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DEFINITION OF A WEIGHTING SYSTEM FOR ECONOMIC SUSTAINABILITY OF BUILDINGS

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ABSTRACT

Assessment systems and sustainability certification of buildings play an important role in the design, construction, operation, maintenance and decommissioning of a building. The Methodology of Assessment of Economic Performance of Residential Buildings (MAEP-RB) is an innovative approach for the systematic assessment of economic performance and sustainability index, based on the Life Cycle Analysis (LCA) according to EN 16627:2015. The method is based on the before-use phase of the building, and allows the comparison of different building solutions with the same functional equivalent, in terms of economic performance. The purpose of this paper is to present the results obtained through questionnaires to civil engineering professionals, of the application of Analytic Hierarchical Process (AHP) for the determination of the hierarchical structure of the weighting system of MAEP-RB in order to achieve a consistent and rational model of analysis.

1. Introduction

The European Standards Set developed by CEN / TC 350 "Sustainability of Construction Works", proposes a system for the assessment of the sustainability of buildings quantifying impacts and aspects to assess the environmental, social and economic performance of buildings, using quantitative and qualitative indicators, measured without value judgment. This system is based on a Life Cycle Assessment (LCA). Based on these, an approach has been developed for systematically assessing the economic performance of a building within the

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concept of sustainability (Methodology of Assessment of Economic Performance – Residential Buildings: MAEP-RB) in the before-use phase as defined in EN 15643-4:2012 [1] and EN 16627:2015 [2]. The assessment of economic performance of a building expressed in monetary terms and at the same time in the allocation of economic sustainability levels for a building needs the definition of a system of weights based on the hierarchical structure of attributes. This system of weights will allow the possibility of integration of MAEP-RB in a global evaluation of sustainability, in which environmental, social and economic dimensions are simultaneously considered. In MAEP-RB, the assessment of the level of economic performance and economic sustainability of a building are achieved by aggregating the attributes at each of the level of the hierarchical structure of the method: parameters, indicators, modules and stages of the life cycle. Although there is no doubt that there are some attributes that are more important to the economic sustainability than others, there is currently no universally accepted method for the definition of the relative weight of each attribute. The weight system adopted depends, among other factors, on the context and local priorities and on the different opinions of different stakeholders in the life cycle of buildings. This paper aims to present the results, obtained through questionnaires sent to 40 civil engineers, for the application of Analytic Hierarchical Process (AHP) for the determination of the hierarchical structure of the weighting system of MAEP-RB in order to achieve a consistent and rational model of analysis. The mathematical formulation of the AHP is presented as well as the developed tool for its application to the hierarchical structure of MAEP-RB. The relative weights calculated for the different levels of the hierarchical structure of MAEP-RB are presented.

2. Methodology MAEP-RB

The MAEP-RB methodology was developed in order to allow the assessment of economic performance and the level of economic sustainability of a residential building during the design phase, based on the expected behaviour for the entire building life cycle. It is a modular approach for compiling information throughout the building's life cycle including the four phases of the life cycle of a building: *before-use* phase, *use* phase, *end-of-life cycle* phase and *beyond-life cycle* phase. Each phase of the life cycle is divided into stages, modules, indicators and parameters. For the moment, MAEP-RB is developed only for the *before-use* phase. The object of assessment is the building, including its foundations and landscaping within the building perimeter [3]. Table 1 shows the hierarchical structure of the method (stages, modules, indicators and parameters) that correspond to the *before-use* phase. At each level, information is obtained by aggregating information at the lower level. For example, each of the twenty-one economic indicators (Level 3, indicators A0.1 to A0.2, A1.1, A2.1, A3.1, A4.1 to A4.2 and A5.1 to A5.14) is estimated by aggregating the results of one or more parameters (Level 4, parameters P1 to P65), following the hierarchical structure presented in Table 1. The assessment of the economic performance of the *before-use phase* is obtained by aggregating of the results of each stage of the building's life cycle (Level 1).

3. Analytic Hierarchy Process

The Analytic Hierarchical Process (AHP) is a multi-attribute decision analysis technique that belongs to the group of simple additive methods. It can be applied to problems where the decision-maker must sort or choose one out of a finite number of alternatives, which are measured by two or more relevant attributes. Overview of the main methods can be found in the vast literature available on the topic, such as Hwang [4] and Chen [5].

Table 1. Stages, modules, indicators and parameters of the MAEP-RB Methodology

Level 1 Stages	**Level 2 Modules**	**Level 3 Indicators**	**Level 4 Parameters**
Pre-construction Stage (PCS)	A0:Site and associated fees and counselling	A0.1: Cost of purchase and rental incurred for the site or any existing building.	P1 to P3
		A0.2: Professional fees related to the acquisition of land.	P4 to P8
Product Stage (PS)	A1:Supply of raw materials	A1.1: Cost of raw materials.	P9
	A2:Transport of raw materials	A2.1: Cost of transportation of raw materials.	P10
	A3:Manufacturing	A3.1: Cost of transformation raw materials.	P11
Construction process Stage (CPS)	A4:Transport	A4.1: Cost of transport of materials and products from the factory gate to the building site.	P12
		A4.2: Cost of transport of construction equipment such as site accommodation, access equipment and cranes to and from the site.	P13
	A5:Construction-installation process	A5.1: Costs with exterior works and landscaping works.	P14 to P20
		A5.2: Cost of storing products including the prevision of heating, cooling, humidity etc.	P21
		A5.3: Cost of transportation of materials, products, waste and equipment within the site.	P22
		A5.4: Cost of temporary works including temporary works off-site as necessary for the construction.	P23
		A5.5: Cost on site production and transformation of a product.	P24 to 27
		A5.6: Cost of heating, cooling, ventilation, humidity control, etc. during the construction process.	P28 to 29
		A5.7: Cost of installation of the products into the building including ancillary materials.	P30 to P32
		A5.8: Cost of water used for cooling, of the construction machinery or on-site cleaning.	P33
		A5.9: Cost of waste managing processes of other wasters generated on the construction site (RCD).	P34 to P36
		A5.10: Transportation cost of waste RCD.	P37
		A5.11: Costs of commissioning and handover related costs.	P38 to P44
		A5.12: Cost for professional fees related to work on de project.	P45 to P48
		A5.13: Costs of the taxes and other costs related to the permission to build and inspection or approval of works.	P49 to P64
		A5.14: Incentives or subsidies related to the installation.	P65

Parameter description is presented in Annex.

In the absence of an objective basis for considering sustainability parameters, the AHP is suggested to determine the weighting of the attributes of the hierarchy by a number of authors Norris [6], Cole [7]. The AHP was originally developed and applied by Saaty [8], and is a fully compensatory analytical tool, applicable to multi-attribute decision problems that can be formulated as a decision tree, where each hierarchical level involves several types of attributes. The decision problem in AHP is to compare the relative importance of attributes in a systematic and quantitative way. Mathematically, the objective is to determine the non-negative weights w_i of attributes (for i varying from 1 to n, where n is the number of attributes). If the weight vector $w = (w_1, ..., w_n)$ is known, the relative importance of attribute A_i compared to attribute A_j, a_{ij}, would be given by the ratio w_i / w_j [9]. All possible n column vectors can be combined in a matrix A. The AHP approach assumes that the comparison matrix A has three special properties: (i) Identity: all diagonal elements of the matrix are equal to 1, because an attribute is always as important as itself; (ii) Reciprocity: if an attribute A is x times more important than an attribute B, then, the attribute B is 1/ x times more important than attribute A. According to this principle, the terms of matrix A read $a_{ij} = 1/a_{ji}$, for all i and j; and (iii) Consistency: for consistency it is meant that, if there are three attributes A, B and C, if A is x times more important than B, and B is y times more important than B, then, A must be xy times more important that C. In this case, by linear algebra, the vector of weights, w, is the eigenvector of the matrix A, with eingenvalues λ, such that $Aw = \lambda w$. With this particular procedure, the AHP formalizes the conversion of a problem of assigning weights to attributes in a more tangible problem of comparing the relative importance of pairs of attributes competing attributes. This series of comparisons is summarized in square matrices, containing the relations between the compared attributes, as presented in Table 2.

Table 2. General form of comparison matrix

	Attribute 1	**Attribute 2**	**Attribute 3**
Attribute 1	1	Importance of Attribute 1 compared to Attribute 2	Importance of Attribute 1 compared to Attribute 3
Attribute 2	Importance of Attribute 2 compared to Attribute 1	1	Importance of Attribute 2 compared to Attribute 3
Attribute 3	Importance of Attribute 3 compared to Attribute 1	Importance of Attribute 3 compared to Attribute 2	1

For the comparison of attributes, a 5-point scale was adopted (4 – much more important; 2 – much important; 1 – equally important; ½ – less important; ¼ – much less important) to avoid incompatibility problems that might occur when three or more attributes are compared [10]. The calculation of the eigenvector of the matrix A can be performed using a simplified approach that calculates the geometric mean of each row [11, 12]. In this case, the normalized weights w_i corresponding to each attribute can be obtained by:

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}\right)}, \quad \text{for} \quad i = 1, n, \quad \text{with} \quad \sum_{i=1}^{n} w_i = 1 . \tag{1}$$

The calculation of the maximum eigenvalue, $\lambda_{\text{máx}}$, associated with the calculated vector can be calculated by:

$$\lambda_{\text{máx}} = \frac{1}{n}\sum_{i=1}^{n}\frac{(Aw)_i}{w_i}. \tag{2}$$

The decision matrix is reciprocal, positive and consistent and has only one nonzero eigenvalue $\lambda_{\text{máx}} \geq n$. The consistency index (*CI*) is defined by $CI = (\lambda_{\text{máx}}-n)/(n-1)$. The consistency index calculated for the decision matrix is compared with the value of the Random Index (*RI*) to provide the consistency ratio (*CR*) so that $CR = CI / RI$. If the *CR* is less than 0,10 then the judgments used to build the decision matrix are considered to be consistent. Otherwise, there is some inconsistency in the judgments and the values of the decision matrix should be revised. The *RI* for the matrix of order *n* can be found in Saaty [13].

4. Application of AHP to MAEP-RB

To structure a problem means to hierarchically divide it into a number of attribute levels, so that each of them is a member of a small group at the same level, all related to a single attribute to the next higher level. The AHP was used to define the weight system of the hierarchical structure of MAEP-RB, consisting of the four illustrated previously defined levels of attributes (level 1: stages; level 2: modules; level 3: indicators; and level 4: parameters). Table 1 shows the hierarchical structure of the MAEP-RB methodology and indication of the attributes of hierarchy levels for the application of AHP. To define the hierarchical structure of the weight system of MAEP-RB methodology, the construction of 31 comparison square matrices ($n \times n$) with different sizes was necessary at all levels of the attribute hierarchy. Table 3 shows the different matrices and respective sizes at all levels [14].

Table 3. The number of comparison matrices by level according to the order

Order Matrix	**1×1**	**2×2**	**3×3**	**4×4**	**5×5**	**7×7**	**14×14**	**16×16**
Level 1			PCS/PS/CPS					
N.º Matrices			1					
Level 2	A0	A1/A2/A3	A4/A5					
N.º Matrices	1	1	1					
Level 3	A1.1/A2.1 A3.1	A0.1toA0.2 A4.1toA4.2					A5.1toA5.14	
N.º Matrices	3	2					1	
Level 4	P9toP13 P21/P22 P23/P33 P37/P65	P28toP29	P1toP3 P30toP32 P34toP36	P24toP27 P45toP48	P4toP8	P14toP20		P38toP44
N.º Matrices	11	1	3	2	1	2		1
Total Matrices	15	4	5	2	1	2	1	1

The hierarchical structure of attributes of MAEP-RB methodology is repeated and detailed in the construction of a Microsoft Excel spreadsheet, where the attributes are compared pairwise. To facilitate interaction with the user and to reduce the filling time, only the upper diagonal of the comparison matrix is accessible for filling, by selecting the values set in the scale of importance (4, 2, 1, ½, ¼). The lower diagonal of the matrix and the column of the relative importance (weights) are automatically calculated.

The inquiry submitted to the 40 civil engineers followed the formatting of the matrices of comparisons "peer-to-peer" among all the attributes that constitute the hierarchical structure of the MAEP-RB methodology and the first page contains the following instructions needed to complete it:

a) To fill only the cells light blue, following the scale of relative importance (¼; ½; 1; 2; 4);

b) The blank fields (matrix diagonal) always have a fixed value = 1;

c) The fields in gray are automatically populated;

d) The relative importance of Wi alternatives (%) is calculated automatically;

e) Check that the consistency ratio (RC) value is less than or equal to 0,10;

f) If yes, "OK !, Go to next page!";

g) If not, "Please review your values!".

An example is shown in Fig. 1 where the pair comparison matrix between the attributes of Level 1: *Stages* for the *before-use phase* is presented. It is 3×3 matrix, and the relative importance and the Consistency Ratio are also presented.

Scale of relative importance	
Much more important	4
Much important	2
Equally important	1
Less important	1/2
Much less important	1/4

	Pre-construction Stage	Product stage	Construction process stage	Relative importance (w_i)
Pre-construction Stage (PCS)	1	2	½	0,286
Product stage (PS)	½	1	¼	0,143
Construction process stage (CPS)	2	4	1	0,571
Consistency Ratio (CR) = 0,000 < 0,10 OK!				

Figure 1. Pairwise comparison matrix for the before-use phase

After filling the matrix, the Consistency Ratio (CR) is automatically calculated and if the value is less than 0,10, then the comparison matrix of judgments is considered consistent with "*CR < 0,10 OK Go to next page!*" being displayed . If not, there is some inconsistency in judgments and the expert is required to review his/her opinion by the message "*RC > 0,10 Please review your values!*"

5. Results and Discussion

From the 40 questionnaires sent, only answers from 22 civil engineers were received. The values of the relative weights W_i (%) between the attributes of the hierarchical structure resulting from the evaluation of the 22 civil engineers allowed the determination of the relative weights W_i (%) between attributes of each level of the hierarchical structure of the methodology [15]. See Table 4.

The AHP was used to define the weight system of the hierarchical structure of MAEP-RB, consisting of the four previously defined levels of attributes (level 1: stages; level 2: modules; level 3: indicators; and level 4: parameters). For the definition of the system of weights, a AHP tool was developed, using Microsoft Excel with Visual Basic macros. At the lowest level, parameters, a total of thirty-one comparison matrices of various orders were defined: 15(1×1); 4(2×2); 5(3×3); 2(4×4); 1(5×5); 2(7×7); 1(14×14); 1(16×16). Systematic comparisons of successive elements pairs were performed for each matrix and the respective weights calculated.

Table 4. Relative weights

Weights for the level 1 attributes: before use phase

Weights	0.319	0.122	0.559
Stages	Pre-construction	Product	Construction process

Weights for the Level 2 attributes: stages

Stages	Pre-construction	Product			Construction process	
Weights	1.000	0.327	0.191	0.483	0.279	0.721
Modules	A0	A1	A2	A3	A4	A5

Weights for the Level 3 attributes: modules (indicators A0.1 to A5.14)

Modules	A0		A1	A2	A3	A4	
Weights	0.73	0.27	1.00	1.00	1.00	0.58	0.42
Indicators	A0.1	A0.2	A1.1	A2.1	A3.1	A4.1	A4.2

Modules	A5													
Weights	0.09	0.05	0.06	0.07	0.08	0.06	0.06	0.06	0.07	0.06	0.07	0.08	0.07	0.11
Indicators	A5.1	A5.2	A5.3	A5.4	A5.5	A5.6	A5.7	A5.8	A5.9	A5.10	A5.11	A5.12	A5.13	A5.14

Weights for the Level 4 attributes: indicators (parameters P1 to P65)

Indicators	A0.1			A0.2					A1.1	A2.1	A3.1	A4.1	A4.2
Weights	0.57	0.22	0.21	0.38	0.20	0.16	0.13	0.13	1.00	1.00	1.00	1.00	1.00
Parameters	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13

Indicators	A5.1							A5.2	A5.3	A5.4	A5.5			
Weights	0.17	0.18	0.13	0.19	0.16	0.10	0.08	1.00	1.00	1.00	0.47	0.22	0.17	0.14
Parameters	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27

Indicators	A5.6		A5.7			A5.8	A5.9			A5.10	A5.11						
Weights	0.58	0.42	0.50	0.31	0.19	1.00	0.42	0.33	0.26	1.00	0.15	0.15	0.16	0.16	0.15	0.12	0.11
Parameters	P28	P29	P30	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40	P41	P42	P43	P44

Indicators	A5.12				A5.13						
Weights	0.36	0.23	0.20	0.21	0.06	0.10	0.05	0.05	0.05	0.05	0.05
Parameters	P45	P46	P47	P48	P49	P50	P51	P52	P53	P54	P55

Indicators	A5.13 (Continue)									A5.14
Weights	0.05	0.06	0.08	0.07	0.06	0.05	0.05	0.06	0.10	1.00
Parameters	P56	P57	P58	P59	P60	P61	P62	P63	P64	P65

The values of Consistency Ratio determined for this set of 31 matrices vary between 0,00 and 0,05, the maximum value corresponding to the matrix of order (14×14). The same procedure was developed for all the four levels.

The results obtained indicate that the construction process stage is the most relevant, accounting for 55,9% of the economic building sustainability in the before-use phase. The *pre-construction stage* (31,9%) has twice the importance of the *product stag*e (12,2%). At the modules level, and within the economic indicators, the economic indicator A5.1 (*Costs with exterior works and landscaping works*) and A5.5 (*Costs on site production and transformation of a product*) are those that have a bigger impact in A5 module (*Construction installation process*), with 9% and 8%, respectively.

6. Conclusions

The definition of the relative importance of the different attributes of the hierarchical structure, a system of weights, is one of the most critical points in the development of an assessment methodology such as MAEP-RB. Although there is no consensus regarding the definition of a method for determining the relative weights, the AHP tool used in the survey formulation of 22 civil engineers produced satisfactory results.

The resulting weights system of the survey refers to all levels of the hierarchical structure of the methodology. That is to say all parameters, indicators, modules and stages are assigned relative weights. The knowledge of the relative weights allowed determining the global weights, which are very useful in comparative studies of economic sustainability of buildings. It clarifies the influence of a parameter, an indicator, a module or a step on the sustainability index obtained for the building in the *before-use* phase. This information, when available in the design phase, is of the utmost importance, as it will serve as a guide for the project team, in search of the improvement of sustainability, since there are parameters with bigger influence in the final evaluation than others.

ANNEX – PARAMETER DESCRIPTION

P1:Costs with the site;
P2:IMT – Municipal tax on onerous transfer of property;
P3:IS – Stamp tax;
P4:Costs related to real estate;
P5:Costs of viability studies;
P6:Costs of legal support;
P7:Costs related to the notary fees;
P8:Costs related to the land registry fees;
P9:Percentage cost of each type of material used;
P10:Percentage cost of each type of material used;
P11:Percentage cost of each type of material used;
P12:Percentage cost of each type of material used;
P13:Percentage of the cost of the building site;
P14:Cost for the earthmoving work;
P15:Cost of support structures and sealing;
P16:Cost concerning pavements;
P17:Cost relative to hydraulic networks;
P18:Cost related to outdoor lighting;
P19:Cost related to recreational equipment;
P20:Cost of sowing and planting;
P21:Percentage of cost for each type of material used;
P22:Cost of equipment related to the achievemen of the subcomponents of the building;
P23:Cost construction site percentage of the total value of direct costs;
P24:Cost of hand labour;
P25:Cost of equipment;
P26:Cost of fuel;
P27:Cost of water;

P28:Cost of equipment;
P29:Cost of electricity;
P30:Cost of hand labour;
P31:Cost of equipment;
P32:Cost of auxiliary materials;
P33:The cost of cooling water and cleaning;
P34:Cost of the screening process of RCD;
P35:Cost of packaging of RCD;
P36:Tax amount;
P37:Cost of transporting the RCD;
P38:Cost of the extension of domestic wastewate sanitation;
P39:Cost of the extension of sanitation storm water;
P40:Cost of extension of water supply;
P41:Cost of extension of electricity;
P42:Cost of extension of gas supply;
P43:Cost of extension of telecommunication;
P44:Cleaning cost;
P45:Fees of the project team;
P46:Fees of the inspection team;
P47:Fees the technical director;
P48: Fees of the health and safety at work team;
P49:Value of the license fee projects;
P50:Value of building permit fee;
P51:Exchange certifications gas project;
P52:Certification fee thermal design;
P53:Certification fee of electrical design;
P54:Rate design verification of fire safety;
P55:Certification fee of telecommunications project;
P56:National health service project certification fee;
P57:Certification fee of the gas network;
P58:Rate of energy certification;
P59:Certification fee electricity grid;
P60:Certification fee telecommunications network;
P61:Rate survey of municipal services;
P62:Rate survey of the firefighters;
P63:Survey national health service fee;
P64:VAT rate;
P65: Value of the incentive

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