Sustainability Requirements for Concrete Block Elements Based on Recycled CDW: A Case Study for Supporting Social Production in Southern Brazil

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Abstract--**Although increasingly criticized and challenged, linear production models, in which goods are manufactured from raw materials to be sold, used and discarded as waste, still dominate the global economy. A deep change is necessary to provide more sustainable production models, based on the concepts of circular economy. In the construction industry, a promising alternative involves recycling construction and demolition waste (CDW) for concrete production, reducing the need for natural aggregates. However, to be successful, CDW products must attend all normative and quality requirements. This paper describes a model created to analyze how different requirements interact and influence the definition of elements to produce using CDW. The case study has special meaning because the results were used to help implement a cooperative production process on a picker's cooperative of southern Brazil, a social technology initiative that helps people overcome poverty barriers while benefiting the environment and respecting strict material standards. To this end, the model was constructed considering customer expectations, environmental and technical requirements, and became a key tool to decide that initial production should focus on concrete blocks. The model can be extended to other situations, helping critical decision-making regarding trade-offs between the different value dimensions considered in the study.**

I. INTRODUCTION

There is a growing concern about reducing the human environmental impact. Many companies are searching for environmental harmless solutions in order to decrease the consumption of natural resources and energy on industry, besides less waste on industrial production. They are also working on better product designs, and developing new ways of reuse or recycling products in their end-of-life as input for new products or processes.

The construction chain, which has a gigantic size, belongs to this context, especially when attending to its function to provide adequate built environment. Due to the size of their products, there is a main concern about the high consumption of natural resources. In addition, the construction chain is considered the largest natural resources consumers in many economies. It is responsible for 50% of natural resources consumption, 40% of total energy consumption, and 50% of the total waste production [1]. Use of natural aggregates is large and grows as concrete consumption grows. The sector also produces a large amount of waste that need to be adequately discharged, e.g., the Japanese construction industry had produced 75 million tons per year, which correspond to 19% of the industrial waste worldwide produced [2].

Studies in construction sector are focused on cement matrix, because concrete is the most widely used building material in the world. Its consumption is estimated of 6 billion tons per year [3]. This scenario demanded the achievement of a more suitable concrete with characteristics, including: extended durability, better performance and efficiency, and environmental friendly. There are several research involving cement matrixes with less impact. These researches are incorporating many types of waste from other industries, like rubber, metal slag, tannery or materials used on Portland cement manufacture such as fly ashes, husk rice ashes and others, as a substitute of natural components. [4, 5, 6].

In the other hand, there are many studies to promote the use of recycled waste produced in own construction [7, 8, 9] with a double benefit: the correct disposal of its own waste and the reduction of environment impact caused with the extraction of natural resources. There are also economic benefits of this practice. In Brazil, despite several studies, the main use of CDW remains as bases and sub-bases for roads. A noble use of waste, as aggregate of parts and precast concrete blocks, has proven itself very effective in research, however, it is hardly used in Brazil. Failure in using the recycled aggregate is justified by construction professionals as a lack of experience in usage of aggregate as a building material, besides the prejudices regarding the product [10].

In Porto Alegre, there are no installed recycling plants of CDW, which hinders dissemination and use of waste as raw material. However, there are some initiatives for CDW recycling. A good example is Solidariedade (Solidarity), a non-governmental organization (NGO) founded by the residents of Cristal District. The Social-Environmental Transformation Center – Centro de Transformação Sócio-Ambiental (CTSA) – is the main project of the NGO cooperative. It emerged as an alternatives to generate incomes for families of carters and pickers. This is due to a new city law (Lei 10.531), in 2008, which states that picking activity should be gradually removed of Porto Alegre's streets. The developed alternative activity involves social action to produce Sealing Concrete Block (SCB) produced from recycled aggregates. In addition, the production of SCB should be environmental friendly.

Although a large number of papers dealing with CDW's recycling is available, there is a lack of research about the comparison of its incorporation on concrete. Some studies evaluate, using its own standards, some performance characteristics and durability of the material. This leads to a great difficulty in comparing the benefits brought by CDW addition, and about to a technical and environmental performance classification. Additionally, there is almost no structured process to compare products containing CDW, using criteria to analyze its development, and technical viability to be a more sustainable material or not. This scenario points out the need of development of an organized and systematic basis of quality requirements, to launch a more sustainable CDW's product on market.

Another consequence of this gap is related to an existing lack of analysis associated of waste usage in products, as a way to improve or reduce environmental impacts. There are no structured systematic to environmental performance evaluation of waste recycling, like CDWs. It is necessary to understand (and perhaps modify) this scenario in order to compare alternatives and to decide on the most promising or impactful, and also to evaluate the real feasibility of use in the moment of processing the product for commercialization. It is necessary to have benchmarks to verify all variables that can affect the product quality as well as the environmental benefits on the use of a particular waste.

Additionally, there is no set of minimum controlling requirements to develop a product. Thus, by making an analysis from stakeholders' requirements of the process, the existing regulations for the product and the environmental sustainability requirements, the quality assessment and environmental performance minimum pattern to a sustainable construction material can be confirmed. That pattern can also propose a primary set of technical and environmental indicators. That can motivate the consumers to choose CDW-based products, and the compliance of those indicators can be the quality beacon of the product.

"Green" products development has a lack of indicators, especially those related to environmental matters. Reuse or recycling don't ensure that the product is going to be environmental friendly, when compared to traditional ones. It is necessary to manage the environmental indicators related to the product, and verify if the way has being used the waste in the product doesn't generate other negative impacts. Based on this, would be interesting to investigate the possibility of producing sealing concrete blocks (SCBs) using CDW, in a small cooperative which intends to work within environmental sustainability concept. Therefore, it is necessary to better understand technical, environmental, and customers' requirements of this product.

Literature presents several tools developed to understand customer's demands on product development. Quality Function Deployment (QFD) is one of them. Akao and Mazur [11] defined QFD as a tool to assure that customer needs are going to be properly deployed into product characteristics. It is an important method within the product development dedicated to translate consumers' requirements into technical specifications. [12] The authors [11] state that the tendency and difficulties to be overcome in future research on QFD is how to cover requirements that go beyond customer's perception. Therefore, QFD challenges are to include demands from other dimensions which represents sustainable economic, social and environmental aspects.

II. METHOD

This section presents the method to reach the requirements' extended list, as well as the existing positive and negative relationships between them, allowing the identification of the main characteristics of the "green" SCB.

A. Quality requirements survey

A marketing research was conducted to identify the customer's requirements (voice of consumer). The survey followed a few steps: stakeholders' identification; qualitative survey; requirements tree diagram; quantitative survey; and customer requirements' importance calculation [13].

Rozenfeld et al. [14] state that these stakeholders may be involved in many stages of the product's life cycle. They can be considered external clients, which will consume the product; the intermediate consumers, the ones who will make the distribution and sale; and internal customers, who are responsible for design and production. The authors also state that the most important are external customers, and their needs should be prioritized over other customers.

Based on this premise, the cooperative identified their external customers: the builders, specifically employees who coordinate the construction site, working directly with the product, and having knowledge about SCB's necessary features. Besides them, there are other decision makers such as architects and design engineers, as well as building materials shoppers, and self-constructors. However, this research had focus only on employees of construction companies, considering them as the main customers of that cooperative.

As the goal of this approach was to achieve a better understanding of the phenomenon, a qualitative survey was conducted, using a structured interview instrument and interviewees by convenience. It was enough to achieve a deeper knowledge on the subject. In addition, the researched product has low complexity, so the customers didn't present large number of requirements about it. In some cases, they mentioned that "(…) the product should comply with the standards". In this way, four senior engineers with large experience on construction site were interviewed. The answers obtained on third and fourth interviews converged, with no new requirement arising. The identified requirements were few and mostly functional, due to product low complexity.

A questionnaire with open questions was used to realize the qualitative survey. Personal interviews were conducted to identify needs and possible problems related to the product. Every interview was audio-recorded with authorization of the interviewees. Environmental issues were included in the questionnaire to identify if interviewees had any concern about it. However, they were unable to answer to these questions. Secondary data from literature review and competitors analysis, of conventional products of concrete block manufacturers, have complemented qualitative survey about the concrete block requirements.

Identified quality requirements from interviews, literature review and competition analysis were grouped in a tree diagram, presented in Figure 1. In the next step to every requirement must be identified, at least, one performance driver (attribute or quality characteristic). They are a technical translation of quality requirements. Performance drivers selected for this study are presented, also, in Figure 1.

B. Environmental requirements survey

Achieving the environmental sustainability requirements was based on a research developed by Projeto REDE MORAR TS' team at UFRGS, which was supported by the Financiadora de Estudos e Projetos (FINEP) agency's resources. This project is being developed in partnership with other Brazilian universities in order to study ways of incorporating Social Technologies (ST) in Social Housing (SH).

Sustainability criteria selected to the study fits within the sub-project which scope is to design project guidelines for housing production incorporating ST. It also aims to identify criteria for the assessment of environmental sustainability of materials and constructive solutions. Define criteria for a higher sustainability, specifically for social housing projects, represents consistent challenges due to the complexity of both topics [15].

Considering the larger analysis existing in the project, which includes assessments of Social Technologies, Social Housing, performance, innovation, health and costs, and environmental sustainability, it was picked for this study the focus on environmental sustainability aspect. Therefore, this section presents partial results of the research conducted by Projeto FINEP REDE MORAR TS UFRGS' team. The method adopted to survey these criteria was based on scientific papers about sustainability.

As reference of environmental sustainability indicators were adopted the criteria from Caixa Economica Federal's Selo Casa Azul, and from international certifications of green buildings LEED® Green Building - New Constructions and Major Renovations V3.0 from United States Green Building Council (USGBC); and the Living Building Challenge 2.0 from International Living Building Institute (ILBI). Environmental requirements identified for the SCB were also organized in a tree diagram (Figure 2).

Quality Demands	Quality Requirements	Quality Performance Drivers
Good mechanical performance	Higher compression resistance	Compressive strength (MPa)
	Higher tensile resistance	Tensile resistance (MPa)
	Higher rigidity	Block deformation modulus (MPa)
	Lower shrinkage	Maximum permissible shrinkage (%)
	Higher compactness	Density (specific mass) (g / cm³)
Good aspect	Higher texture variety	Number of texture variations
	Higher color variety	Number of color variations
	Lower dimensional variation	Width and height dimensional tolerance (mm)
	Good aspect	Visual color uniformity scale (1 to 5)
	Good plumb and alignment assurance	Edge angle (°)
Easy application and use	Lower weight	Mass (kg)
	Good block packaging	Percentage of damaged blocks in delivery
	Better plaster grip	Average absorption (%)
	Easy modularity	Number of family variations
	Higher lot traceability	Lot information quantity
Good durability	Good sealing	Maximum Permeability (%)
	Lower wall finishing needs	Surface regularity visual scale (1 to 5)
	Lower incidence of damaged blocks	Percentage of damaged blocks at work (%)
	Good performance in high temperatures	Flame Spread Index
	Lower carbonation rate	Maximum optical smoke density
		Carbonation depth (mm)

Figure 1 - Tree Diagram Of Concrete Block's Quality Requirements.

Environmental demands	Environmental requirements	Environmental performance drivers
Lower energy consumption for raw materials	Use of waste composition	Recycled aggregates percentage of use (%)
	Lower consumption of cement	Cement percentage in trace (%)
	Use of regional materials	Maximum distance from the source of the components (Km)
Lower impact transformation	Lower consumption of natural resources (water)	Water consumption in production (l)
	Lower aggregate consumption of energy (electricity)	Electricity consumption in production (Kw/h)
	Lower natural resources consumption (natural aggregates)	Natural aggregates percentage of use (%)
	Lower waste generation and emissions	Waste generation percentage (%)
Lower impact in use and discard	Absence of toxic materials	Toxic materials percentage (%)
	Modularity	Number of blocks variations per family
	Higher potential for reuse or recycling	Number of components in block manufacturing

Figure 2 - Deployment of quality characteristics on environmental requirements

C. Regulatory requirements survey

Regulatory requirements were based in applicable standards to SCBs, as well as to masonry walls building system. Thus, normative references identified were related to concrete block masonry of Brazilian standard NBR 6136 – Concrete hollow blocks for masonry – Requirements (ABNT, 2007); and NBR 15575-4 – Residential Buildings – Performance, Part 4: Internal and external vertical sealing systems (ABNT, 2013).

NBR 6136 [16] establishes the requirements for plain hollow blocks of concrete, intended for masonry with or without structural function. This standard evaluated, therefore, the requirements refer only to the class of blocks without structural function which are called “D” class. The NBR 15575-4 [17] sets out the performance requirements on internal and external vertical seals system to residential buildings and it is used as a performance evaluation procedure for building systems. Only requirements and standards directly connected to SCBs were focused, since this standard is quite large and it also consider many different aspects of the systems and components. Figure 3 displays the regulatory requirements collected in both two standards, along with the quality characteristics for each requirement.

Regulatory demands	Regulatory requirements	Normative performance drivers
NBR 6136	Homogeneous and compact concrete	Visual homogeneity scale (1 to 5)
	Good laying	Edge angle (°)
	Fulfil with the minimum thickness of the block wall	Wall Thickness (mm)
	Fulfil with minimum size hole	Hole dimensions (mm)
	Minimum size of accommodation corbels	Radius of accommodation corbels (mm)
	Good sealing	Permeability (%)
	Minimum Compression Resistance	Compressive strength (MPa)
	Good absorption and adherence of mortar	Average absorption (%)
	Lower shrinkage	Admitted shrinkage (%)
	Lower dimensional variation (width, height)	Width and height dimensional tolerance (mm)
NBR 15575-4	Good resistance to fixing objects	Resistance to suspended items request (kN)
	Good resistance to soft body impacts	Resistance to soft body impacts (J)
	Good resistance to actions transmitted by doors	Resistance to actions transmitted by doors (J)
	Good resistance to hard body impacts	Resistance to hard body impacts (J)
	Good fire safety	Flame spread index
		Maximum smoke optical density
	Good tightness	Sum of areas of moist spots maximum percentage
	Good thermal performance	Maximum thermal transmittance (W/m².K)
		Minimum thermal capacity (kJ/m².K)
	Good acoustic performance	Weighted noise reduction index

Figure 3: Deployment of the quality characteristics of regulatory requirements

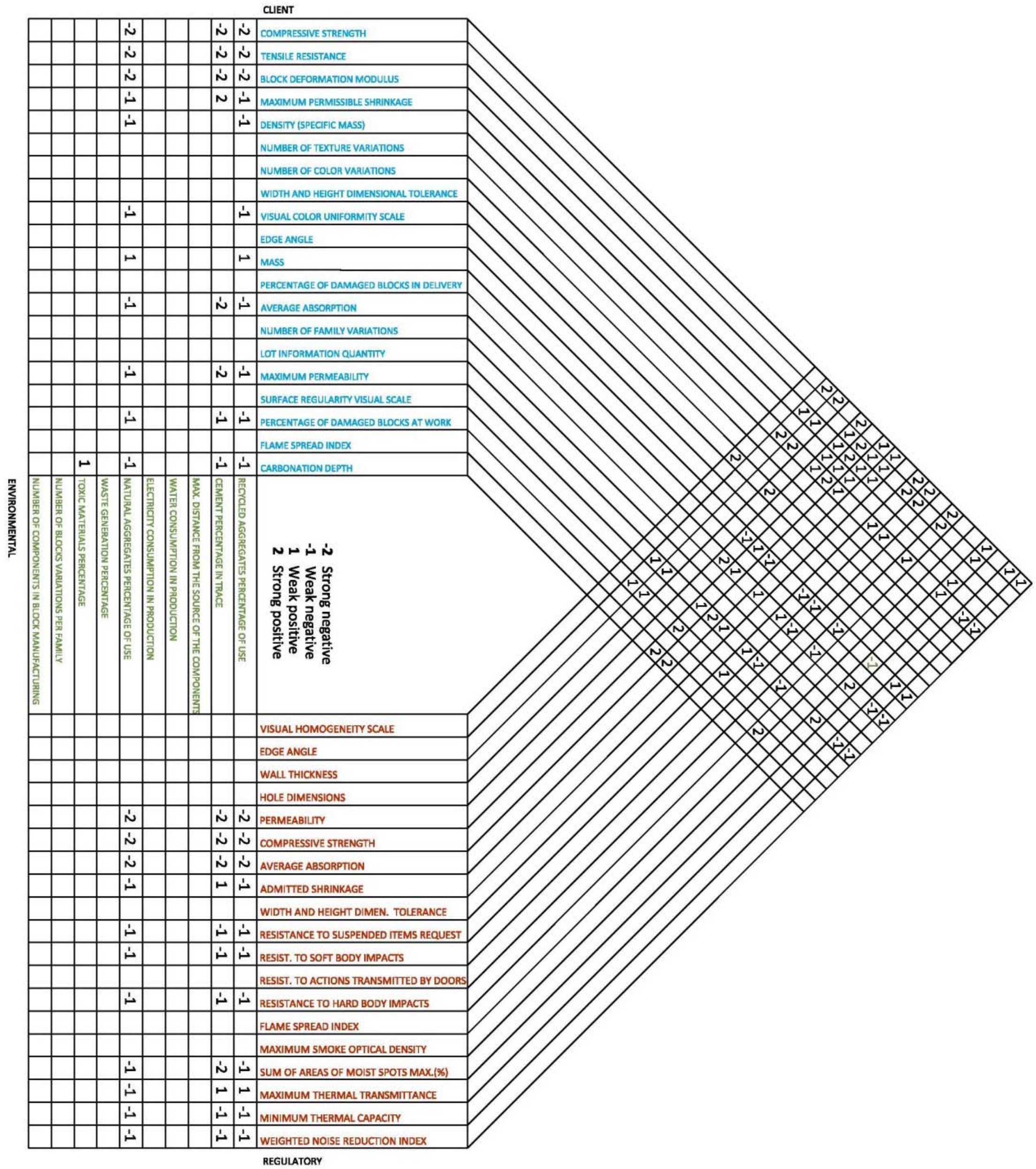

Figure 4: Correlation matrix diagram

III. RESULTS

This section presents the extended list of requirements (quality, environmental and regulatory), as well as the main positive and negative relationships between them, which allows the prioritization of more important drivers of SCB that CTSA cooperative should control. This step requires a deep and careful attention to realize the assessment, and should be realized as a work group. Meetings were held with researchers of Laboratório de Ensaios e Modelos Estruturais - LEME (Models and Structural Testing Laboratory (MSTL)) to identify the relationships between requirements and performance drivers.

Complementarily, a correlation analysis was realized between the three types of performance drivers. Thus, the matrix of correlations was constructed. It allows product developers understand the existence or not of trade-offs between these drivers. This evaluation is relevant to identify conflicting goals. Trade-offs should be managed to a better product design, e.g., assess if quality performance drivers are whether favorable or unfavorable to the environmental ones. [18]

So it was developed a Y-type matrix which is the combination of three L-type matrices. It allows evaluating relationships among three dimensions [19]. This type of matrix facilitates the visualization of all relationships established in a single diagram. Correlations were evaluated in terms of positive or negative, strong or weak, using the following scale: strong negative (-2); weak negative (-1); weak positive (1); and strong positive (2). Each performance driver was examined pairwise and checked its correlation (Figure 4). Thus, should be highlighted the negative correlations (strong and weak) enabling quick visualization of trade-offs.

The conclusion of this research leads that among both the customers and standards items there are few negative correlations and the ones which appears are weak. Most of negative correlations indicated by the matrix happen between environmental items, in opposition to both customers and standards' items. These environmental matrix items are those related to SCB composition. This result is consistent since these environmental characteristics interfere negatively in physical characteristics and also in mechanical performance characteristics and durability of the block.

However, the cooperative has among its objectives the intention of developing an environmentally friendly product, suitable to the sustainability issues which means that these negative relationships founded cannot be neglected. At this point, the product developer must make a trade-off between these relationships to guarantee that the full implementation of one single feature does not adversely affects many others in order to find a good balance between all needs and also to developing a product that fully meets the standards, meets the customer and meet the environment benefit.

IV. CONCLUSIONS

Discussions about products environmental sustainability are very common today. Waste recycling in constructions is considered an important sustainable aspect, but the activity often neglects others environmental requirements. Recycling is considered a main form to ensure environmental benefits. However, sometimes, to make it feasible results in an even higher environmental damage and these occurrences are often not discussed.

The Cooperative wanted to explore a spot in the sustainability market. Therefore, this study sought to answer which requirements and performance drivers should be met for the development of a SCB with use of CDW regarding the environmental logic. Thus, the product has the use of recycled materials as its essence, but this research found other needed environmental demands to understand how those components could affect the product. To answer that question it was necessary to identify requirements regarding to quality (customers), environmental, and normative demands.

Regards to them, this study allowed to reach some interest considerations:

a) Quality: As a low complexity product, it was expected a reduced number of requirements. The customers' requirements show an important concern about standards compliance, as well as uniformity and product regulatory, which means quality control. Standards compliance was so important for customers that many of the presented requirements were regulatory.
b) Standards: the performance requirements of NBR 15575-4 (ABNT, 2013) standard showed considerable difficulty in its interpretation since, regarding some topics, it does not make clear what requirement is associated to which part of the building system. So, as the concrete block item is part of the constructive masonry wall system, it has become difficult to identify what characteristics and specifications were or could be attributed to the product.
c) Quality and standards requirements: in general, the requirements of these two approaches do not come into conflict, thus generating a larger easiness to meet the demands of these two sources of information.
d) CDW recycling, cement and sustainability: the question that stood out in the development of the method was the necessary trade-off to control the quality performance drivers of 'compressive strength', 'lower cement consumption' and 'higher recycled aggregates used proportion'. These last two drivers showed similar amounts among the environmental demands by the end of the examinations, indicating that a balance is needed between them. In conclusion, the main performance driver to be controlled is regulatory "minimum compression resistance", since it's the main concrete feature. Besides, it is a key action to manage the concrete dosage in order to obtain the better balance between the "proportion of recycled aggregates" and the "cement consumption", which is one of the most impactful construction products. Another solution that might be studied and implemented is the incorporation of other waste to cement, such as, for example, rice husk ash.

ACKNOWLEDGMENTS

The authors would like to thank CAPES Foundation (Process number 002-16-0, and Process number 2644-15-0), Ministry of Education of Brazil, by its financial support of scholarship grant to develop this research.

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