Sustainability Assessment of Building Solutions
A Methodological Approach

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Keywords: Sustainability, Assessment, Building Solutions

Abstract: The building sector plays a major role in the sustainable development. It is responsible for a major part of the raw materials extraction, energy consumption, waste production and it is the centre of the human life: the major part of the human life is spent inside a building. Nowadays, the society is making an effort regarding environmental protection and building ambient quality and a greater attention is being given to pollution control, energy efficiency, proper waste disposal, heritage preservation, social integration, indoor ambient quality, etc. This paper presents a methodology for the comparative sustainability assessment of construction solutions. This first methodological approach allows the users to define and qualify the indicators that are related to the requirements of the assessment and the proprieties of building solution. With this methodology is possible to consider different alternatives for the buildings elements, aiming the selection of the most sustainable solution. At the end of this paper, the methodology will be applied to some conventional and non-conventional floors construction solutions in order to find, inside the sample, the most sustainable solution.

1 INTRODUCTION

Construction industry is one of the most important European economical sectors, but it still relies too much on traditional construction methods and unskilled handwork, being characterized by an excessive use of natural resources and energy. This implies great environmental, social and economical impacts that could easily be reduced. This industry, in general, and the buildings sector in particular, contributes to the degradation of the environment through the dilapidation of natural resources. Building construction consumes 40% of the raw stone, gravel, and sand globally used each year, and 25% of the virgin wood. Building also account for 40% of the energy and 16% of the water annually used worldwide (Roodman 1995). This reality is incompatible with the sustainable development aims that seek the balance between the environmental, economic and social dimensions.

One of the possible solutions for this problem is the use of building technologies more compatible with the environmental balance. In the last years, even with a small impact, an evolution in this domain has been observed, and now there are new materials and construction solutions more sustainable than the conventional ones.

In the majority of the less developed countries, this subject is still very recent. In these countries, the biggest part of the construction companies and the population in general, are not sufficiently informed about the individual and collective advantages of the "Sustainable Construction" concept. In the developed countries, this subjective is no more an environmentalist's exclusive flag, being nowadays one of the most important aspects in the global quality assessment of construction.

The sustainability of a building solution depends on the decisions taken by a large quantity of actors in the construction processes: owners, managers, designers, firms inhabitants, etc. Thus there is a necessity to help these actors to evaluate their choices in early stage of the projects.

This paper aims the developing of a methodology for the building design assessment, from a sustainable point of view. It is conceived to help the decision makers (engineers, architects, etc.) in the early stages of the projects, aiming the selection of more sustainable building solutions.

2 SUSTAINABLE ASSESSMENT METHODOLOGIES

In the sustainability assessment, several parameters could be analysed. The assessment needs the integration of a huge number of evaluation criteria, some quantitative, other purely qualitative. On the other hand, the way that each parameter influences the sustainability is neither consensual nor unalterable along the time. Therefore the assessment is very hard to carry out with a real methodological work.

The sustainability is a relative subject that should be assessed comparatively and relatively to the most widely used solution – conventional /reference solution – in a certain country/local. This way, comparing each of the selected sustainability indicators it is possible to verify, at the level of each one, if the solution under analysis is better or worse than the conventional one. The most sustainable solution depends on the technological limit of each moment.

In a building solution sustainability assessment process, the first step consists in gathering the most relevant functional and technical data about the construction solution. The second step consists in selecting an appropriate method that allows the quantitatively assessment of the sustainability. The methodology to adopt should be simple and flexible, to conveniently help the design teams in choosing a certain technology in detriment of others less sustainable.

In certain developed countries, some systems and tools for the sustainability assessment are being implemented or in the development phase, for instance, the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy & Environmental Design (LEED) and Green Building Challenge (GBTool).

The above methodologies aim the evaluation of the global sustainability of a building. Its application is complex and needs the anticipated knowledge of a great amount of data. Some of the sustainability assessment tools have datasheets that gather some of the needed data, although the data is related with the particular aspects of the country of origin, which turns its application in a different country very difficult. These systems focus mainly the building environmental impact assessment in a global perspective.

This way and for the propose of this work a methodology named Methodology for the Relative Assessment of the Construction Solutions Sustainability (MARS-SC), is presented (Mateus, 2004).

3 METHODOLOGY FOR THE RELATIVE ASSESSMENT OF THE CONSTRUCTION SOLUTIONS SUSTAINABILITY (MARS-SC)

In the MARS-SC the assessment of the sustainability is accomplished comparing the solutions that are being assessed with the most used solution – conventional/reference solution – in a certain place. In this methodology three groups of indicators are approached: environmental, functional and economic. The following paragraphs present the steps of the methodology.

3.1 Selection of indicators

The major function of the indicators is to characterize and quantify the criteria allowing choosing the best solution for the project. Since the indicators are the base of every sustainable assessment method, their selection is a very important step. The number and type of indicators evaluated should be compatible with the project requirements, specific characteristics of the building solution, its functional requirements and the available data. Table 1 presents some of the most important indicators that can be assessed in this method.

3.2 Quantification of indicators

Once the indicators were selected, they need to be quantified or qualified. To fulfil this objective the method of quantification should have been anticipated and different methods can be used: previous studies, expert's opinions, data base processing and simulation (Cherqui, 2004).

Table 1 Indicators that can be analysed in the MARS-SC methodology

Indicators		
Environmental	**Functional**	**Economical**
Global warming potential	Air born sound insulation	Construction cost
Primary energy consumption	Impact sound insulation	Utilization cost
Recycled content	Thermal insulation	Rehabilitation cost
Recycling potential	Durability	Demolition cost
Raw material's reserves	Fire resistance	Residual value
Eutrophication potential	Flexibility of use	End use treatment cost

3.3 Normalization of indicators

Normalization of indicators is necessary in order to avoid the scale effects in the averaging and solve the problem related to the fact that some indicators are the type "more is better" and others are the type "worse is better". The normalization used in this method consists in two steps.

The first step consists in the indexes quantification. The indexes represent the relationship between the value of an indicator in the solution under analysis and the value of the same indicator conventional solution. This way it is possible to verify, at the level of each indicator, if the solution under study is better or worse than the conventional construction solution. The indexes are quantified using equation 1 if the indicator is of the type "less is better". If the indicator is of the type "more is better" equation 2 must be used.

$$I_i = \frac{V_i}{V_i^*} \tag{1}$$

$$I_i = \frac{V_i^*}{V_i} \tag{2}$$

In these equations, I_i represents the relation between the outcomes of the i^{th} indicator in the solution under analysis *(V_i)* and in the conventional solution (V^*_i).

The second step consists in giving a score to each indicator *(N_i)*, once the indexes have been calculated. Using this system, the indicators of sustainability have no dimension and are bounded between -3 (worse value) and 3 (better value). If the score is negative the solution under analyse is worst than the conventional one, at the level of that indicator. Otherwise the solution is better. After the indexes quantification and using Table 2 it is possible to give a score to each indicator.

Table 2 Indicators score (N_i) through the value of the comparison indexes (I_i)

I_i	Score (N_i)
≤ 0.6	• 3
] 0.6; 0.8]	• 2
] 0.8; 1.0[	• 1
1.0	• 0
] 1.0; 1.2[	• -1
] 1.2; 1.4]	• -2
≥ 1.4	• -3

3.4 Graphical representation

Once the normalized values of each indicator have been calculated, they are graphically represented. The representation is global, involving all indicators evaluated and it is named Sustainable Profile. To fulfil this objective, the Amoeba or "radar" diagram is used. This way it is possible to have a clear and global representation of the solutions performance at the level of each indicator. Moreover, two or more solutions can be easily compared. As nearest to the centre of the diagram is the representation as worst is the solution.

3.5 Aggregation of the indicators

Assessing a solution across different fields and involves the use of several indicators. A long list of indicators and their respective values will only be useful in order to compare the solution at the level of each indicator and won't be useful to compare the performance of the solutions at the level of each requirement (environmental performance, functional performance and environmental performance). This way, the best solution is to combine, inside each group, the indicators with each other in order to obtain "global indicators", allowing assessing each objective of the project. With the aggregation it is possible to synthesise in a single value the performance of the indicator inside each group. In this method is used a complete aggregation method for each global indicator, according the following equations:

$$ND_A = \sum_{i=1}^{m} WA_i x NIA_i \quad (3)$$

$$ND_F = \sum_{i=1}^{n} WF_i x NIF_i \quad (4)$$

$$ND_E = \sum_{i=1}^{o} WE_i x NIE_i \quad (5)$$

$$\sum_{i=1}^{m} WA_i = \sum_{i=1}^{n} WA_i = \sum_{i=1}^{o} WA_i = 1 \quad (6)$$

In the equations, ND_A represents the aggregation of the environmental indicators; ND_F represents the aggregation of the functional indicators; ND_E is the aggregation of the economic indicators; WA_i, WF_i and WE_i represent, respectively, the weight of the i^{th} environmental, functional and economical indicator; m, n, o are, respectively, the number of environmental, functional and economical indicators in study; NIA_i, NIF_i, NIE_i represent, respectively, the normalized values of the i^{th} environmental, functional and economical indicator.

The weigh of each indicator in the quantification of the three performance scores is not consensual and is a major inconvenient of this method. The weights are strongly linked to the objectives of the evaluation: greater values should be given to indicators representative of criteria of major importance in the project.

At the level of the environmental indicators there are some studies which allow the near consensual definition of its weights. One of the most used is the study performed by the United States Environmental Protection Agency (EPA). EPA's study identified, for a list of twelve environmental indicators, the relative importance of each one among the others through their environmental pressure (EPA, 1990). MARS-SC uses, directly or by extrapolation, the weights presented in that study.

There are no studies about the functional indicators. Therefore, it is considered an equal weight distribution per each indicator. More consensual values could be possible making inquires to the potential users and using a Multi-attribute Decision Analysis methodology as the AHP (Analytic Hierarchy Process).

Measuring the economic performance of a building is more straightforward than, for instance measuring the environmental performance. Standardized methodologies and quantitative published data are readily available. Considering that the biggest period of the building's life cycle is the operation phase, in this method it is suggested that the maintenance and operational costs should have bigger weights than, for instance, the construction costs, in the economical performance assessment.

Another way of measuring the economic performance is using a life-cycle cost analysis method (LCCA). LCCA is a method for assessing the total cost of a facility owner-ship. It takes in account all costs of acquiring, owning, and disposing of a building or building system. LCCA is especially useful when project alternatives that fulfil the same performance requirements, but differ with respect to initial cost and operating costs, have to be compared in order to select the one that maximizes the net savings.

3.6 Quantification of the Sustainable Score

After evaluating the performance of the solutions in each global indicator (environmental, functional, social and economic) it is possible to define a single score (Sustainable Score) to evaluate the global performance. The sustainable score could be evaluated using the following formula (Bragança et al 2004):

$$SS = w_2.ND_A + w_2.ND_F + w_3.ND_E \qquad (7)$$

In this formula, *SS* (Sustainable Score) is the result of the weighting average of the solution performance in each indicator (ND_A – environmental; ND_F – functional; ND_E – economic) and w_j represents the weight of each indicator in the sustainability. In order to obtain a Sustainable Score bounded between *-3* and *3* the sum of all weights of formula 7 weigh must be equal to 1.

Nevertheless, this single score should not be used alone to assess the sustainability, since the compensation between the values of each parameter could cause some distortions in the results and moreover the solution has to be the best compromise between all different indicators: every indicator has to be represented.

The way that each indicator group influences the sustainability is also not consensual. Some results of the sustainability assessment have shown that the most compatible solutions with the environment are generally the most expensive. However, considering that the main goal of the concept "sustainable construction" is a bigger compatibility between the artificial and the natural environments, without compromising the functional performance, easily it's understood that the weight of the environment and functional indicators must be higher than the weight of the economic indicators in the sustainability evaluation. This way, MARS-SC uses the following distribution of weights: w_1 = 0.40; w_2 = 0.40; w_3 = 0.20.

Considering the sustainable score (*SS*) and using the Table 3 it is possible to classify the relative sustainability of a building solution.

Table 3 Classification of the relative sustainability of a building solution

SS	Classification of the Sustainability
<-1	• Mediocre
[-1, -0[	• Unsatisfactory
0	• Reference
] 0,1[	• Better
[1, 2 [	• Good
[2, 3]	• Very good
3	• Excellent

4 COMPARATIVE ASSESSMENT OF FLOOR SOLUTIONS

4.1 Methodology

The Methodology for the Relative Assessment of the Construction Solutions Sustainability (MARS-SC) is used in this assessment. The objective of this assessment is the evaluation of five floors assemblies, in order to find the must sustainable one. The requirements of this assessment are: two environmental indicators (global warming potential –GWP– and primary energy consumption –PEC–); three functional indicators (airborne sound insulation – $D_{n,w}$ –, impact sound insulation –$L'_{n,w}$– and thermal insulation –U–); and one economic indicator (construction cost –CC–).

The global warming potential (GWP) is expressed in units of carbon dioxide (CO_2) equivalents. Of gases that increase the greenhouse effect, the most common is carbon dioxide, which is released from most industrial processes, primarily as a result of burning of fossil pollutants (Berge 2004). The materials Primary Energy Consumption (PEC), means the energy resources spent for its production, including the energy directly related to the extraction of raw materials, their processing and the energy needed for their transport. As lower are these two environmental indicators as lower is the environmental pressure of the solution.

The airborne sound insulation index ($D_{n,w}$) is evaluated using the analytical methodology proposed by Meisser (1973). The impact sound insulation index ($L'_{n,w}$) was predicted using the invariant method. The presented U values are the average of the ascendant and descendent U values of each solution.

For the economic assessment, the presented construction costs (CC) values are based on the actual unitary prices of the Portuguese construction market.

The weights considered in the quantification of global indicators (*NDi*) and in the quantification of Sustainable Score (SS) are presented in Table 4.

Table 4 Weights considered in the assessment

Group	Indicator	Indicator's weight	Group's weight
Environmental	GWP	0.75	0.40
	PEC	0.25	
Functional	$D_{n,w}$	0.33	
	$L'_{n,w}$	0.33	0.40
	U	0.33	
Economic	CC	1.00	0.20

4.2 Characterization of the building solutions

The conventional/reference solution (floor 1) is one of the most used floor assemblies in the North of Portugal. The solution is a ceramic pot and beam slab.

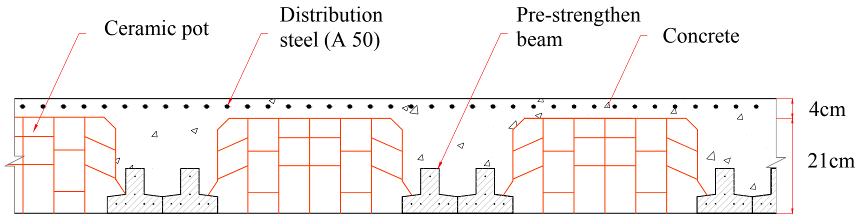


Figure 1 Cross section of the conventional/reference solution (Floor 1)

Besides the conventional solution, more four building solutions were assessed. All solutions were defined aiming an equal structural performance.

The other analysed building solutions were:

Floor 2) Reinforced concrete slab (Figure 2).

Floor 3) Hollow concrete panel slab (Figure 3).

Floor 4) Steel and concrete composite slab with collaborating steel moulds (Figure 4).

Floor 5) Wood slab (Figure 5).

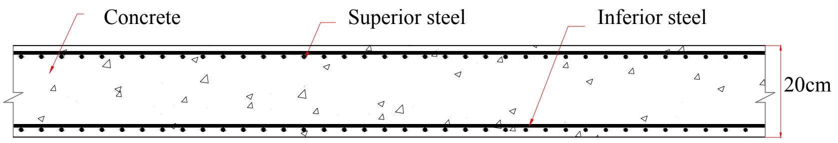


Figure 2 Cross section of Floor 2

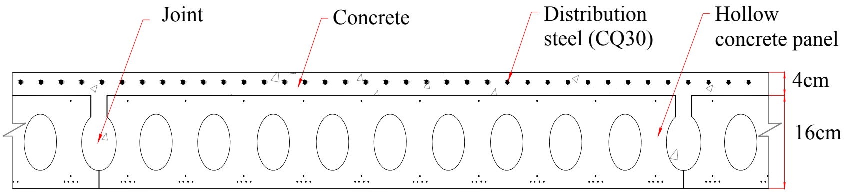


Figure 3 Cross section of Floor 3

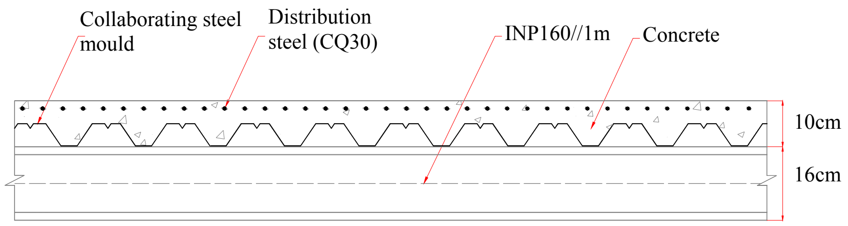


Figure 4 Cross section of Floor 4

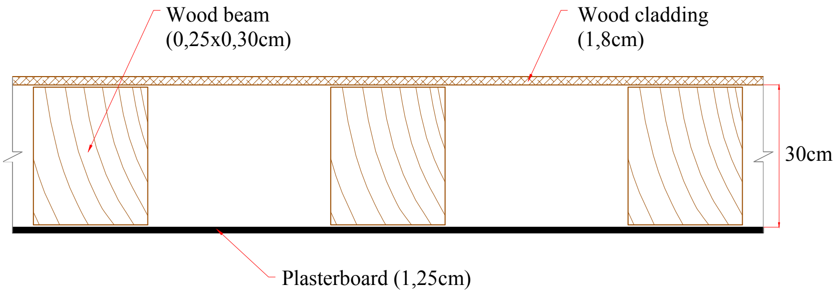


Figure 5 Cross section of Floor 5

4.3 Results

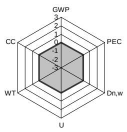
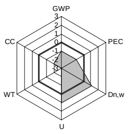
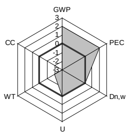
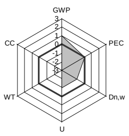
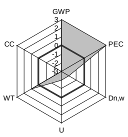
Table 5 presents the outcome of the indicators quantification. Table 6 presents the sustainable profile, the global indicators and the sustainable score, for each building solution.

Table 5 Value of indicators

Indicator	Floor 1	Floor 2	Floor 3	Floor 4	Floor 5
GWP (g/m^2)*	42 809.04	46 235.87	33 720.90	38 925.53	7 244.25
PEC (k.W.h/m^2)*	177.38	186.84	137.32	176.97	46.14
$D_{n,w}$ (dB)	53	55	53	49	38
$L'_{n,w}$ (dB)	75	78	75	84	83
U (W/m^2.ºC)	2.35	3.50	2.89	4.95	1.90
CC (€/m^2)	35.45	47.90	113.50	66.45	166.80

* Source: This data is based in the unitary values that Berge (2000) presented for Central Europe.

Table 6 Sustainability of the construction solutions

Construction solution	Sustainable profile	Global Indicators			Sustainable score (SS)	Relative sustainability
		Env. (ND_A)	Fun. (ND_F)	Econ. (ND_E)		
Floor 1		0.0	0.0	0.0	0.0	Reference
Floor 2		-1.0	-0.3	-2,0	-0.9	Unsatisfactory
Floor 3		2.0	0.7	-3.0	0.5	Better
Floor 4		0.8	-1.7	-3.0	-1.0	Unsatisfactory
Floor 5		3.0	-0.7	-3.0	-0.3	Unsatisfactory

4.4 Discussion

The assessment of the sustainability will come from the visualization of the sustainable profile, and from the interpretation of global indicators and the sustainable score. The worst solution is the nearest to the diagram's centre.

Inside the analysed sample and in accordance with the considered indicators and their respective weight, the results show that the most sustainable solution is the hollow concrete floor assembly (floor3). This solution is optimised for environmental performance and is slightly better than the conventional solution for the functional performance. The most important lack of it is the higher construction cost. The worst solution is the composite floor with collaborating steel moulds (floor 4). This solution is slightly better than the conventional solution at the level of environmental performance but there are very important lacks in the functional and economic fields.

The results illustrate that floor 5 has the best environmental performance, the functional performance is optimised in floor 3 and the economic performance is optimised in the conventional floor (floor 1).

This way the actors in the building process could easily compare the sustainability of the possible solutions in order to select the most sustainable one. Moreover in this methodology the user can identify the weak spots of each solution. Therefore, using an interactive process, it is possible to search for different ways to improve the solution.

5 CONCLUSION

The project teams have big responsibilities in searching the sustainability in the building and real estate sectors, through the selection of construction solutions with improved environmental, functional and economical performances, during their entire life-cycle.

Despite of numerous studies on sustainable indicators, there is a lack of a consensual methodology for the sustainability assessment. The development and use of consensual methodologies for building design, construction and rehabilitation processes, from a sustainable point of view, are fundamental aspects for these goals.

The results of the sustainable assessment depend, above all, in the indicators used in the building solution assessment. Therefore, the future work is defining precisely an objective set of indicators adapted to each building element (roof, floor, interior wall, exterior wall, etc).

The presented results and methodology intends to be a contribution to the sustainability in the construction industry domain, through the use of construction solutions with improved environmental, functional and economical performances.

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