as supplementary lines on the discriminant axis.

The buildings' projection coordinates on the discriminant axis are the sustainability score of each (re-scaled for easily understanding to 0 to 10), based on their materials, which provides a comparison and ranking among the several buildings of the sample, according to the methodology applied in this paper.

Table 1: Assessment's material preferences for each component and for both stages.

Components	Construction stage	Occupation stage
Structure	Concrete	Concrete
	Mixed	Mixed
	Metallic	Metallic
Rooftop structure	Concrete	Concrete
	Mixed	Mixed
	Metallic	Metallic
External walls	Brick masonry	Concrete
	Concrete	Brick masonry
	Glazing	Glazing
Internal walls	Gypsum board	Brick
	Brick	Gypsum board
Insulation	Without insulation	EPS
	Mineral fibers	XPS
	Thermal glass	Mineral fibers
	XPS	Thermal glass
	EPS	Without insolation
External wall coverings	Stone	Stone
	Wood	Ceramic
	Glass	Paint
	Paint	Glass
	Ceramic	Wood
Floor coverings	Stone	Stone
	Wood	Linoleum
	Linoleum	Ceramic
	Ceramic	Wood
Ceiling coverings	Wood	Gypsum board
	Gypsum board	Wood
	Paint	Paint
Rooftop coverings	Stone	Ceramic
	Wood	Concrete
	Concrete	Stone
	Ceramic	Wood
	Zinc	Zinc
Window frames	Wood	Lacquered metal
	Mixed	Aluminum
	Aluminum	Mixed
	Lacquered metal	Wood
Additional equipment	Water-saving equipment (–)	Water-saving equipment (+)
	Electricity-saving equipment (–)	Electricity-saving equipment (+)
	Solar panels (–)	Solar panels (+)
	HVAC (–)	HVAC (–)
	Home automation and steam distribution network (–)	Home automation and steam distribution network (+)

Table 2: Disjunctive complete matrix.

Building	Structure			…	Insulation					…	Additional equipment									
											Water sav		Elect. sav		Solar pan		HVAC		Domot	
	Conc	Mix	Met	…	MF	TG	XPS	EPS	WI	…	Y	N	Y	N	Y	N	Y	N	Y	N
1	1.0	0.0	0.0	…	0.0	0.3	0.7	0.0	0.0	…	1.0	0.0	1.0	0.0	0.0	1.0	1.0	0.0	1.0	0.0
2	1.0	0.0	0.0	…	0.0	0.3	0.7	0.0	0.0	……	1.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
10	0.0	1.0	0.0	…	0.5	0.5	0.0	0.0	0.0	…	1.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0	0.0
…				…						…										
29	1.0	0.0	0.0	…	0.0	0.2	0.4	0.4	0.0	…	1.0	0.0	1.0	0.0	1.0	0.0	0.0	1.0	1.0	0.0
30	1.0	0.0	0.0	…	0.0	0.2	0.8	0.0	0.0	…	1.0	0.0	1.0	0.0	0.0	1.0	0.0	1.0	0.0	1.0
CSUS	0.9	0.1	0.0	…	0.25	0.1	0.05	0.0	0.6	…	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0
CNUS	0.0	0.1	0.9	…	0.05	0.1	0.25	0.6	0.0	…	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0
OSUS	0.8	0.2	0.0	…	0.2	0.05	0.35	0.4	0.0	…	1.0	0.0	1.0	0.0	1.0	0.0	0.0	1.0	1.0	0.0
ONUS	0.0	0.2	0.8	…	0.2	0.35	0.05	0.0	0.4	…	0.0	1.0	0.0	1.0	0.0	1.0	1.0	0.0	0.0	1.0

5 RESULTS

Fig. 3 shows the sustainability score obtained by each building at the construction stage. The residential and office buildings are shown on the same graph, in order to compare the sustainability of both typologies.

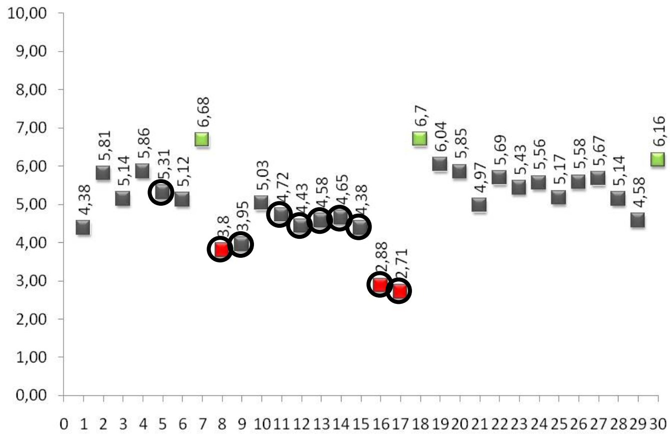

Figure 3: Sustainability scores for the construction stage of residential buildings (squares) and office buildings (squares and circles). *(Source: Adapted from Barreto [12].)*

In general, the residential buildings are best scores than the office buildings, stating a difference between typologies. This difference is not clearly defined, and there is a slight overlap between the residential and office buildings. Residential building #1 have a low score than four office buildings, and eight residential buildings have a low score than the top-ranked office building. The residential buildings obtain the three best scores and the office buildings obtain the three worse scores.

However, can be concluded that in terms of materials used in construction, residential buildings are more sustainable than office ones. This could be explained due to a higher amount of equipment, such as HVAC and home automation, in office buildings rather than in residential ones. Another reason for the lower scores achieved by the office buildings is concerning the architectural design options, where the curtain walls are predominant in the office buildings' façade.

However, as shown in Fig. 4, in a global analysis, the buildings studied did not show very high sustainability scores nor too low, and the large majority of buildings (26 buildings) had sustainability scores in the interval [4, 6]. Many buildings (21 buildings) present scores of 5 and 6, only seven buildings were classified under 5, and only two were classified as 7.

Fig. 5 shows the sustainability score obtained by each building at the occupation stage. The residential and office buildings are shown on the same graph, in order to compare the sustainability of both typologies.

The difference between residential and office buildings is still evident in the occupation stage. The office buildings, at the occupation stage, have significantly increased the sustainability scores, approaching the scores achieved by residential buildings. Three residential buildings (#3, #7, and #18) have a low score than six office buildings, and eighteen

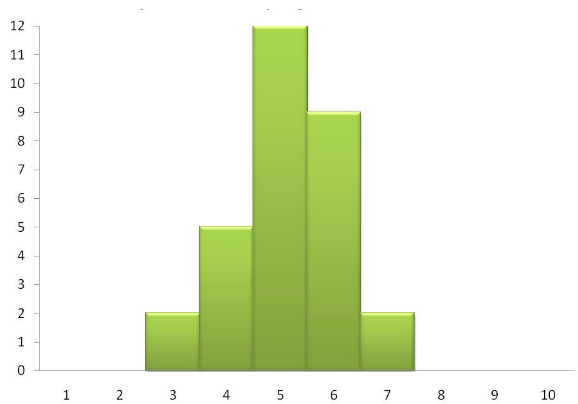

Figure 4: Distribution of sustainability scores for all the buildings, in the construction stage [12].

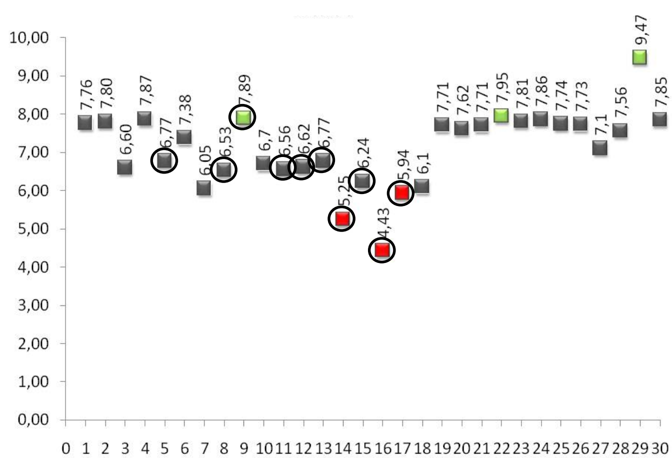

Figure 5: Sustainability scores for the occupation stage of residential buildings (squares) and office buildings (squares and circles). *(Source: Adapted from Barreto [12].)*

residential buildings have a low score than the top-ranked office building. However, the office buildings obtain the three worse scores, but an office building obtains the third best place.

However, contrary to expectations, the sustainability scores achieved by the office buildings are not clearly higher than the scores reached by residential buildings. It is thus demonstrated that the performance of buildings in the occupation stage can't be judged solely by the materials used, or that the variables most directly related to the occupancy should be more valued in the analysis, by introducing weights to assign more importance to these variables.

Fig. 6 shows the distribution of sustainability scores in the occupation stage for all the buildings, where it could be concluded that most buildings (23 buildings) have sustainability scores belonging to the interval [7, 8], i.e. with high values.

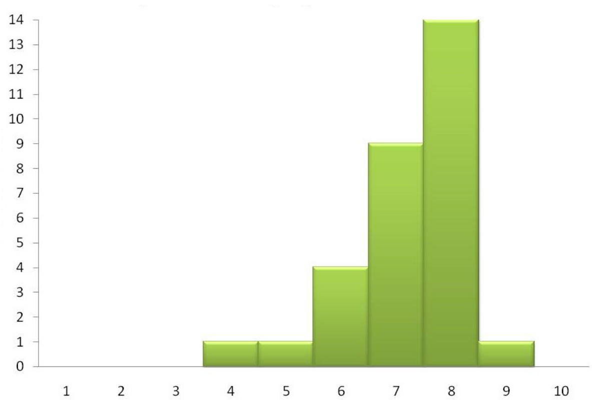

Figure 6: Distribution of sustainability scores for all the buildings, in the occupation stage [12].

Regarding all buildings in both phases, and calculating the average of two sustainability scores – construction and occupation stages – were obtained the results given in Fig. 7. It is also noticeable the difference between typologies, having the residential buildings achieve the best sustainability scores.

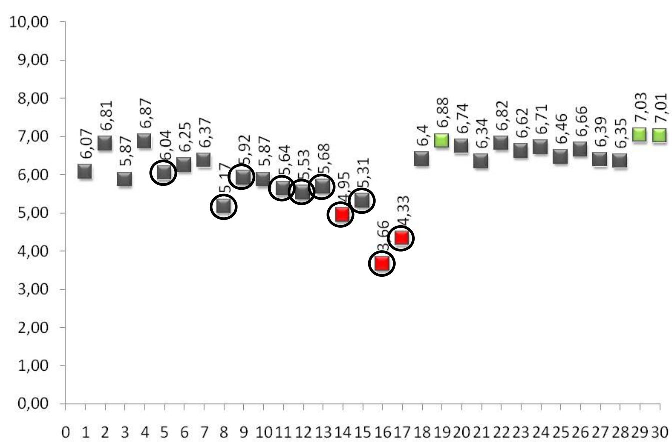

Figure 7: Sustainability scores of residential buildings (squares) and office buildings (squares and circles) for both stages. *(Source: Adapted from Barreto[12].)*

Residential building #29 – the Green Tower – is the better-scored building. This is not surprising, since it was one of the few buildings designed from the beginning with sustainability purposes, improving thermal comfort and reducing energy consumption. Residential building #30 also obtains a good score, due to its best classification in the construction stage, achieved through the use of covering materials with low embodied energy like natural stone.

At the bottom of the scale, office building #16 – the Zen Tower – have materials that contribute to its worst score like a metallic structure, large glazed area, metal roof, and HVAC system.

The distribution of sustainability scores, both in the construction and occupation stages can be seen in Fig. 8, which shows that the sustainability of buildings reaches medium–high values, with the large majority (25 buildings) displaying sustainability scores in the interval [6, 7].

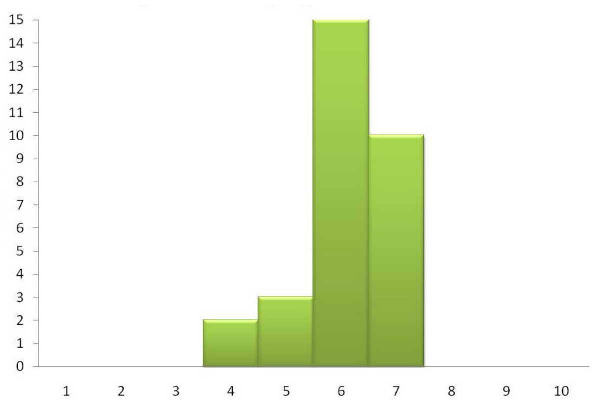

Figure 8: Distribution of the sustainability scores of all buildings, in the construction and occupation stages [12].

This analysis shows that it is possible to obtain a sustainability score in a simple way and easy understanding for professionals and non-professionals. It also shows the importance of materials choice and reaching a balance in the choice, taking into account the constructive factors such as embodied energy, landscape damage, and pollution, but also usage factors such as maintenance, durability, reuse, and recycling of materials.

It is recognized that the sustainability scores in the occupation stage should be the focus of more attention and require more tests, in order to be applied unambiguously.

The validation of this methodology through the monitoring of the construction or through the availability of this data with more precision by the municipal authorities would facilitate the data collection, leading toward the adoption of this assessment system for buildings. Thus, it is concluded that the methodology can be applied in this field of knowledge, being able to quantify the buildings sustainability, and establishing a decision support system for the architectural project design.

6 CONCLUSIONS

This paper highlights the importance of sustainability in the current context and the construction sector's impact on it.

It is implemented a methodology to quantify the buildings' sustainability in relative terms, basing the assessment on the materials' choice. Other criteria could be added to the set of variables used. The methodology is also useful in sustainability certification.

In some buildings it is perceived as the architecture and in particular, the selected materials can contribute to improving the environment. The buildings already included concerns about efficiency and comfort in their project design, which are shown through this analysis.

However, it is still possible to do better by introducing passive and even active measures such as solar energy and wind power.

The future of sustainability in the construction sector involves the environmental awareness of the project design team and the changing project design and construction habits. While there may have been significant steps in the path of sustainable construction, including the regulations aimed at improving the energy performance of buildings, it is important to emphasize that the path should also be covered in the preceding stages, i.e. before the buildings' construction. The Portuguese legislation is mainly focused on the use of the building, ignoring the constructive stage, equally important.

The findings presented in this paper are a starting point for further studies in other urban areas of Portugal, assessing the buildings and proposing solutions that improve the environmental performance of the construction sector.

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