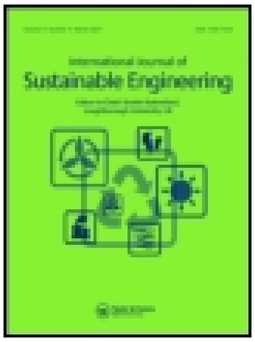

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Sustainable New Product Development: a decision-making tool for the construction industry

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ABSTRACT
During the last decades, environmental sustainability has acquired growing importance in different productive sectors. The construction sector, aware of its environmental impacts, searches for mitigation within both processes and inputs. One of these mitigation strategies is the recycling of construction and demolition waste within the production chain. This paper deals with the proposition and application of a systematic decision-making tool in the context of the construction industry. The proposed procedure introduces a tool for Sustainable New Product Development using Quality Function Deployment to analyse the use of recycled aggregate for making concrete blocks in a multivariate context. That tool allows requirements identification and prioritisation considering the perspectives of both customers and developers, as well as standards and environmental aspects. Some results of a real case application are presented, and the benefits and potential barriers related to its adoption are discussed. These results contributed to the identification of trade-offs associated with the challenge of comparing alternative construction materials. It was also possible to identify that the use of recycled materials does not necessarily ensure that a product is more environmentally friendly than others.

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1. Introduction

There is growing concern about the need to reduce negative environmental impacts. Within this context, the construction industry is concerned about negative environmental impacts derived from its sector. This is particularly important considering the magnitude and size of its products, and the high dependence on natural resources within its production chain. Quantitative data regarding natural resources utilisation associated with the construction sector are significant, representing 60% of raw material consumption (Bribián, Capilla, and Usón 2011). Among these features, natural aggregates are widely used, tending to increase directly associated with concrete production, which is the main input of the production chain. It is a well-known factor that concrete is the most widely used building material with a production of more than 10 billion tons per year in the world (Meyer 2013). Natural aggregate is the major components of concrete, consisting of the world's number one nonfuel mineral commodity in terms of volume and value (Langer 2016).

Moreover, the construction sector is a substantial generator of waste and approximately 35% of waste is landfilled (Kabirifar et al. 2020). The European construction sector produces around 46% of the total amount of total waste generated (Eurostat 2017). Estimates show that China CD&W total waste represents 30% to 40% of the total amount of waste. (Huang et al. 2018). In Brazil, the volume of construction and demolition waste represented 57% of the solid waste generated in the country, totalling approximately 122.012 tons (Abrelpe 2018).

With these demand levels, it has become necessary to develop up-to-date and more suitable concrete and building materials, whose performance meets the needs of increased durability, efficiency, and environmental compliance including recycling alternatives. This presents many excellent opportunities for using recycled aggregates. Although studies are dealing with CD&W recycling (Yap et al. 2018; Wijayasundara, Mendis, and Crawford 2018; Omrane et al. 2017), or with different industries wastes, such rubber waste (Aslani et al. 2018), electric arc furnace slag (Faleschini et al. 2015) including Life Cycle Assessment (Fořt and Černý 2020), there still is a lack of structured comparisons about the incorporation of alternative waste in concrete in the early-stage project, when it is necessary to consider the trade-offs management. This makes it more difficult to assess the relative benefits and costs of merging these materials and comparatively classifying their technical and environmental performance. In general, there is no consensus on a structured process for developing more sustainable products for the construction industry, and enabling technical comparative performance evaluations of potentially sustainable building materials (John and Prado 2010). This situation is aggravated by the lack of consolidated quality requirements for these sustainable products, especially related to the developing products that must comply simultaneously with, among others, different regulatory standards, market demands, and environmental protection requirements.

In this context, the systematisation of the decision-making process can use a series of multi-criteria approaches and a combination of methods to include environmental principles

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(Guarnieri and Trojan 2019). Rossi et al. (2019) present an approach that jointly considers different aspects as technical, economic and environmental, identifying the trade-offs in the early stages design. Although there are a series of tools for decision-making process, Doualle et al. (2019) point out that the methods are not well adapted to take into account a systemic view between the various sustainability pillars and mainly different stakeholders. Additionally, there is a lack of decision-making methods to help the early stages design of products for the construction sector peculiarities, especially dealing with waste recycling.

In the early stages design, the Quality Function Deployment approach is suitable, where it does not require detailed information about the product. QFD is used to include customers' demands by defining and correlating requirements and technical specifications during design development (Haiyun et al. 2021). A variety of different approaches has been developed based on the QFD method (Callegaro et al. 2016; Yazdani et al. 2017).

Associated with the development of environmentally sustainable products, the work of Abele, Anderl, and Birkhofer (2005), simultaneously consider customers, regulations, and environmental requirements to determine product standards. This extended list of requirements is obtained from the quality deployment of the product's life cycle (Life Cycle QFD) for environmental requirements and adds environmental performance and customer requirements. In this process, the requirements come from; the Voice of Customer – VOC; the Voice of Environment – VOE; and the Voice of Regulations – VOR, which thus generates the House of Quality. Although the Life Cycle QFD model presents a more comprehensive requirements approach, this model still does not consider technical standards requirements and how they can be incorporated into the matrix. Furthermore, their proposed relationship matrix does not include the regulations, because the model considers them mandatory. However, the interrelations between all requirements are important for understanding the complete range of implications for incorporating environmental requirements.

When considering sustainability, Ahmad et al. (2018) show that a series of tools based on the QFD concept had been developed and used for the design, mainly in the early stage, of sustainable products development. However, any of them present a procedure to integrate and ensure the technical and regulatory standards in sustainable product development. The novelty of the study was to analyse the development of concrete blocks using C&DW by identifying holistic criteria for customer, environmental and standards requirements, and ensuring these requirements at each stage of the QFD in order to result in key indicators.

In this context, this article presents a decision-making tool for Sustainable New Product Development (SNPD), which uses C&DW. The tool, based on the QFD method, aims to take into account at the same time both requirements of customers, and technical-environmental performance. Afterwards, the proposed systematic tool was subsequently applied in the early stages of the development of sustainable concrete building block produced by a Non-Governmental Organization (NGO). The aim was to illustrate the tool's methodological strengths and opportunities. As a result, it is expected that the tool may improve the NGO decision-making process regarding sustainable new products development, considering not only traditional technical approaches but also embracing customer and environmental aspects, reducing the arbitrary assumptions. The theoretical implications of the application can benefit also researchers who can apply the tool in future research into other building products.

This article is divided into four sections. This first section has presented the work's main assumptions and purpose, while the next section details the development of the systematic tool. The third section presents partial results from the tool's practical application. Finally, the closing section draws conclusions about the practical uses of this systematic tool and provides suggestions for future research.

2. Methods and techniques

The tool developed in this paper associate the adapted QFD tool (Callegaro et al. 2016) and the methods that add the environmental third dimension to QFD (Kaebernick, Kara, and Sun 2003; Abele, Anderl, and Birkhofer 2005; Vinodh and Jayakrishna 2014). In order to accomplish the needs of the construction sector context, the tool extends these methods into three new approaches. The first approach is related to the requirements of the technical standards that specify characteristics for new product development. Therefore, this article proposes to extend the scope of requirements, including the mandatory prescriptive rules of the product as well as the standards that set the performance requirements for the building. These requirements become necessary due to previous interviews with consumers, who attributed quality to products that only minimally met the standard requirements.

The second approach further distinguishes the tool through an extension to include the environmental requirements. It also uses methods that assess the environmental quality of buildings together with the products' environmental requirements with the support of green building rating systems. This criteria list can pave the way for practitioners to meet those requirements. The third approach is associated with the relationship between the proposed matrices. By applying the customer, standards, and environmental matrices, it establishes a relationship network between all of the various requirements. Though all regulatory requirements must be fully accomplished, it is important to know which standards requirements are the most impactful during product development. With this integration, more effective strategies can be identified for construction sector industries. The proposed systematic decision-making tool structure linking customer, environmental, and standards requirements is presented in Figure 1.

The goal of the systematic tool is to identify the relationships between customer, environmental, and standards requirements and their respective indicators. Both positive and negative correlations between these indicators were also verified. Therefore, firstly (phase 01) the requirements of each group (customer, environmental, and standards requirements) were identified. Then each of the requirements lists generated a matrix (phase 02), in which the relationships between the requirements and its indicators were verified. The

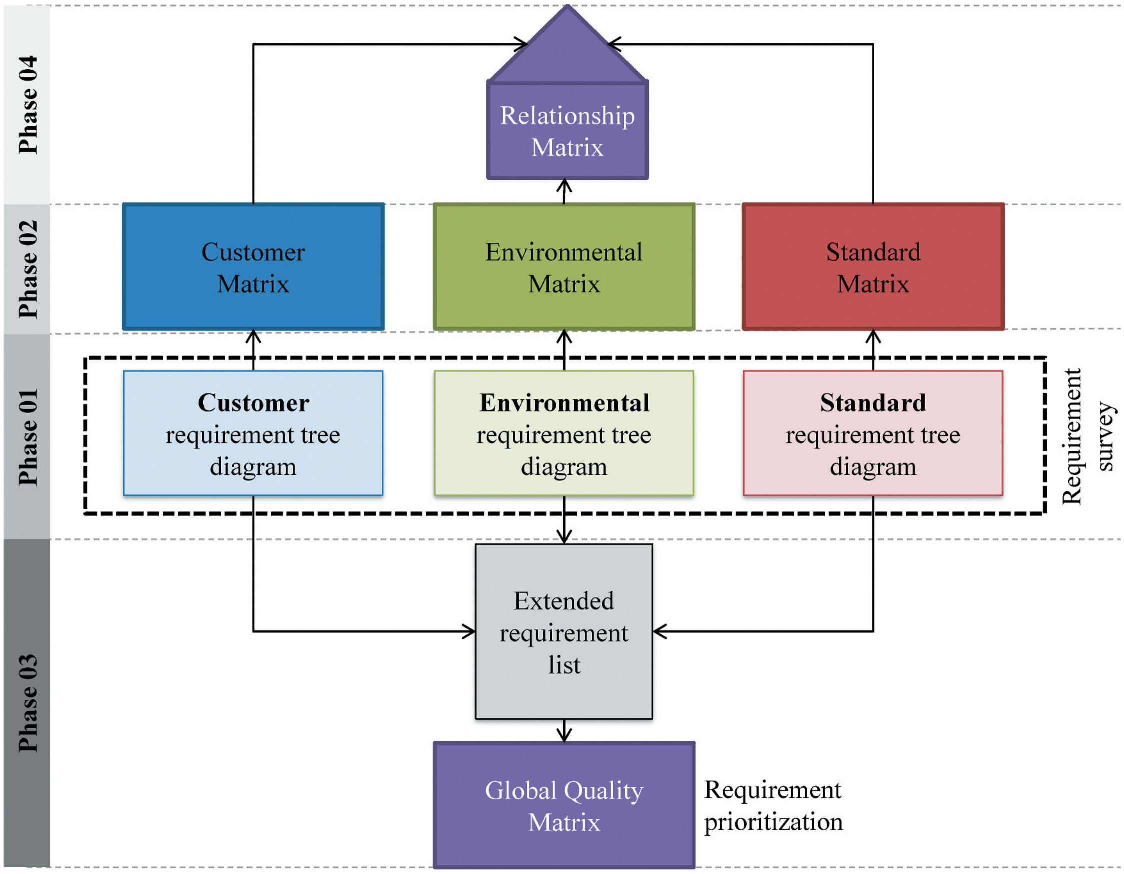


Figure 1.

development of these matrices allows the prioritisation of indicators to consider every group (customer, environmental, and standards).

Putting together all three lists of requirements (customer, environmental, and standards) meant an extended list of requirements and indicators was formed for environmentally sustainable products (phase 03). The extended requirements list also helped eliminate repeated requirements. This phase is important because it represents a complete database regarding the mandatory requirements (standards) and the desired requirements (environmental and customer) for product development. This extended list then generates a single matrix, called the Global Quality Matrix, in which the existence of potential new relationships between the three groups is identified. As a result, it becomes possible to obtain a general prioritisation of the extended list of the quality features (customer, environmental, and standards).

In the fourth and last phase (phase 04), positive and negative correlations between the indicators of the extended list were identified by using a Y-type matrix. This type of matrix allows for an evaluation of the relationships between the combination of the three dimensions (Shahin, Bagheri Iraj, and Vaez Shahrestani 2018), namely customer-environmental, customer-standards, and environmental-standards. The purpose of this phase is to identify the existence of potential trade-offs between these indicators. This is especially necessary for negative correlations between two indicators, where one indicator increases as the other decreases, and vice versa. This situation implies the necessity to optimise these two indicators. Furthermore, it is easier when positive correlations are identified, because it allows for the maximisation of both indicators. Trade-off management is an important challenge for product developers, and clearly identifying potential trade-offs can be quite useful. The next section presents a practical application of the systematic tool for SNPD, which considers the use of C&DWs to develop a product for the construction industry.

3. Results for the systematic tool for sustainable New Product Development application

The results described in this section were obtained by the application of the systematic tool in the development of concrete blocks with recycled-content C&DW. This section is divided into: (i) the collection and organisation of the requirements (phase 01 and 02); (ii) the global quality matrix (phase 03); and (iii) the correlations matrix (phase 04).

3.1 Research field

The UFRGS Engineering School is providing research and educational leadership for the Porto Alegre Sustainable Innovation Zone (ZISPOA), the first major implementation step of Global Urban Development's World Bank-funded Leapfrog Economic Strategy for Rio Grande do Sul to become the most sustainable and innovative place in Latin America by

2030 (Weiss, Sedmak-Weiss, and Rodriguez 2015; Weiss and Nascimento 2016; Weiss 2017, 2018). Generating a circular economy in production and consumption through Zero Waste approaches to recycling and resource recovery is a vital aspect of Sustainable Innovation. A partner in this initiative is the 'Solidariedade' NGO. This group aims to produce building concrete blocks using recycled aggregate generated from construction and demolition waste, cooperatively. Besides the initiative, there still a lack of knowledge about which requirements should be introduced in the product to be offered to customers, that comply with all standards and regulations of the construction sector and ensuring its environmental orientation.

3.2 Collection and organisation of the requirements

Phase 01, the collection and organisation of the requirements, is the basis for the three matrices developed in phase 02. Every step needed to accomplish these phases and the results are organised and shown as developed for each matrix (customers, environmental and standard), as follows.

3.2.1 The customer matrix

A survey was employed to ascertain customer requirements. To accomplish this, four activities were developed: the identification of the costumers; the identification of the requirements; the elaboration of a tree diagram of the requirements; and, a definition of the requirements' relative importance. The customers of construction concrete blocks have been identified as construction companies, architects, civil engineers, and building materials retail stores.

The requirements identification was conducted through semi-structured interview including open questions, in which the customers could freely express their point of view about the topics presented. The respondents (total of 20) were selected based on accessibility and judgement sample. The sample size is determined in line with theoretical saturation since the data collection process goes the same time as data review and analysis (Oppong 2013). The saturation point was considered when specific views were repeatedly mentioned and new information failed to emerge. The semi-structured interview questions are presented in Table 1.

Table 1. Interview questions.

No.	Questions
1	Which characteristics are important when selecting an element for a masonry wall?
2	Which execution characteristics are relevant when selecting the element for a masonry wall?
3	Which main problems are detected nowadays in the products offered for masonry walls?
4	Which factors are relevant when choosing a concrete block instead of bricks or ceramic blocks?
5	Which aspects are important in a concrete block wall?
6	Regarding the concrete block's characteristics and benefits, which points are valued considering the Performance, Appearance, Delivery, and Environmental Issues?
7	What is the relevance concerning the environmental issues of this product?
8	Suggest environmental requirements to a concrete block.

Based on these interviews, the requirements were identified and organised into a hierarchical three-tier tree diagram (primary, secondary, and tertiary). For the Customer Matrix, the primary level, 'customer satisfaction', which is deployed in the secondary and tertiary levels, represents different degrees of the requirements' details. Based on this tree diagram and the listed requirements, a quantitative questionnaire was developed in order to evaluate the importance of each customer's requirements.

The questionnaire, which aimed to establish the importance ranking for each requirement, was sent by email to 20 experts in the construction sector (civil engineers and architects). The scale used to evaluate the importance of the tertiary items was a 10-point grade, in which 10 was considered most important and 1 was considered least important. Following the questionnaire responses, the secondary level items were listed in order of importance, from the 'most important' to the 'least important'. The result is the Requirements Index (Ri).

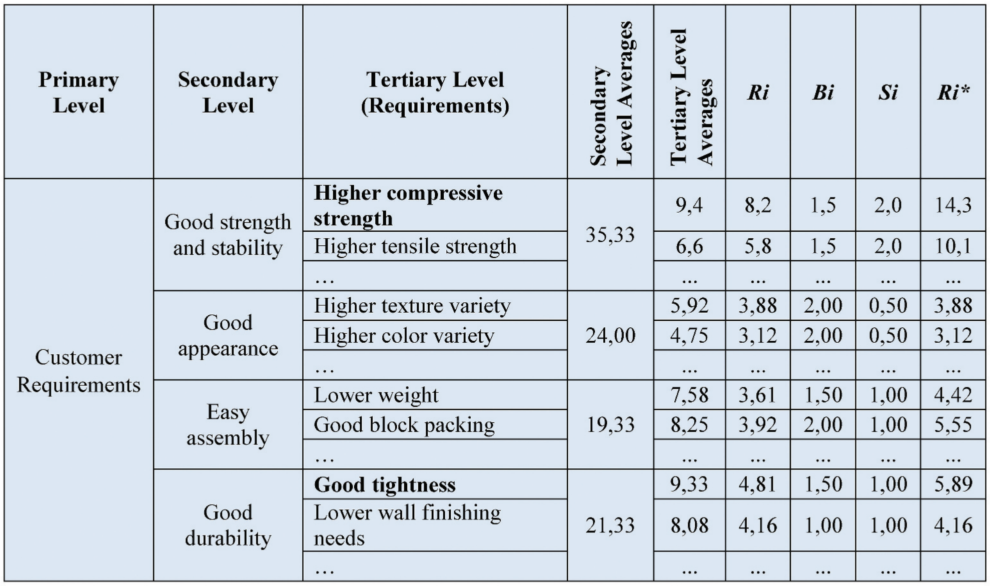
At this point, the NGO's point of view is added to the Requirements Index; therefore, the Ri value is influenced by two factors: Benchmarking (Bi) and Strategic contribution (Si). Benchmarking is an analysis related to competitors (for example, companies that manufacture concrete blocks using natural aggregates). The Strategic contribution considers the importance of demand factors in achieving the company's strategies. The parameters to evaluate the Benchmarking (Bi) and Strategic contribution (Si) factors are presented in Table 2.

The result is the Fixed Requirements Index (Ri*). Figure 2 contains a partial representation of the original development in the secondary and tertiary levels and the final Ri and Ri*. The boldly marked requirements highlighted in Figure 2 are not only applied on the Customer matrix but also will appear in both the Environmental and the Standards matrices.

Phase 02 starts by identifying at least one Indicator (I) for every existing requirement. In the next step, the subsequent and important task for the systematic tool was to complete the customer's matrix core. In order to complete this matrix, the concrete blocks developers (NGO consultants) group was consulted. At this point, the intensity of the relationship between the requirements and indicators was evaluated. It was suggested that the developers' group answer the following question: if indicator 'x' is properly meeting its specifications, can it assure the accomplishment of the customer's requirements 'y'? If the answer was yes, the team assigned a scale value of 1 (for Weak), 3 (for Moderate) and 9 (for Strong) relationships, and if the answer was 'no', it meant there is no relationship between the indicators and the requirements, leaving it as a blank cell.

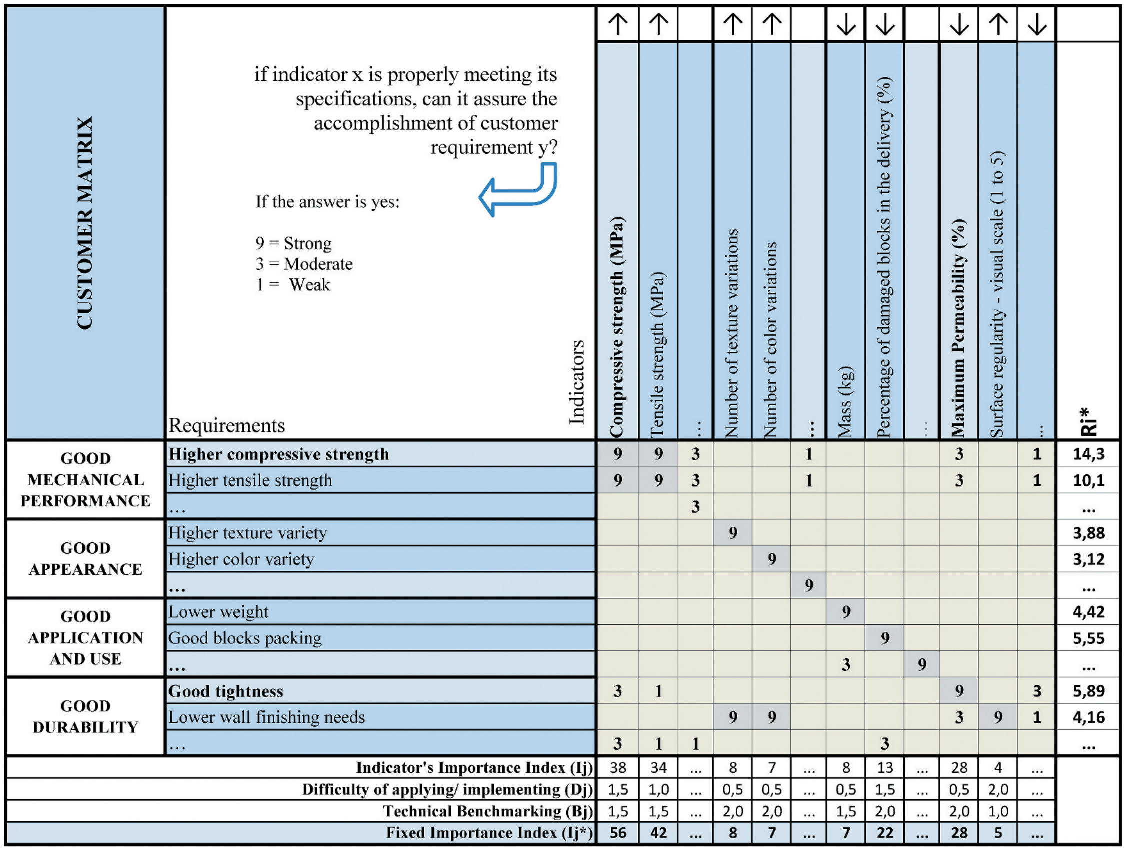
Table 2. Parameters for requirements index (Ri) adjustment.

Scale	Parameter
Benchmarking (Bi)	
0.5	company is above its competitors
1.0	similar to its competitors
1.5	below its competitors
2.0	far below its competitors
Strategic contribution (Si)	
0.5	less important
1.0	moderately important
1.5	important
2.0	very important



Primary Level	Secondary Level	Tertiary Level (Requirements)	Secondary Level Averages	Tertiary Level Averages	*Ri*	*Bi*	*Si*	*Ri**
Customer Requirements	Good strength and stability	**Higher compressive strength**	35,33	9,4	8,2	1,5	2,0	14,3
		Higher tensile strength		6,6	5,8	1,5	2,0	10,1
		…		…	…	…	…	…
	Good appearance	Higher texture variety	24,00	5,92	3,88	2,00	0,50	3,88
		Higher color variety		4,75	3,12	2,00	0,50	3,12
		…		…	…	…	…	…
	Easy assembly	Lower weight	19,33	7,58	3,61	1,50	1,00	4,42
		Good block packing		8,25	3,92	2,00	1,00	5,55
		…		…	…	…	…	…
	Good durability	**Good tightness**	21,33	9,33	4,81	1,50	1,00	5,89
		Lower wall finishing needs		8,08	4,16	1,00	1,00	4,16
		…		…	…	…	…	…

Figure 2.



CUSTOMER MATRIX

if indicator x is properly meeting its specifications, can it assure the accomplishment of customer requirement y?

If the answer is yes:

9 = Strong
3 = Moderate
1 = Weak

	Requirements / Indicators	**Compressive strength (MPa)**	Tensile strength (MPa)	…	Number of texture variations	Number of color variations	…	Mass (kg)	Percentage of damaged blocks in the delivery (%)	…	**Maximum Permeability (%)**	Surface regularity - visual scale (1 to 5)	…	**Ri***
		↑	↑		↑	↑		↓	↓		↓	↑	↓	
GOOD MECHANICAL PERFORMANCE	**Higher compressive strength**	9	9	3			1				3		1	14,3
	Higher tensile strength	9	9	3			1				3		1	10,1
	…			3										…
GOOD APPEARANCE	Higher texture variety				9									3,88
	Higher color variety					9								3,12
	…						9							…
GOOD APPLICATION AND USE	Lower weight							9						4,42
	Good blocks packing								9					5,55
	…							3		9				…
GOOD DURABILITY	**Good tightness**	3	1								9		3	5,89
	Lower wall finishing needs				9	9					3	9	1	4,16
	…	3	1	1					3					…
Indicator's Importance Index (Ij)		38	34	…	8	7	…	8	13	…	28	4	…	
Difficulty of applying/ implementing (Dj)		1,5	1,0	…	0,5	0,5	…	0,5	1,5	…	0,5	2,0	…	
Technical Benchmarking (Bj)		1,5	1,5	…	2,0	2,0	…	1,5	2,0	…	2,0	1,0	…	
Fixed Importance Index (Ij*)		56	42	…	8	7	…	7	22	…	28	5	…	

Figure 3.

Figure 3 presents both the matrix and the relationships, in which the strong relationships are emphasised. It is also relevant to indicate the trend of the indicators in the matrix. The symbols connected to each indicator express whether the feature is 'bigger is better' (↑ – up arrow), 'smaller is better' (↓ – down arrow), or par value (ϴ – limited point).

Additionally, Figure 3 also shows the importance of each Indicator Importance Index (Ij) calculated, which in the next step, is weighted by two factors: the Difficulty of acting/implementing the specifications (Dj), and the technical Benchmarking (Bj). The parameters to evaluate the Difficulty of acting/implementing the specifications (Dj) Benchmarking (Bj) factors are presented in Table 3. This adjustment generates the Fixed Importance Index ($I_j{}^*$) presented in Figure 3.

The development of this matrix was important especially in the construction material sector where customer expectations

Table 3. Parameters for indicator importance index (Ii) adjustment.

Scale	Parameter
Difficulty of applying/implementing the specifications (Dj)	
0.5	very difficult to act
1.0	difficult to act
1.5	moderate to act
2.0	easy to act
Technical Benchmarking (Bj)	
0.5	the company is above its competitors
1.0	similar to its competitors
1.5	below its competitors
2.0	far below its competitors

are rarely considered. The results of this matrix demonstrate that this understanding could be the most important innovation strategy for the NGO, since requirements as 'different colours and textures' for example, should orient the development of a new and varied range of products.

3.2.2 The environmental matrix

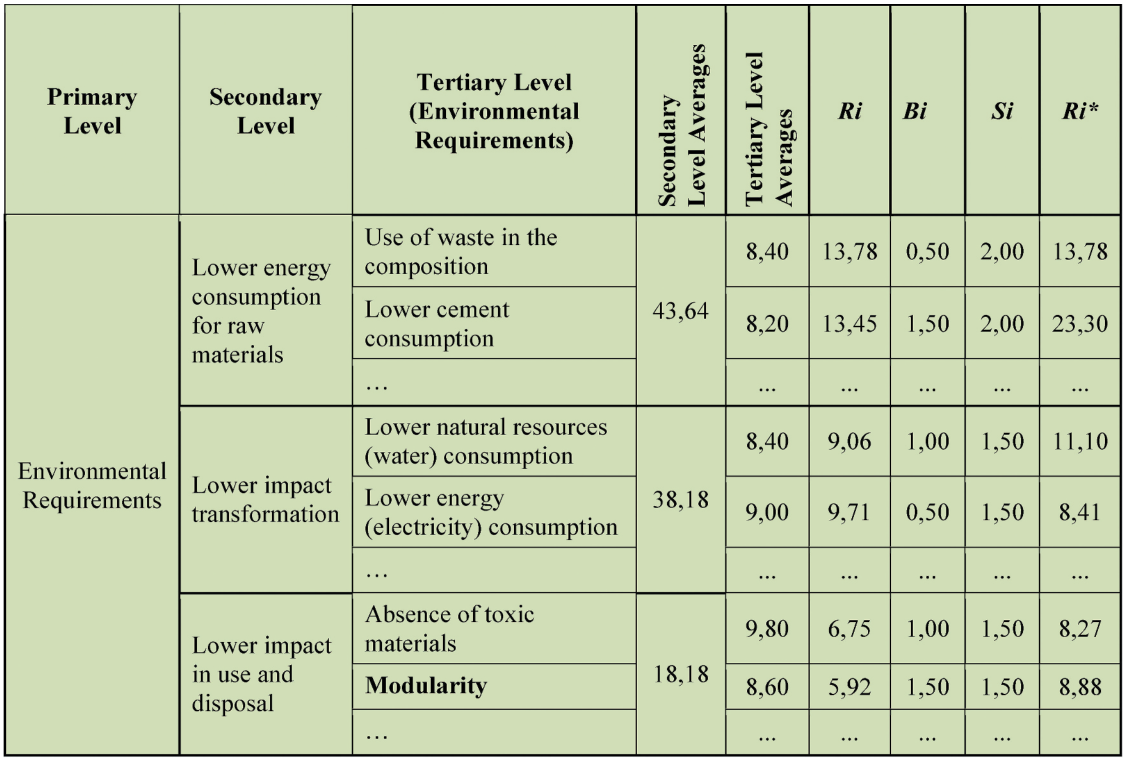
The survey method used to identify the environmental requirements was based on green building rating systems measuring environmental sustainability in the building sector. References to environmental sustainability indicators adopted the criteria of Caixa Economica Federal's Blue House certification (*Selo Casa Azul*) for Brazil, Leadership in Energy and Environmental Design (LEED ™) from the United States Green Building Council (USGBC), and the Living Green Building Challenge from the International Living Building Institute (ILBI). These green building certification criteria were used as environmental requirements for both buildings and materials. Similar to the step developed for the Customer Matrix, the environmental requirements were analysed and organised in a requirement tree diagram with primary, secondary, and tertiary levels.

The completion of the Environmental Matrix was based on the weights given in response to the quantitative questionnaire, following the methods previously described and using the same criteria as those adopted in the Customer Matrix. In Figure 4, it is possible to check the relative weights of the primary and secondary levels, and the values assigned to the Bi and Si factors, which were adopted to calculate the Fixed Requirement Index (Ri*) for the Environmental Matrix. For this stage, respondents chosen were environmental experts.

Following, for the second step of the Environmental Matrix, the requirements were translated into measurable indicators. To identify the links in the Environmental Matrix, the same methodology was employed as for the customer matrix; however, the question was changed to, 'if indicator x is properly meeting its specifications, can it assure the accomplishment of the environmental requirements y?' Figure 5 depicts the Environmental Matrix with the relationship between the environmental requirements and their indicators.

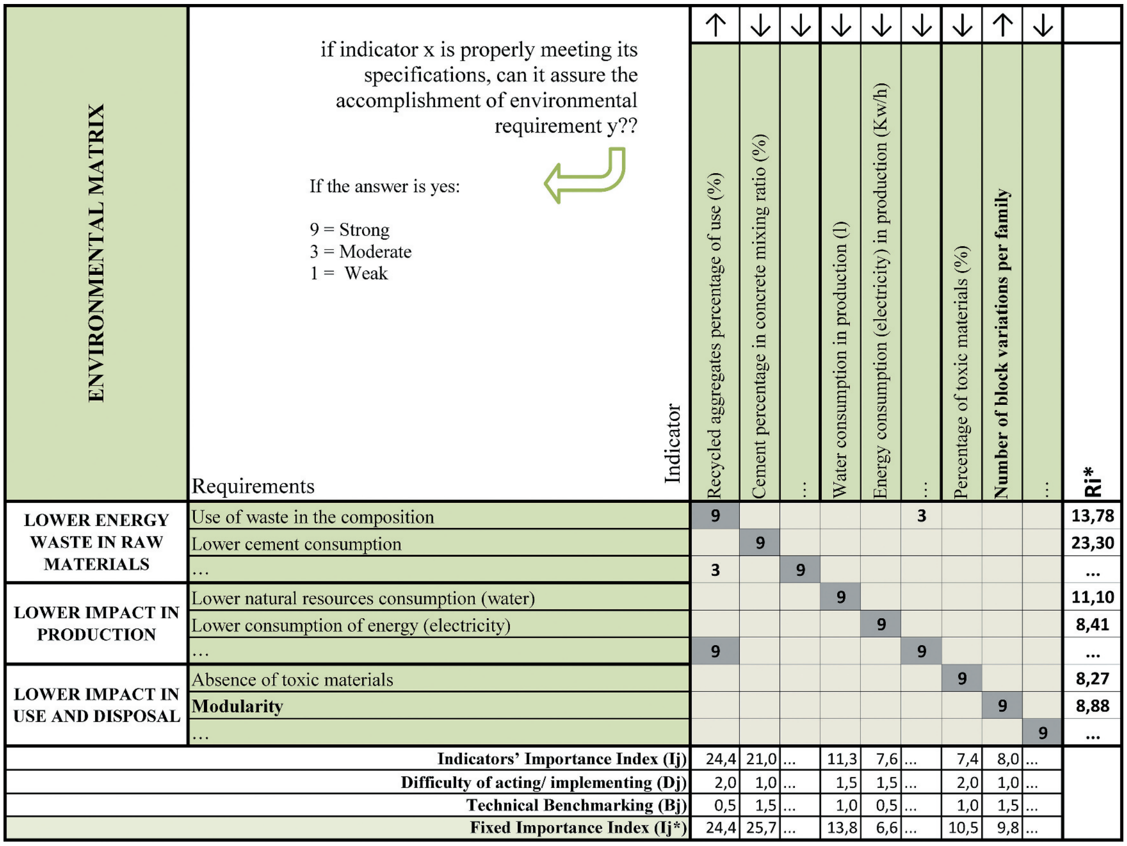
The results of this matrix show the calculation of the Indicator Importance Index (Ij), which generates the prioritisation of the environmental indicators. As indicated in the Customer Matrix, the Ij index is influenced by two factors: Difficulty for Applying/Implementing (Dj) the specifications, and technical Benchmarking (Bj).

As a result of phase 02, Figure 5 demonstrates that the indicators of 'increase of recycled aggregates percentage' and 'reduce of cement percentage in the concrete mixing ratio' has the first rank in the criteria, while the indicators related to the 'lower impact in use and disposal of the block' is listed at the last. It is important to note that this matrix highlighted the two



Primary Level	Secondary Level	Tertiary Level (Environmental Requirements)	Secondary Level Averages	Tertiary Level Averages	*Ri*	*Bi*	*Si*	*Ri**
Environmental Requirements	Lower energy consumption for raw materials	Use of waste in the composition	43,64	8,40	13,78	0,50	2,00	13,78
		Lower cement consumption		8,20	13,45	1,50	2,00	23,30
		…		…	…	…	…	…
	Lower impact transformation	Lower natural resources (water) consumption	38,18	8,40	9,06	1,00	1,50	11,10
		Lower energy (electricity) consumption		9,00	9,71	0,50	1,50	8,41
		…		…	…	…	…	…
	Lower impact in use and disposal	Absence of toxic materials	18,18	9,80	6,75	1,00	1,50	8,27
		Modularity		8,60	5,92	1,50	1,50	8,88
		…		…	…	…	…	…

Figure 4.



ENVIRONMENTAL MATRIX

if indicator x is properly meeting its specifications, can it assure the accomplishment of environmental requirement y??

If the answer is yes:

9 = Strong
3 = Moderate
1 = Weak

ENVIRONMENTAL MATRIX	Requirements / Indicator	Recycled aggregates percentage of use (%)	Cement percentage in concrete mixing ratio (%)	...	Water consumption in production (l)	Energy consumption (electricity) in production (Kw/h)	...	Percentage of toxic materials (%)	**Number of block variations per family**	...	**Ri***
		↑	↓	↓	↓	↓	↓	↓	↑	↓	
LOWER ENERGY WASTE IN RAW MATERIALS	Use of waste in the composition	9					3				13,78
	Lower cement consumption		9								23,30
	…	3		9							...
LOWER IMPACT IN PRODUCTION	Lower natural resources consumption (water)				9						11,10
	Lower consumption of energy (electricity)					9					8,41
	…	9					9				...
LOWER IMPACT IN USE AND DISPOSAL	Absence of toxic materials							9			8,27
	Modularity								9		8,88
	…									9	...
	Indicators' Importance Index (Ij)	24,4	21,0	...	11,3	7,6	...	7,4	8,0	...	
	Difficulty of acting/ implementing (Dj)	2,0	1,0	...	1,5	1,5	...	2,0	1,0	...	
	Technical Benchmarking (Bj)	0,5	1,5	...	1,0	0,5	...	1,0	1,5	...	
	Fixed Importance Index (Ij*)	24,4	25,7	...	13,8	6,6	...	10,5	9,8	...	

Figure 5.

most relevant environmental concerns related to the development of concrete products with recycled aggregates. Yazdanbakhsh et al. (2018) show that the replacement of natural aggregates by recycled aggregates has high environmental benefits just when it is used in high volumes (above 20%). On the other hand, a small reduction in cement consumption reduces substantially the CO_2 production thanks to the avoided production of this high energy-demanding product (Fořt and Černý 2020).

3.2.3 The standards matrix

Phase 01, for the Standard Matrix, it was necessary to identify which was regulatory standards that the concrete block must comply. In building development, compliance with the standards, regulations and building codes must be considered one of the key market factors. Besides, compliance with the prescriptive standards of every individual material within the construction sector meant that it is also necessary to meet the requirements of the building performance standards approach. Therefore, this matrix considered the regulations standards of building block and the standard of masonry walls performance.

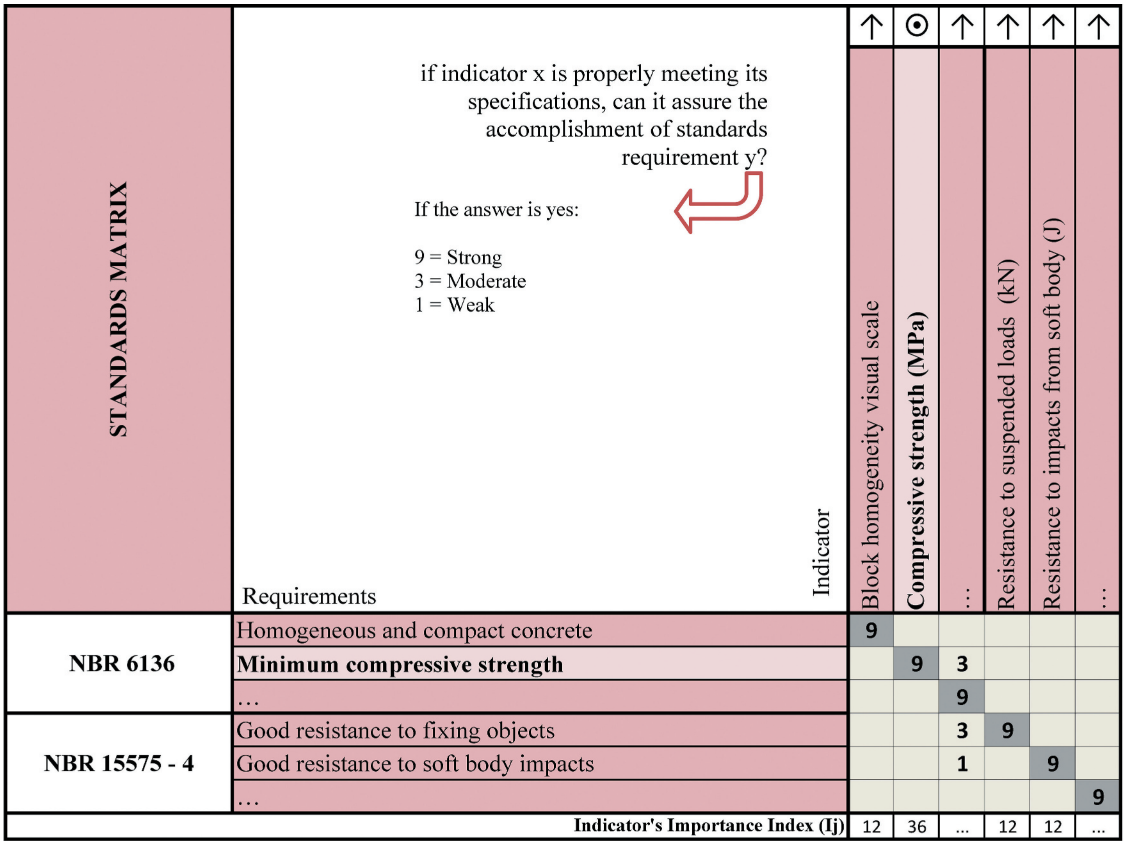
It should be noted that, for the standards, it is compulsory that all requirements be accomplished, so it is not necessary to quantify the importance weightings. This eliminates the step of assigning a weight to its requirements. However, the completion of the relationship matrix, phase 02, allows for the identification of the indicators that have higher impacts when dealing with all of the requirements of the standards.

The completion of the Standards Matrix followed the same method used in the previous matrices, except for the application of the question: 'if indicator x is properly meeting its specifications, can it assure the accomplishment of the standard requirements y?' Figure 6 depicts the standard requirements matrix, with its respective relationships. Due to simplification, the Ij evaluation was done by simply adding together all of the identified relationships.

As a result, (Figure 6), the mechanical performance, especially the compressive strength, was the indicator that has higher impacts on all requirements. Considering the development of concrete blocks with recycled aggregates this requirement is important since the high decrease in compressive strength was observed in several studies of replacement of natural aggregates in concrete by recycled aggregates (Cachim 2009; Zhang et al. 2019), however, the use of recycled aggregates could be still acceptable for other building purposes (Vieira and Pereira 2015).

3.3 Global quality matrix

The phase 03, the global quality matrix is obtained by unifying the requirements of the customer, environmental, and standards matrices. This phase aimed to avoid any repetition of requirements and indicators among the three matrices for the final decision-making indicators list. Besides, allow a holistic understanding of the importance of the indicators. Its completion followed the same pattern used before, adopting the scale



STANDARDS MATRIX

if indicator x is properly meeting its specifications, can it assure the accomplishment of standards requirement y?

If the answer is yes:

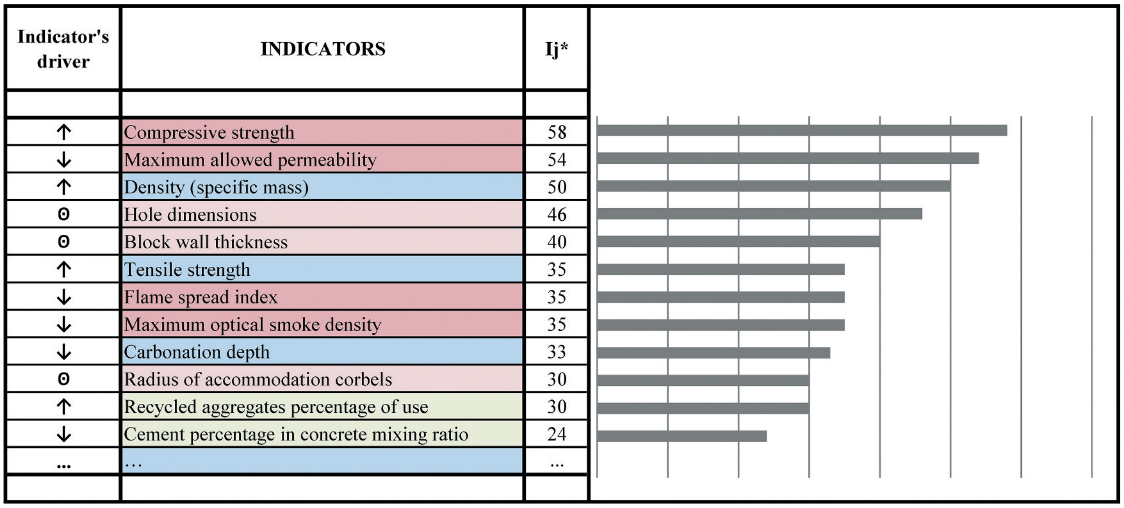
9 = Strong
3 = Moderate
1 = Weak

Standards	Requirements \ Indicator	↑ Block homogeneity visual scale	⊙ **Compressive strength (MPa)**	↑ …	↑ Resistance to suspended loads (kN)	↑ Resistance to impacts from soft body (J)	↑ …
NBR 6136	Homogeneous and compact concrete	9					
	Minimum compressive strength		9	3			
	…			9			
NBR 15575 - 4	Good resistance to fixing objects			3	9		
	Good resistance to soft body impacts			1		9	
	…						9
	Indicator's Importance Index (Ij)	12	36	…	12	12	…

Figure 6.

of 1 (weak), 3 (moderate), and 9 (strong) to identify the level of the relationship. To calculate the Ij, the same proposed simplification was used as in the Standards Matrix.

Based on the results, a Pareto chart ranking all indicator indices was generated representing the importance of an indicator for the concrete block developers (Figure 7). The decision-making, with regards to the extended indicators list and the definition of how many items will be managed and the key indicators, is relative to each company and its available resources. This definition may consider the prioritising order; for instance, one company may select the top 10 indicators or select priority indicators that consider specific areas, while another company may choose three customer priorities, three environmental priority and three standards priorities. In another example, the quantitative considerations may also vary, by picking three priorities from the customer chart, with four from the environmental and five from the standards, whereas another company can develop a larger workgroup mostly based on environmental issues and according to its available resources. In the presented NGO case, the first twelve



Indicator's driver	INDICATORS	Ij*
↑	Compressive strength	58
↓	Maximum allowed permeability	54
↑	Density (specific mass)	50
⊙	Hole dimensions	46
⊙	Block wall thickness	40
↑	Tensile strength	35
↓	Flame spread index	35
↓	Maximum optical smoke density	35
↓	Carbonation depth	33
⊙	Radius of accommodation corbels	30
↑	Recycled aggregates percentage of use	30
↓	Cement percentage in concrete mixing ratio	24
…	…	…

Figure 7.

indicators were chosen, as shown in Figure 7, since this list guaranteed that the two requirements prioritised in the environment matrix were also addressed.

3.4 Relationship matrix

Phase 04 verifies the existence of positives and negatives, as strong and weak correlations between the indicators of the different matrices, and aims to help developers define the final product specifications and possible trade-offs. The objective of this evaluation is to determine the influence of any indicator of a matrix on other matrices' indicators. For example, it makes possible evaluation of the existence (or not) of positive/negative influences between customer indicators relative to environmental indicators, and much more.

This phase is relevant because, in some situations, maximising one particular indicator (even if this one was perceived as a high priority in the Global Quality Matrix) can be prejudicial to another, bringing conflicting goals and inducing necessary trade-offs management between those features of the product. These trade-offs are directly related to negative correlations and can be considered a more appropriate management approach of the indicators involved in each case (Santos, Danilevicz, and Tubino 2017). Additionally, the Relationship Matrix's configuration facilitates the visualisation of all the relationships assembled in the same figure (Figure 8).

In this application case, for example, there were a few negative correlations between both customers and standards indicators, most of which were weak. On the other hand, many of the strongest negative correlations were identified between the environmental and both the customer and standards indicators. These findings are consistent, since, the environmental requirements compliance can adversely affect both traditional physical performance as well as durability of the concrete blocks.

4. Discussion

The transition to the circular economy in the construction industry has ambitions to solve the sustainability problems

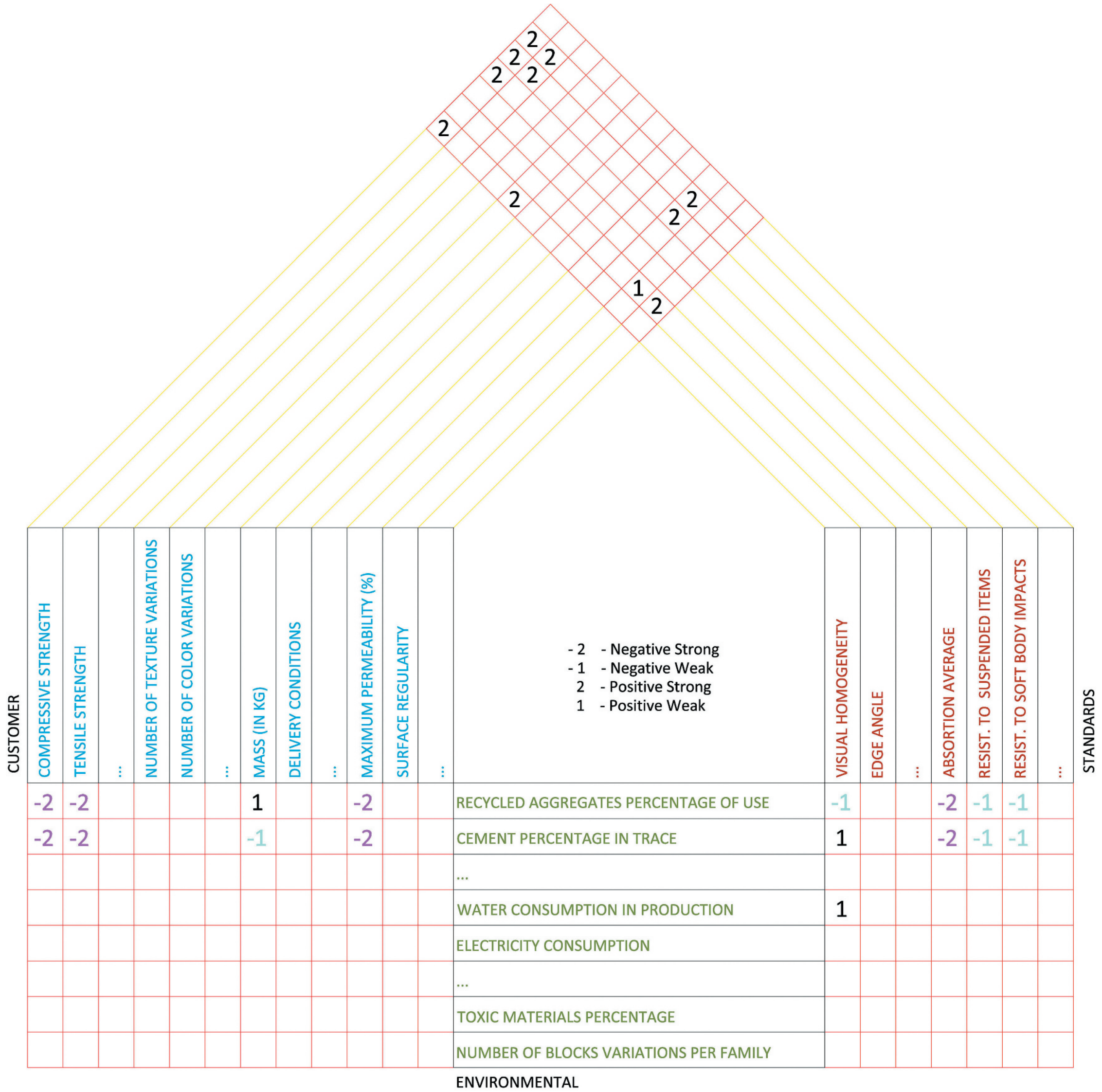


Figure 8.

by improving recycling and a closed-loop approach (Horckmans et al. 2019; Zhang et al. 2019). The construction sector's current practice for recycling the C&DW is the downcycling strategy by using at road construction, for example. However, this cannot be accepted as a solution for the transition to a circular economy (Fořt and Černý 2020). Therefore, a tool that helps practitioners conceive different alternatives for using recycled aggregates is paramount.

This article presented a circular economy and decision-making tool to be used before the Life Cycle Assessment. The tool aggregate three groups of requirements, the customer's, the standards, and the environment. Finally presents key indicators that the developers must monitor during the new product development process. By knowing these key indicators, the developer can conceive different construction industry products using recycled materials. Subsequently, LCA's application in the alternatives developed to verify which scenario has the lowest environmental impact must be considered.

Although several studies add the environmental perspective to the two-dimensional matrix (customer requirements and technical requirements) (Kaebernick, Kara, and Sun 2003; Rathod, Vinodhb, and Madhyasta 2011), none was applied to the construction material sector in which the technical requirements are usually a major concern. For that reason, it is necessary to understand the important challenges when attempting to compare alternative construction materials. It is also important to decide which waste materials are the most promising for the development of environmentally sustainable products. As such, it is necessary to develop benchmarks, identifying key variables directly related to product quality, together with measuring the environmental benefits of incorporating recycled waste. Using recycled materials does not necessarily ensure that a product is more environmentally friendly than others are which is why multivariable comparative performance research is necessary for reviewing relevant environmental indicators to assess if new sustainable products with recycled materials generate any negative impacts.

The phases of the tool reveal the key indicator for each matrix, that besides they are isolated it must be taken into account. Following, phase 03, the prioritisation list derived from the Global Quality Matrix is more than just a chart that shows the indicators that should primarily be monitored. It had become an important database for NGO future improvements.

The relationship matrices (phase 4) make it possible to improve and strengthen the decision-making process at the early stage design, especially because it can help with trade-off management by identifying potential critical situations between the product's multiple indicators. Considering that all indicators must be taken into account during the product development process, the trade-offs are associated with situations where it is necessary to find an optimal solution. That requires addressing many indicators rather than just maximising one indicator, which is especially relevant for compliance with environmental requirements.

Therefore, when considering environmentally friendly product development, these negative relationships cannot be neglected. At this point, the product developer group must manage trade-offs between these relationships to guarantee that the implementation of one particular feature does not adversely affect others. It is possible to balance different requirements and develop a product that fully meets regulatory standards, customer requirements and legitimately benefits the environment.

Concerning the NGO case study, the alternatives vary to the percentage of recycled aggregate and cement used in the block to reach a minimum compressive strength. The higher the recycled aggregate percentage use in relation to natural aggregate, the higher the cement percentage must be incorporated into the concrete block mixture for achieving the demanded compressive strength. As an alternative, a pre-treatment of the C&DW could be carried out to obtain a better quality of the recycled aggregate allowing to maintain or higher the percentage of recycled aggregate in the mixture. The disposal of the poor quality aggregates remaining would become a problem, but the solution could be the development of other products with key indicators coming from the customer's matrix, which sought products with other colours, textures, and formats for use in landscaping and design furniture in general that do not require minimal compressive strength. This alternative could be a source of diversification and starting the paths for innovation within the NGO.

Another vital function related to the completion of the matrices (both individual and global) was the knowledge generation and transfer within the product development team and NGO members. The generation of knowledge can occur through the meetings discussing the indicators, from growing professional relationships, and from participants sharing their product knowledge. Besides this, knowledge transfer also occurs through a product's visual formatting, in the sense that it becomes possible to quickly confirm all relationships and transfer the information to all members.

5. Conclusions and recommendations

Concerns about products' environmental sustainability have become increasingly important in today's society. The use of recycled waste instead of natural resources for the development of new products is studied in different fields of knowledge, including the construction sector. However, products that incorporate waste in their composition may not necessarily be environmentally sustainable. This might happen because some relevant dimensions/requirements were not considered either at the product development early-stage or within the product life cycle assessment.

This paper presented a decision-making tool for sustainable new product development incorporating C&DW for the construction industry. This systematic tool incorporates three sets of requirements – customers, standards, and environmental – using Quality Function Deployment matrices for the development of concrete blocks, produced by an NGO which aim is to produce environmentally sustainable products. The use of this tool makes identification, prioritisation, and strategic decision-making possible based on trade-offs, and the optimisation of relevant requirements for product development that consider both environmental sustainability and technical viability.

Some considerations can be made regarding the application of the systematic tool for the SNPD process. It was found that, unlike the standards' requirements, cited from the beginning by the customers, environmental issues generally were not been mentioned by them. Therefore, it is possible to affirm that the incorporation of the three matrices could help guide product developers within a holistic development system, considering not only the technical standards and customer demands but also key environmental issues. It can also contribute to the development and supply of new green products to market and the reduction of primary material extraction, by incorporating recycled waste materials.

Finally, it is important to highlight that the systematic tool can be applied to any sustainable new product development where environmental issues are important, regardless of incorporation of waste. Although the three proposed matrices remain fixed in this tool, the requirements vary according to the type of product to be developed. Nevertheless, its primary purpose is associated with developing green products and can be viewed as an extension of the design process in the building sector, which generally focus on the optimisation of only the technical standard approach and potentially lead to difficulties in finding trade-off solutions.

The tool developed in this work is valuable to provide guidance for practitioners to clarify alternatives for recycled aggregates for the circular economy in the construction sector. Further research should replicate this tool with other construction materials, as exemplified for the concrete blocks, which is the case of study. Future studies should present the requirements for production process steps. In addition, it is also desirable to conduct a life cycle assessment of the new products developed by the NGO, in order to identify potential environmental consequences from incorporating waste in their composition.

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