

## Selecting Criteria for Assessing “Environmentally-Friendly” Material Options in Construction: Part II

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**Abstract.** *One of the design team's tasks is assuring that their project has a low negative impact on the environment. This comes from regulations as well as expectations of direct benefits (reduction of operating cost, the project's improved image in the eyes of the public, etc.). To fulfill this task, one needs to define criteria for assessing the design options. These are to correspond to the individual qualities of the project, and they should be significant and possible to assess. The paper, divided into two parts, presents a review of the literature concerning the criteria for the assessment of design solutions defined as "green" or "environmentally friendly". Part I presented the method of the analysis and investigates into the number and type of criteria adopted in the sample of papers being the object of analysis. This part focuses on the ways of defining criteria values, weights, and methods of multicriteria assessment.*

**Keywords:** *Sustainable Construction, Component Selection, LCA, Literature Review.*

### 1 Introduction

In the face of resource depletion and the likely suffocation with its own refuse within decades, humanity is dragged towards a sustainable economy and, in particular, sustainable construction (Goh, Chong, Jack and Mohd Faris, 2020). One of the aspects of construction sustainability is reducing the project's and the resulting built facility's impact on the environment. This impact is typically assessed in the course of a Life Cycle Analysis (LCA) (Ortiz, Castells and Sonnemann, 2009). The idea of LCA evolved into many methodologies that share the element of assessing the consequences of using particular construction materials in the building's fabric. However, even in this narrow aspect, the analyses' scope, criteria, and measures are not identical (Park, Yoon and Kim, 2017). The standards and methodologies evolve (Allacker, Mathieux, Pennington and Pant, 2017). Due to the proliferation of LCA methodologies, the comparability of information on products' environmental qualities becomes an issue (European Union, 2013).

This paper is a second part of the review of the most recent literature on selecting the “environmentally friendly” material and component options in construction. The authors discuss a sample of papers devoted to assessing the sustainability of alternative solutions (materials, material supply chains, component design) and optimizing construction components, focusing on the ways of defining criteria values, the criteria's relative importance, and selecting the methods of multicriteria assessment.

## 2 Materials and Methods

The sources' approach to the life cycle phases was juxtaposed to the life cycle phases used in LCA and adopted for Environmental Product Declarations (EPDs). The “environmentally friendly” aspects were considered only those covered by the scope of environmental impacts, aspects of resource use, and generation of waste as defined in EPDs prepared according to EN 15804:2012. The query was limited to one database (Web of Science), publications from the years 2016-2020, and a particular structure of search terms, as presented in Part I. The selection was manually refined. The final sample comprised 43 publications. The sample was analyzed in terms of aspects of sustainability covered by the analysis, life cycle stages considered, sources of input, and mathematical methods used for selecting the best option (if applicable).

## 3 Results and Discussion

77% of papers of the sample focused on assessing the sustainability of alternative solutions. The problems differed much in terms of the object of the analysis: from comparing particular types of materials in the context of a local market, through types of complex components of buildings or civil engineering structures, to alternative ways of conducting whole projects or selecting supply chains to serve certain projects or regions.

Table 1 list the papers whose authors proposed some form of an integrated measure of sustainability with reference to alternative construction products (like bricks, windows, water pipes, paints) offered in a particular market.

**Table 1.** Works on ranking or selecting most sustainable construction products in a certain market/region (not adopting a project perspective).

Paper	Aspects	Life cycle	Criteria list	Weights, method of calculation	Env. criteria	Criteria values:	Method, output
(Govindan <i>et al.</i> , 2016)	Ec, En, S	not explicit	Arbitrary	M. experts, DEMATEL +ANP	10	Expert ratings: 1-5 scores used in example	TOPSIS, combined index
(Bissoli-Dalvi <i>et al.</i> , 2016)	En	A-D	Arbitrary	1 expert, ISMAS	7	Expert: ratings in 3-level scale	ISMAS, combined index
(Roy <i>et al.</i> , 2019)	Ec, En, S	not explicit	Arbitrary	M. experts, fuzzy pairwise comparisons, linear programming; sensitivity analysis	4	M. experts,, Fuzzy ratings	IVIF-CODAS. combined index
(Zhang <i>et al.</i> , 2017)	T, Ec, En	A1-A3+ disposal	Arbitrary	M. experts, DEMATEL +ANP; sensitivity analysis	5	Expert ratings in scale 1-5 in example	G-TOPSIS, combined index
(Mathiyazhagan <i>et al.</i> , 2019)	Ec, En, S	not explicit	team of experts /literature	M. experts, integrated by averaging; BWM	9	Expert ratings	fuzzy TOPSIS, combined index
(Rochikashvili and Bongaerts, 2016)	T, Ec, En, S	not explicit	Arbitrary	M. experts, ANP	1	Expert pairwise comparisons	ANP, combined index
(Maiolo <i>et al.</i> , 2018)	T, Ec, En	A1-A3	LCA (Impact 2002+)	Acc. to Impact 2002+	n/a	databases & calculations	multiplying two indices, combined index

A common feature of these papers is analyzing the options in abstraction from projects they might be used for. In this group, all papers but two presented analyses from the perspective of developing countries and based on criteria values rated by experts (though some methods were applicable also for measurable criteria).

For instance, Govindan, Madan Shankar, & Kannan (2016) used DEMATEL combined with ANP to establish the set of criteria and their relationships on the basis of opinions of multiple experts, and then TOPSIS for the assessment of options. They illustrated their approach on the example of selecting the “most sustainable” type of brick as perceived by the construction professionals (clients, architects, contractors) in UAE market. In this case, all 10 criteria related to the environmental impact would be possible to express as quantitative measures established in the course of LCA, but the authors were vague about the way of the source of their values; judging by the presentation of illustrative example, the values were expressed as arbitrary scores in a 1-5 scale. Bissoli-Dalvi *et al.* (2016) compared the sustainability of different types of windows used in Brazilian housing using an original ISMAS method. Due to the lack of databases of environmental product properties, they resorted to an individual set of “green” criteria and expressed their values by ratings in a unified 3-point scale (-1 for “worse than average requirements”, 0 for “standard practice”, 1 for qualities considered “better than acceptable”). The ratings were then treated as additive scores that, after being weighted, were combined into a quantitative index for direct comparison of options.

Rochikashvili and Bongaerts (2016) aimed at conducting the comparison of products to appeal to non-experts. For this reason, the authors did not use precise measures of environmental impact. Their criteria were selected arbitrarily and grouped into 4 categories: benefits, costs, opportunities, and risks. The sub-criteria related to the environmental impact belonged to the latter. Maiolo *et al.* (2018), to select the best type of water pipes applicable in particular soil conditions, conducted a thorough LCA (cradle to gate) of 10 products offered in the market using Impact 2002+ methodology, assuming Western European conditions. Then they combined its overall measure of environmental profile with the coefficient capturing mechanical properties. This was the only paper from this group resting upon precise measures of environmental impact.

Shipping large quantities of materials, as required in the case of construction projects, generates high cost, consumes fossil fuels and pollutes the natural environment. Therefore, the A2 and A4 phases of the lifecycle are a natural focus of construction sustainability researchers. In the sample, two papers were devoted to analyzing supply chains. Ahmadian *et al.* (2017) considered different sources, levels of prefabrication, modes and distances of transport. Designing their BIM-based supply chain management system, they argued that the environmental criteria should be project-specific and might be defined by experts, though they should refer at least to the material production, transport to the site and installation phase, as well as they should consider the potential of re-use and recycling. Basti (2018) analyzed the problem managing large quantities of earthquake debris, a current problem of Italian regions struck by natural disasters. He focused on environmental issues of deconstruction, transport, depositing, and reusing this material, as well as on constraints resulting from regulations. This was done not in a “per project” approach, but from the point of municipal strategies that consider the network of local enterprises to be engaged in the process, restrictions on road use for heavy transport, selection of means of transport with regard to location of debris processing, landfilling and reuse areas.

The biggest part of the sample of papers dealt with the problem of comparing alternative products of complex components from the perspective of a project (particular location, particular quantities, individual constraints due to the design of the building/civil engineering structure – Table 2).

**Table 2.** Works on comparing options of building components assuming perspective of a particular project.

Paper	Aspects	Life cycle	Criteria list	Weights, method of calculation	Env. criteria	Criteria values:	Method output
(Ananin <i>et al.</i> , 2018)	En	A1-A3	Arbitrary	-	1	databases & calculations	ranking acc. to energy embodied in materials
(Gomez-Soberon <i>et al.</i> , 2016)	En	A4-C?	Arbitrary	-	1	databases & calculations	calculation of the quantity of 5 types of waste for each option
(Potkany <i>et al.</i> , 2018)	Ec, En	A1-A3	LCA (EPD)	-	6	databases & calculations	calculation of a set of measures for each option
(Svajlenka and Kozlovskaja, 2018)	Ec, En	A1-A3	LCA	-	3	databases & calculations	calculation of a set of measures for each option
(Hassan and Johansson, 2018)	T, Ec, En	A1-A3?	Arbitrary	-	1	databases & calculations	calculation of a set of measures for each option
(Al-Nassar <i>et al.</i> , 2016)	Ec, En, S	A-C	LCA	Arbitrary; sensitivity analysis	8	databases & calculations	weighted sum combined index
(Chen <i>et al.</i> , 2019)	T, Ec, En, S	not explicit	Experts	M. experts BULI-based QFD; sensitivity analysis	5	M. experts	ELECTRE III combined index
(Casanovas-Rubio <i>et al.</i> , 2019)	Ec, En, S	A	Experts	T. of experts AHP; sensitivity analysis	5	databases & calculations	MIVES combined index
(Alberti <i>et al.</i> , 2018)	Ec, En, S	A-B	Experts	Arbitrary (literature);	5	databases & calculations	MIVES combined index
(Kripka <i>et al.</i> , 2019)	T, Ec, En, S	A	LCA (selected)	Arbitrary, AHP; sens analysis	1	databases & calculations	AHP, VIKOR combined index
(Kumanayake and Luo, 2017)	Ec, En	A-C	LCA (selected)	<i>not decided yet</i>	1	databases & calculations	<i>not decided yet</i> combined index
(Sarkkinen <i>et al.</i> , 2019)	T, Ec, En, S	not explicit	LCA	M. experts, AHP (geometric mean); sensitivity analysis	2	databases & calculations	AHP combined index
(J Santos <i>et al.</i> , 2019)	Ec, En, S	A-C	Arbitrary (selection justified)	3 approaches; sensitivity analysis	10	databases & calculations	PROMETHEE II combined index
(Joao Santos <i>et al.</i> , 2017)	Ec, En	A-C	LCA	Arbitrary (as in BEES); sensitivity analysis	8	databases & calculations	TOPSIS combined index
(Zheng <i>et al.</i> , 2019)	Ec, En, S	A-B	LCA	M. experts, AHP (geometric mean); sensitivity analysis	5	databases & calculations	VIKOR combined index
(Pavlovskis <i>et al.</i> , 2016)	T, Ec, En	A-C	Arbitrary	M. experts WASPAS-G for aggregation	5	M. experts	WASPAS-G, combined index; Compared with results of o. methods

Five works produced sustainability measures without combining them into overall scores

(less convenient for comparison, but not affected by subjectivity in normalizing criteria values and setting weights). Among them, two papers considered a sole measure of the environmental impact. Among them, two papers considered sole measures of environmental impact: Ananin *et al.* (2018) looked for the best type for walls of a residential building in Russia with the lowest energy embodied in wall materials, while Gomez-Soberon *et al.* (2016) compared 3 options of floors according to the type and quantity of waste generated by replacement.

As the number of factors worth considering in the assessment may be large, some generalized measures to facilitate a clear distinction between options may be useful. 11 papers presented such measures. Among them, Chen *et al.* (2019) presented an interesting problem of designing components to the liking of various stakeholders by using Quality Function Deployment and ELECTRE III. They proposed a new group decision making method and illustrated its use on the example of selecting flooring for office space. With this approach, the set of criteria was individually defined for each case, expressing the stakeholders' point of view.

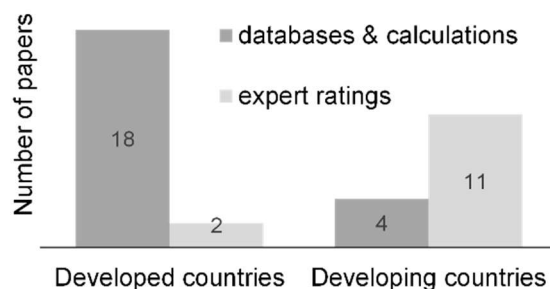
Casanovas-Rubio *et al.* (2019) assessed sustainability of trenching methods. Their method, MIVES, normalizes criteria scores by utility functions based on relative preferences expressed by experts. The values of criteria were expressed as precise numbers (e.g. water consumption in dm<sup>3</sup> per 1m of trench) or as scores (if the effort to estimate the precise measure was considered too great; however, justification for calculating the scores was provided). The analysis produced a single measure, Sustainability Index for Trenches, to compare the options. Alberti *et al.* (2018) used the same method to assess sustainability of two options of a structural component, namely a tunnel slab of reinforced concrete, that differed in the type of reinforcement. Interestingly, they based on the evidence on the components' performance over 3 years of use in the same conditions. This was a unique feature of this research.

Santos *et al.* (2019) presented a decision-support tool for ranking alternative pavement designs. The tool allows the user to define their own weights of criteria or to select the weights as found by the authors in a survey. All 10 sustainability indicators related with environmental impact were measurable, clearly defined in the literature, with the methods of calculation or sources of values of confirmed reliability. To exclude selection of options that compensate poor performance in some aspect by good performance in others, an outranking method with threshold values was selected as the core of the decision support tool. Out of the sample of papers, this one was considered to present the most convincing line of reasoning for selection of criteria (though the authors direct the reader to their subsequent publications for details) and methods for the ranking of options.

The remaining papers (not listed in Table 2) were not devoted to assessing predefined component options, but to solving multicriteria design problems. BuHamdan *et al.* (2019) presented a simulation model built to assess effects of combined design changes in a number of components (the size of glazed area, type of windows and thermal resistance of envelope) on the building's cost, measures of environmental impact in the construction, operation and demolition phase. Marti, Garcia-Segura and Yepes (2016) constructed an automated design optimization tool that prompts the best beam profile, concrete class and contents of prestressing and reinforcing steel of a prefabricated U-beam used in bridge construction. The model produces solutions that satisfy structural requirements at minimum cost and embodied energy in phase A of the lifecycle.

## 4 Summary and Conclusions

Values of the criteria related to the environmental impact were either calculated or rated arbitrarily by experts, in the latter case using a variety of rating scales or in the course pairwise comparisons. Among 35 papers that compared/ranked options or aimed at finding an optimal solution, a dependence was observed ( $p$ -value in  $\chi^2$  test of 0,00124) between the location of the object of analysis and the authors' method to define the criteria values (Figure 1). This observation is rather obvious: the geographical coverage of construction products' life cycle inventory databases is only slowly expanded on South America, Africa, and Asia.



**Figure 1.** Methods of defining criteria values vs origin of the paper.

Nevertheless, a detailed and laborious calculation of criteria values in interval or ratio scales was not automatically an asset. As most of the authors who calculated criteria values this way (14 out of 22) aimed at providing an integrated index of sustainability to make the comparisons easier, they normalized the values in a way specific to the method of multicriteria analysis. Frequently, the precision of criteria measures was lost in this process, especially if measures were subject to pairwise comparisons. Four authors decided to directly account for the uncertainty of criteria ratings by expressing them by fuzzy or grey numbers.

Defining criteria weights, a key aspect of most multicriteria assessment methods, was most frequently done by collecting expert opinions. They were collected during panel meetings for direct consensus (10%) or independently, in interviews or questionnaire surveys (40%). Thus, 50% of authors based on weights prompted by the literature or decided to use arbitrary values, then check the sensitivity of their results to changes in criteria weights. Multiple opinions were aggregated in a number of ways: from mean scores to elaborate analysis in stakeholder groups.

As for the multicriteria assessment methods in use, the most popular of the established ones were TOPSIS (6 papers), AHP (5 papers), and VIKOR (3 papers). Some authors used a combination of methods or proposed their own to precisely account for the character of the problem. Nevertheless, out of 27 works that provided one combined measure for ranking options, 9 did not explicitly refer to any form of checking the sensitivity of the results to weights nor juxtaposed their ranking with rankings obtained by means of other methods.

The sample of papers analyzed above is certainly not representative of the state-of-the-art research on the environmental impact of construction. However, it indicates that this field is still in the stage of development. There is no agreement on the type of criteria, on their importance, nor the methods of assessment in analyzing the sustainability of construction products and components.

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