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A Multi-Criteria Decision-Making Framework for Prioritizing and Overcoming Sectoral Barriers in Converting Agricultural Residues to a Building Material

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Abstract: Biological products utilization are increasingly encouraged in different sectors such as building construction to facilitate moving towards a circular economy. However, this task is facing several barriers in supply chain and construction sectors. This study identified common barriers in converting agricultural residues to building materials and products in the agriculture sector, transportation, and manufacturing, as well as construction and operation phases in the building sector. The feasibility level to overcome the barriers has been scored. In addition, the barriers and sectors have been prioritized through ordinal priority approach. The results ranked the priority of the barriers as technology (0.3083), policy (0.2211), knowledge (0.1972), cost (0.1500), social and cultural (0.0739), and infrastructure (0.0494). Sectors were ranked in feasibility level to overcome the barriers from lowest to highest as operating, construction, manufacturing, transport, and agriculture. It is recommended to local communities to give priority to the building sector rather than supply chain and work under an integrated framework to enhance the feasibility level, which should include localization, prevention, collaboration, and digitalization. In particular, Chile should promote converting agricultural residues to building products as the project aligns with several initiatives existing in its circular economy roadmap.

Keywords: circular economy; Chile; construction sector; insulation; nature-based materials; ordinal priority approach

MSC: 90B50; 90B90

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1. Introduction

Waste streams are mainly known as municipal and industrial waste. However, there are other types of waste, such as agricultural residues, that are the basis of land fertility, bedding the animals, and potential resources of energy and material production [1,2].

The literature on this topic focus mainly on estimating the amount of residues. Karan and Hamelin [3] estimated the residual production by a spatially explicit assessment method in France for several type of crops. The estimation consist of a range of production from cereal crops, such as wheat, barley, maize, oats, rye, and rice, to oil crops, for instance rapeseed, sunflower, soy, etc. Estimating crop residues is considered for bioenergy application. However, there are other competitive industrial demands such as construction industry. Such application is mainly divided into two categories either using agricultural residues (and sometimes forestry residues) as insulation panels/materials or processing agricultural residues as well as other byproducts for developing bio-based concretes and bricks. There are several studies investigating the thermal and acoustic characteristics of different combinations of agricultural residues, for instance rice husk and wheat husk to produce composites [4], wheat straw and corn husk [5], eucalyptus globulus leaves and wheat straw fibers [6], straw and olive tree waste [7], and wheat straw with timber [8,9].

Understanding the mechanical and thermal behavior of these materials and their production process are of vital importance to deliver required performance in construction sector and make them competitive to traditional industrial materials [10–12]. On the other side, solutions for concrete and brick production have been introduced, such as as sunflower and wheat stalk for mortar preparation [13], the combination of rice husk or coir pith in mud bricks [14], and rice husk ash-based mortar [15].

The building industry is responsible for 40% of the input materials to the world economy. However, only 20–30% of these materials are recycled or reused [16]. The construction sector is associated with several massive environmental impacts including resource input such as energy, water, and material, as well as massive resource loss in the form of waste generation. In the context of the circular economy (CE), several ideas such as the application of local environmentally friendly materials are being developed. The application of these nature-based materials often presents certain advantages such as lower energy demand and cost [11]. CE encourages narrowing the resource flow loops by reducing resource use and/or finding material replacements that are renewable [17]. Narrowing the loops and the application of other CE goals such as closing and slowing them are necessary in construction sector, which can be promoted by all "R" strategies such as reuse, reduce, repair, and refuse rather than only recycling. These strategies aim to improve resource exploitation efficiency and accelerate switching the mindset from only waste management practices [18–20].

Despite good progress on finding technical performance and identifying the properties of agricultural residues, there are little advancement on know-how to design supply chain of these materials, identifying the stakeholders, assigning their roles, and defining the collaborative environment to complete agro-waste conversion to a building product. This gap should be filled by a cross-sectorial vision in order to address the challenges beyond technological progress and to consider the whole value chain of the agricultural residue [21]. In the early stage of addressing the challenges in macro-scale collaboration, it is of vital importance to identify common barriers in different sectors that are involved in future CE models of agricultural residue's application as building product. The second gap that is addressed in this paper is to identify the common barriers in different sectors that are responsible for converting agricultural residues to a building product considering the perspective of all actors across the supply, design, construction and utilization stages. This can facilitate a successful transition from a linear economy towards a circular economy to reduce the environmental impact of the building sector in each society [16].

As far as barriers in CE are concerned, their identification was limited more to a particular sector or stakeholder, for instance a lack of information on the type and quantity of materials at the refurbishment or demolition stages, uncertainty in market demand for secondary resources, and the flow of returned goods [22]. Bakajic and Parvi [23] identified barriers in the EU waste management supply chain to closing waste loops as part of the CE program. The barriers include cultural, regulatory, financial, operational, structural, and technological ones. By using qualitative semi-structured interview, it was found that financial barriers were the leading issue against implementing CE programs. In one of the most comprehensive studies, Bilal et al. [18] identified seven key barriers to the circular economy in the building sector for designing a mitigation framework. It has been reported that a lack of environmental regulations and laws is the main barrier to the circular economy. Despite good progress in analyzing the barriers and corresponding priorities, the work has some limitations in cross-sectoral vision in supply chain of CE. Giorgi et al. [20] resolved the issues raised in previous studies by investigating the main drivers and barriers from the perspectives of multi-actors of building value chain in different countries. The stakeholders were listed in four categories: the decision-making phase, such as investors, owners, banks, and designers; the construction phase, such as manufactures and construction companies; the use phase, such as users; and the end-of-life phase, such as demolition companies and waste managers. By interviewing these stakeholders, several barriers in implementing circular strategies across building process have been found. However, systematic prioritization of the barriers in different sectors such as transportation and logistics was not discussed in that paper. On the other side, Mahpour [24] has worked on prioritizing barriers to adopt circular economy approaches in construction and demolition waste management using the fuzzy TOPSIS multi-criteria decision-making (MCDM) model. This study identified 22 potential barriers as alternatives through a literature review. Then, experts in the fields ranked those barriers in three criteria: behavioral, technical, and legal. The results on ranking the priority to overcome the barriers in this paper could be useful by changing the mind-set from waste management to circular economy policies. However, the subject was mainly limited to the disposal stage.

Application of MCDM in prioritizing the barriers in CE subjects is not common, while in other fields, such as reverse logistics or supply chain, it has been widely used [25–28]. On the other side, MCDM application has been combined with other tools such as benchmarking in logistics service providers to address the gap in firms' performances and prioritizing the required elements or organizational practices [29]. Chejarla et al. [30] found some trends in MCDM applications in assessing logistics performance. They reported that the most common data collection approach was expert data, while in data processing analytical methods are dominant. Additionally, they have stated that the most common method used in the field is Analytic Hierarchy Process (AHP). Considering all progress, the third gap that is covered by this study is to use MCDM approach to rank common barriers and feasibility level to overcome those barriers in multi-sector scale. In this context, this study presents a multi-criteria framework based on applying the Ordinal Priority Approach (OPA) methodology. In the following section, an improved algorithm of the OPA method is presented, eliminating one of the limitations of the conventional OPA methodology presented by [31].

2. Methodology

2.1. OPA Methodology

The OPA methodology belongs to the group of newer multi-criteria techniques that has become a reliable tool for rational and objective reasoning. Furthermore, the effectiveness and efficiency of the OPA methodology has been confirmed through several published studies, including OPA-based project selection [32] and performance evaluation [33–35].

The conventional OPA methodology [31] is based on determining the performance of alternatives based on predefined ranks of alternatives, criteria, and experts. This implies that it is necessary to transform the data that represent the alternative into home matrices. This transformation of information into ranks of alternatives generalizes data, which affects the quality and accuracy of results. Therefore, this study presents an improved algorithm of the OPA method (OPA-I), which enables objective reasoning based on the current information in the home matrix.

In the traditional OPA methodology, alternatives and criteria are prioritized according to predefined ranks. In this work, the ranks of alternatives were established according to the actual score of alternatives, not by their ranks. For example, suppose we have an actual score of alternatives A_1 and A_3 under criteria C_1, and we obtain 2.320 for A_1 and 2.374 for A_3. Alternative A_1 is ranked as second, while alternative A_3 is ranked first based on the obtained values. However, if we look at actual scores, alternative A_3 has an advantage of only 2.3% over alternative A_1. An improved algorithm of the OPA methodology was developed to practically consider the impact of alternatives in the decision-making model, which enables the realization of real values of the actual score of alternatives.

2.2. OPA Algorithm

The algorithm of the OPA-I method is implemented through the steps presented in the following section:

Step 1: Expert ranking. If the OPA-I method is implemented in group decision-making, it is necessary to define a set of experts participating in the research; otherwise, this step is omitted. For example, suppose that b experts $\Im_t$ $(t = 1, 2, \ldots, b)$ participate in the study.

After selecting the experts, it is necessary to define the degree of their qualifications and the degree of knowledge of the problem. Finally, based on experiential and theoretical competencies, experts are ranked.

Step 2: Criteria ranking. Suppose that the research defined a set of n criteria $B_j(j = 1, 2, \ldots, n)$ and that the experts defined the significance of the criteria within the linguistic matrix $\Re^p = \left[\partial_j^p\right]_{n\times 1}$ $(1 \leq p \leq b)$, where ∂_j^p represents the relative importance of the criterion j defined by the expert p $(1 \leq p \leq b)$. For the criterion to have a better rank, it is necessary to have the highest possible value of ∂_j^p.

To satisfy that condition $C_j^{(r)} \geq C_j^{(r+1)}$, then the significance of successive criteria should meet the condition that $\zeta_j^{p(r)} \geq \zeta_j^{p(r+1)}$, where $\zeta_j^{p(r)}$ represents the significance of jth criteria at the kth rank assigned by the pth expert. Then we can define the condition that the weighting coefficients of successive criteria should meet as follows:

$$p\left(j\left(\zeta_{pj}^{(r)} - \zeta_{pj}^{(r+1)}\right)\right) \geq 0;\ \ \forall p, j \tag{1}$$

where $\zeta_{pj}^{(r)}$ represents the weighting coefficient of the jth criterion at the rth rank defined by the pth expert.

Thus, expression (1) can be represented as follows:

$$p\left(\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^p\right\}}{\partial_j^{p(r)}}\left(\zeta_{pj}^{(r)} - \zeta_{pj}^{(r+1)}\right)\right) \geq 0; \forall p, j \tag{2}$$

where $\partial_j^{p(r)} \in \Re^p$ represents the significance of the jth criterion at the rth rank defined by the pth expert.

To define the weight coefficients of the criteria, a multi-objective nonlinear mathematical model (3) was defined.

$$\begin{aligned}
&Max\ Min\left\{p\left(\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^p\right\}}{\partial_j^{p(r)}}\left(\zeta_{pj}^{(r)} - \zeta_{pj}^{(r+1)}\right)\right); p\left(\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^p\right\}}{\partial_j^{p(r)}}\zeta_{pj}^{(m)}\right)\right\}; \forall j, i\\
&s.t.\\
&\sum_{t=1}^{b}\sum_{j=1}^{n}\zeta_{tj} = 1;\\
&\zeta_{pj} \geq 0;\ \forall p, j
\end{aligned} \tag{3}$$

Model (3) can be transformed into a linear mathematical model as follows:

$$\begin{aligned}
&Max\ \theta\\
&s.t.\\
&p\left(\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^p\right\}}{\partial_j^{p(r)}}\left(\zeta_{pj}^{(r)} - \zeta_{pj}^{(r+1)}\right)\right) \geq \theta; \forall p, j\\
&p\left(\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^p\right\}}{\partial_j^{p(r)}}\zeta_{pj}^{(m)}\right) \geq \theta; \forall p, j\\
&\sum_{p=1}^{b}\sum_{j=1}^{n}\zeta_{pj} = 1;\ \zeta_{pj} \geq 0;\ \forall p, j
\end{aligned} \tag{4}$$

where $\partial_j^{p(r)} \in \Re^p$ represents the significance of the jth criterion at the rth rank defined by the pth expert.

Step 3: Ranking alternatives. In this step, the final significance of the alternatives within the considered set of alternatives S_i $(i = 1, 2, \ldots, m)$. Suppose that experts $\Im_t$ $(t = 1, 2, \ldots, b)$ evaluated alternatives within the home matrix $\aleph^p = \left[\psi_{ij}^p\right]_{m \times n}$ $(1 \le p \le b)$, where ψ_{ij}^p represents the relative importance ith alternative in relation to criterion jth defined by the pth expert. The weighting coefficients of successively ranked alternatives should meet the condition that $\zeta_{ji}^{p(r)} \ge \zeta_{ji}^{p(r+1)}$, where $\zeta_{ji}^{p(r)}$ represents the significance ith the alternative at the kth rank under the jth criterion assigned by the pth expert. We can then define the condition to be met by the weighting coefficients of the alternatives as follows:

$$p\left(\frac{\min\limits_{1\le j\le n}\{\zeta_j\}}{\zeta_{pj}^{(r)}}\left(\frac{\min\limits_{1\le i\le m}\{\psi_{ji}\}}{\psi_{pji}^{(r)}}\left(\zeta_{pji}^{(r)} - \zeta_{pji}^{(r+1)}\right)\right)\right) \ge 0; \forall p, j, i \tag{5}$$

where $\psi_{ji}^{(r)} \in \aleph^p$ represents the significance ith the alternative on the rth rank defined by the pth expert under jth criteria.

To define the final rank of alternatives, a linear mathematical model (6) for determining the weight coefficients of alternatives is defined as follows:

$$\begin{aligned} & Max\ \theta \\ & s.t. \\ & p\left(\frac{\min\limits_{1\le j\le n}\{\zeta_j\}}{\zeta_j^{(r)}}\left(\frac{\min\limits_{1\le i\le m}\{\psi_{ji}\}}{\psi_{ji}^{(r)}}\left(\zeta_{pji}^{(r)} - \zeta_{pji}^{(r+1)}\right)\right)\right) \ge \theta; \forall p, j, i \\ & p\left(\frac{\min\limits_{1\le j\le n}\{\zeta_j\}}{\zeta_j^{(r)}}\left(\frac{\min\limits_{1\le i\le m}\{\psi_{ji}\}}{\psi_{ji}^{(r)}}\zeta_{pji}^{(m)}\right)\right) \ge \theta; \forall p, j, i \\ & \sum_{p=1}^{b}\sum_{j=1}^{n}\sum_{i=1}^{m}\zeta_{pji} = 1;\ \zeta_{pji} \ge 0;\ \forall p, j \end{aligned} \tag{6}$$

where $\psi_{ji}^{p(r)} \in \aleph^p$ represents the significance ith the alternative on the rth rank defined by the pth expert under jth criteria.

3. Results and Discussion

3.1. Case Study

A case study for the application of methodology is related to prioritizing the barriers in each sector involved in converting agricultural residues to a building material or product as well as their application. Although the proposed methodology and defined sectors and barriers can be employed in regional scales worldwide, the policy implication that is extracted through the development of methodology is devoted to Chile, in particular its central–south zone due to massive availability of agricultural residues in the region. This zone also hosts wood production activities, and therefore there is the potential to adapt the supply chain of the wood industry for another bio-product originating from agricultural residues. The other reason for this is that the region is susceptible due to inefficient space heating such as wood burning with massive consequences of atmospheric pollution on public health [5]. Any changes in the construction sector, such as efficient energy systems, building envelopes, and reducing embodied carbon are encouraged. The other challenges in Chile include illegal waste disposal sites with the lowest rank in material productivity of all OECD countries [36]. To solve these issues it is important to identify and remove the barriers that might boost local opportunities for CE, and therefore could play the role of a pilot in CE for other Latin American and Caribbean societies.

In the case study presented in this paper, the application of the OPA-I methodology for the evaluation of five alternatives S_i (I = 1, 2, . . . , 5) under six criteria B_i (j = 1, 2, . . . , 6) is presented. Alternatives include sectors/phases involved in the production to use phase:

- S_1: Agriculture;
- S_2: Transport;
- S_3: Manufacturing/fabrication;
- S_4: Building construction;
- S_5: Operation, and maintaining the building, as well as energy auditory.

Criteria/indicators are defined the common barriers existing in aforementioned sectors according to the authors' perspectives and literature review [37–40]. It should be noted that the definition of specific criteria, i.e., barriers in a specific sector, is a common approach rather defining common barriers in different sectors. However, having a large number of criteria and specific sub-criteria with different names and definitions may lead to confusion and miscommunication among stakeholders, resulting invalid measurements. Therefore, the common criteria should be simple and understandable. In addition, they should facilitate communication between different stakeholders. Therefore, the proposed set of common barriers is a combination of financial or economic (first barrier in the present study) and other type of assets. These assets are required for a project in accordance to different dimension of sustainable development goals. Additionally, the strategic management and performance measurements in macro level, such as in the scale of regional collaboration, is no longer dependent on only financial capital [41,42]. The list of criteria is presented as follows:

- B_1—cost: lack of initial investment, risk of market failure (transaction costs, search costs, compliance issues).
- B_2—infrastructure: lack of facilities such as buildings and warehouses, roads, land, machinery and specialized equipment, installations.
- B_3—technology: lack of advanced and updated engineering systems in implementing the tasks, measurement, material characterization, and data analysis.
- B_4—knowledge: lack of specialized knowledge, incomplete and imperfect information, standardizations and codes, unknown safety.
- B_5—policy: missing the price control and incentives, unfavorable and uncertain fiscal policies, unfavorable and uncertain regulations, unfavorable and uncertain statutes, weak intellectual property, failure in reaching all stakeholders.
- B_6—social and cultural: such as resistance to change.

3.2. Results of Case Study

The evaluation of alternatives was performed using the OPA-I methodology, which was carried out through the steps presented in the following section:

Steps 1 and 2:

Five experts $\Im_t$ $(t = 1, 2, \ldots, 5)$ from different sectors participated in the research. These five experts were asked to evaluate the importance of barriers and to score the feasibility level to overcome these barriers considering existing strategies and solutions. All these experts have a significant experience in their corresponding sector. Four experts are working in industry, and the fifth has participated in their sector as an academic. The experts' profiles are as follows:

- Agriculture sector (18 years of experience, mainly in agricultural engineering).
- Transport and logistics sector (10 years of experience, mainly in logistics and transport management).
- Industrial sector (15 years of experience, mainly in bio-based products' manufacturing and fabrication).
- Construction sector (16 years of experience, mainly in construction engineering and corresponding business administration).

- Energy efficiency and maintenance sector (12 years of experience, mainly in mechanical engineering and building energy management).

All experts have minimum 10 years of experience presenting their detailed knowledge gained by being involved in several projects and being aware of the required local conditions of the corresponding sector to implement similar projects.

Based on expert assessments, the criteria within the expert groups were ranked according to the following:

(1) Expert in agriculture sector: $B_5 > B_1 > B_3 > B_4 > B_6 > B_2$;
(2) Expert in transport sector: $B_3 > B_4 > B_6 > B_5 > B_1 > B_2$;
(3) Expert in manufacturing sector: $B_5 > B_4 > B_3 > B_1 > B_2 > B_6$;
(4) Expert in building sector, construction phase: $B_3 > B_1 > B_4 > B_2 > B_6 > B_5$;
(5) Expert in building sector, operation and maintenance phase: $B_3 > B_4 > B_5 > B_1 > B_6 > B_2$.

Each expert group was assigned the same importance, so based on the defined ranks of the criteria, the OPA-I model (4) was created and used to define the weight coefficients of the criteria:

$$
\begin{array}{lcl}
Max\ \theta & & \\
s.t. & & \\
1(1(\zeta_5-\zeta_1))\geq\theta; & & 1(1(\zeta_3-\zeta_1))\geq\theta;\\
1(2(\zeta_1-\zeta_3))\geq\theta; & & 1(2(\zeta_1-\zeta_4))\geq\theta;\\
1(3(\zeta_3-\zeta_4))\geq\theta; & & 1(3(\zeta_4-\zeta_2))\geq\theta;\\
1(4(\zeta_4-\zeta_6))\geq\theta; & & 1(4(\zeta_2-\zeta_6))\geq\theta;\\
1(5(\zeta_6-\zeta_2))\geq\theta; & & 1(5(\zeta_6-\zeta_5))\geq\theta;\\
1(6\cdot\zeta_2)\geq\theta; & & 1(6\cdot\zeta_5)\geq\theta;\\
1(1(\zeta_3-\zeta_4))\geq\theta; & & 1(1(\zeta_3-\zeta_4))\geq\theta;\\
1(2(\zeta_4-\zeta_6))\geq\theta; & & 1(2(\zeta_4-\zeta_5))\geq\theta;\\
1(3(\zeta_6-\zeta_5))\geq\theta; & \ldots & 1(3(\zeta_5-\zeta_1))\geq\theta;\\
1(4(\zeta_5-\zeta_1))\geq\theta; & & 1(4(\zeta_1-\zeta_6))\geq\theta;\\
1(5(\zeta_1-\zeta_2))\geq\theta; & & 1(5(\zeta_6-\zeta_2))\geq\theta;\\
1(6\cdot\zeta_2)\geq\theta; & & 1(6\cdot\zeta_2)\geq\theta;\\
1(1(\zeta_5-\zeta_4))\geq\theta; & & \sum_{p=1}^{6}\sum_{j=1}^{6}\zeta_{pj}=1;\\
1(2(\zeta_4-\zeta_3))\geq\theta; & & \zeta_{pj}\geq 0;\ \forall p,j\\
1(3(\zeta_3-\zeta_1))\geq\theta; & & \\
1(4(\zeta_1-\zeta_2))\geq\theta; & & \\
1(5(\zeta_2-\zeta_6))\geq\theta; & & \\
1(6\cdot\zeta_6)\geq\theta; & &
\end{array}
$$

Lingo 18.0 software was used to solve the linear model. By solving the linear model, the following values of the weight coefficients of the criteria were obtained:

$$
\begin{aligned}
\zeta_1 &= 0.1500;\\
\zeta_2 &= 0.0494;\\
\zeta_3 &= 0.3083;\\
\zeta_4 &= 0.1972;\\
\zeta_5 &= 0.2211;\\
\zeta_6 &= 0.0739.
\end{aligned}
$$

A graphical representation of the significance of the criteria is shown in Figure 1.

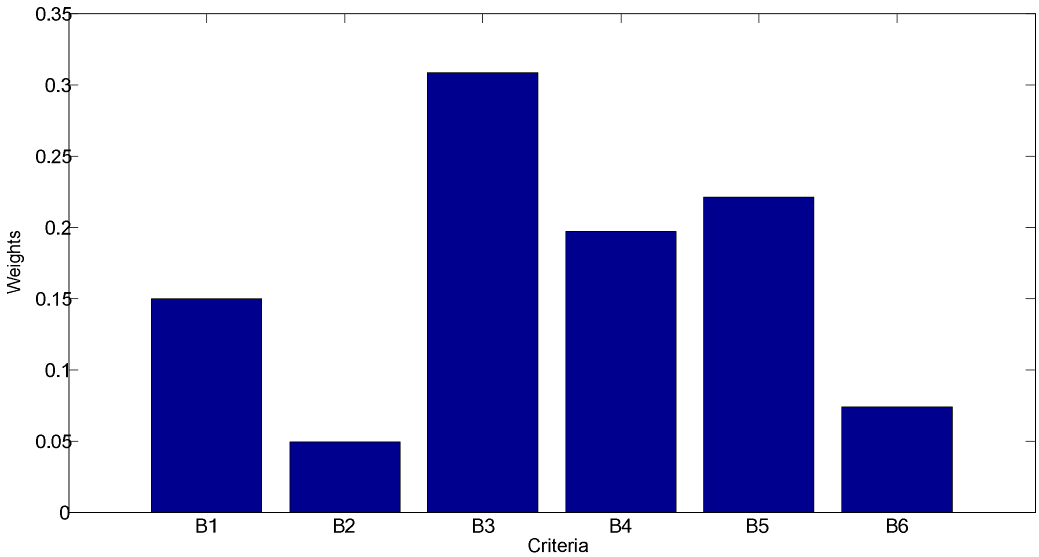

Figure 1. Criteria weighting coefficients.

The analysis of the results from Figure 1 shows that criterion B_3 has the greatest influence on the choice of the optimal alternative, i.e., its influence is 30.83%. Next in importance is criterion B_5, which affects 22.11%, followed by criterion B_4, which has a significance of 19.72%. Based on the obtained results, we can define the rank of the criteria according to the following $\zeta_3 > \zeta_5 > \zeta_4 > \zeta_1 > \zeta_6 > \zeta_2$.

Step 3:

In this step, the experts scored the alternatives under defined criteria. Experts used a scale of 1–100 to evaluate alternatives, where a more score is better. Then, each expert group evaluated the alternatives within the criteria in their field according to the following:

(1) Expert in agriculture sector: $B_5 > B_1 > B_3 > B_4 > B_6 > B_2$;

Group 1	B_1	B_2	B_3	B_4	B_5	B_6
S_1	60	90	90	95	60	70

(2) Expert in transport sector: $B_3 > B_4 > B_6 > B_5 > B_1 > B_2$;

Group 2	B_1	B_2	B_3	B_4	B_5	B_6
S_2	60	70	90	95	50	90

(3) Expert in manufacturing sector: $B_5 > B_4 > B_3 > B_1 > B_2 > B_6$;

Group 3	B_1	B_2	B_3	B_4	B_5	B_6
S_3	80	90	90	50	40	40

(4) Expert in building sector, construction phase: $B_3 > B_1 > B_4 > B_2 > B_6 > B_5$;

Group 4	B_1	B_2	B_3	B_4	B_5	B_6
S_4	70	90	40	50	50	80

(5) Expert in building sector, operation and maintenance phase: $B_3 > B_4 > B_5 > B_1 > B_6 > B_2$;

Group 5	B_1	B_2	B_3	B_4	B_5	B_6
S_5	80	90	50	40	25	20

For ease of processing, expert assessments are presented within the home matrix $\aleph^p = \left[\psi_{ij}^p\right]_{5\times 6}$:

$$\aleph = \begin{matrix} \\ S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \end{matrix} \begin{matrix} B_1 & B_2 & B_3 & B_4 & B_5 & B_6 \\ \end{matrix} \begin{bmatrix} 60 & 90 & 90 & 95 & 60 & 70 \\ 60 & 70 & 90 & 95 & 50 & 90 \\ 80 & 90 & 90 & 50 & 40 & 40 \\ 70 & 90 & 40 & 50 & 50 & 80 \\ 80 & 90 & 50 & 40 & 25 & 20 \end{bmatrix}$$

Based on the values from the home matrix $\aleph$ and the weight coefficients of the criteria calculated in the previous step, we can create a linear mathematical model (6) to define the final priority of alternatives as follows:

$$\begin{aligned}
&Max\ \theta \\
&s.t. \\
&\begin{cases}
0.160(0.444(\zeta_{3,S_1} - \zeta_{3,S_2})) \geq \theta; \\
0.160(0.444(\zeta_{3,S_2} - \zeta_{3,S_3})) \geq \theta; \\
0.160(0.444(\zeta_{3,S_3} - \zeta_{3,S_5})) \geq \theta; \\
0.160(0.800(\zeta_{3,S_5} - \zeta_{3,S_2})) \geq \theta; \\
0.160(1.00 \cdot \zeta_{3,S_4}) \geq \theta; \\
0.224(0.417(\zeta_{5,S_1} - \zeta_{5,S_2})) \geq \theta; \\
0.224(0.500(\zeta_{5,S_2} - \zeta_{5,S_4})) \geq \theta; \\
0.224(0.500(\zeta_{5,S_4} - \zeta_{5,S_3})) \geq \theta; \\
0.224(0.625(\zeta_{5,S_3} - \zeta_{5,S_5})) \geq \theta; \\
0.224(1.00 \cdot \zeta_{5,S_5}) \geq \theta; \\
0.251(0.421(\zeta_{4,S_1} - \zeta_{4,S_2})) \geq \theta; \\
0.251(0.421(\zeta_{4,S_2} - \zeta_{4,S_3})) \geq \theta; \\
0.251(0.800(\zeta_{4,S_3} - \zeta_{4,S_4})) \geq \theta; \\
0.251(0.800(\zeta_{4,S_4} - \zeta_{4,S_5})) \geq \theta; \\
0.251(1.00 \cdot \zeta_{4,S_5}) \geq \theta; \\
0.330(0.750(\zeta_{1,S_3} - \zeta_{1,S_5})) \geq \theta;
\end{cases}
\cdots
\begin{cases}
0.330(0.750(\zeta_{1,S_5} - \zeta_{1,S_4})) \geq \theta; \\
0.330(0.857(\zeta_{1,S_4} - \zeta_{1,S_1})) \geq \theta; \\
0.330(1.00(\zeta_{1,S_1} - \zeta_{1,S_2})) \geq \theta; \\
0.330(1.00 \cdot \zeta_{1,S_2}) \geq \theta; \\
0.669(0.222(\zeta_{6,S_2} - \zeta_{6,S_4})) \geq \theta; \\
0.669(0.250(\zeta_{6,S_4} - \zeta_{6,S_1})) \geq \theta; \\
0.669(0.286(\zeta_{6,S_1} - \zeta_{6,S_3})) \geq \theta; \\
0.669(0.500(\zeta_{6,S_3} - \zeta_{6,S_5})) \geq \theta; \\
0.669(1.00 \cdot \zeta_{6,S_5}) \geq \theta; \\
1.00(0.778(\zeta_{2,S_1} - \zeta_{2,S_3})) \geq \theta; \\
1.00(0.778(\zeta_{2,S_3} - \zeta_{2,S_4})) \geq \theta; \\
1.00(0.778(\zeta_{2,S_4} - \zeta_{2,S_5})) \geq \theta; \\
1.00(0.778(\zeta_{2,S_5} - \zeta_{2,S_2})) \geq \theta; \\
1.00(1.00 \cdot \zeta_{2,S_2}) \geq \theta; \\
\sum_{j=1}^{6} \sum_{i=1}^{5} \zeta_{ji} = 1; \\
\zeta_{ji} \geq 0;\ \forall p, j
\end{cases}
\end{aligned}$$

By solving the linear model, we obtain the weight coefficients of the alternatives as follows:

$$\zeta_i = \begin{matrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \end{matrix} \begin{bmatrix} 0.3956 \\ 0.2627 \\ 0.2022 \\ 0.1037 \\ 0.0786 \end{bmatrix}$$

Based on the significance of the alternatives, we can define the following rank $S_1 > S_2 > S_3 > S_4 > S_5$. A comparison of the proposed OPA-I methodology with the conventional OPA algorithm was performed to validate the obtained results. The results are shown in Figure 2.

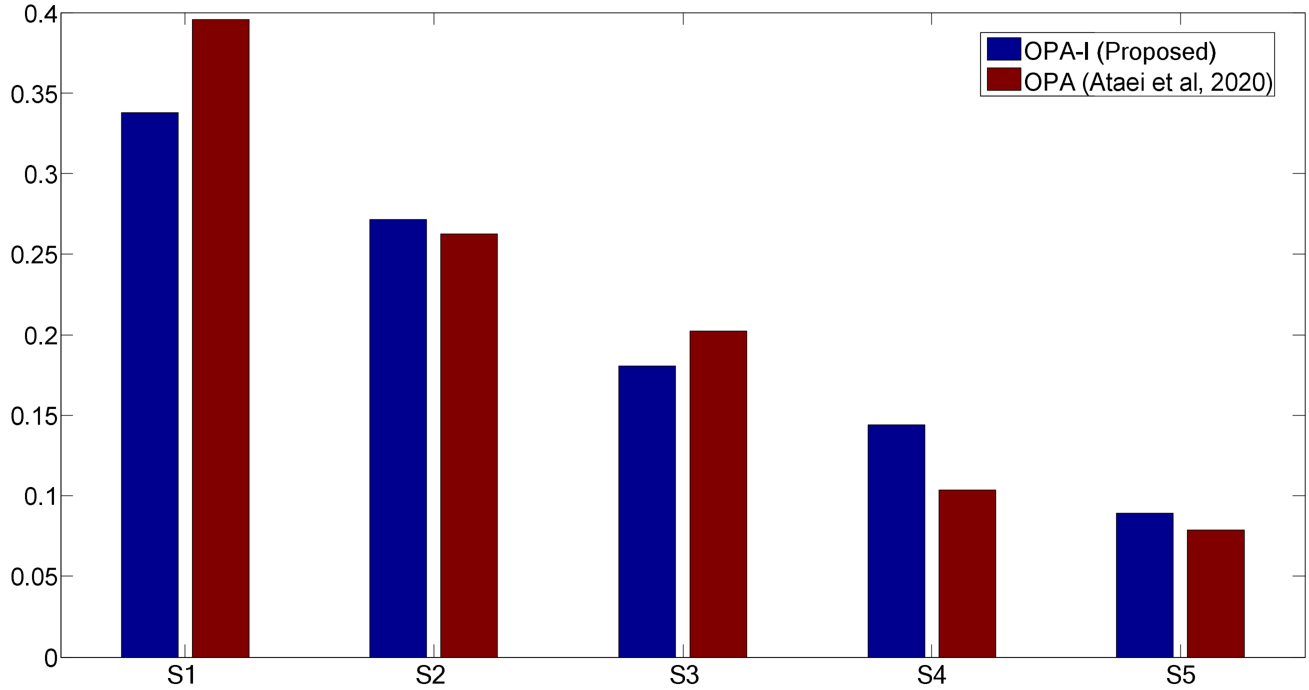

Figure 2. Comparison of OPA-I and OPA methodology [31].

Based on the comparison of the results (Figure 2), it can be concluded that S_1 is the best alternative according to both methodologies, i.e., the same order of alternatives $S_1 > S_2 > S_3 > S_4 > S_5$ is obtained based on both methodologies. However, one of the key advantages of the OPA-I algorithm compared to the conventional OPA model [31] is the consideration of the total score of alternatives under the considered criteria. On the other hand, the classical OPA methodology does not consider the total score of alternatives. The data from the home matrix are generalized, so the evaluation of alternatives is performed based on modified values (ranks). Generalization of information can lead to the wrong decision in some situations, especially if it is about alternatives that have approximately the same values in the home matrix. Thus, for example, within criterion B_6, alternative S_2 is ranked first and has a normalized value of 0.222, while alternative S_4 is ranked second and has a normalized value of 0.250. In the case of value generalization, only the information that alternative S_2 is ranked first and alternative S_4 is ranked second would be considered. However, alternative S_2 has a higher significance by only 11.2% in yield on S_4, which is not considered when deciding on the OPA algorithm.

However, suppose there is not enough information in the multi-criteria model to define the significance of alternatives within the home matrix. In that case, the OPA-I algorithm can simply be transformed into the conventional OPA algorithm. These characteristics of the OPA-I method represent a significant advantage that affects the flexibility of the presented methodology when applied in real applications.

3.3. Discussion

The OPA-I methodology has advantages from the methodological aspect, which distinguishes it from previously developed methods. Most of the subjective models for determining the weighting coefficients of criteria/alternatives, including the AHP [43] and (BWM) [44], are based on comparisons in pairs of elements. This increases the number of comparisons in case of an increase in the number of criteria/alternatives. However, with increasing the number of comparisons, the quality of the obtained solution deteriorates since the consistency of the model decreases. On the other hand, the OPA-I method defines weighting coefficients of criteria/alternatives based on predetermined information in initial matrix, which facilitates the presentation of expert preferences.

In case of assigning the weights of criteria, the current methodology is capable of removing the issue existing in the relationships between remote criteria. Such an issue will often result in inconsistency in subjective models, such as the AHP and BWM [45] in which there are many criteria (more than eight). The issue is related to the small-scale range in AHP and BWM models. A nine-point scale puts a limitation on the elaboration of expert preferences to a maximum ratio of 9:1, which further causes inconsistencies in comparisons. However, the methodology used on this paper will end such a limitation by a comparison among adjacent criteria for achieving weighting coefficients in circumstances where there are several criteria, because the model is not imposed to utilize a predefined scale. This allows decision-makers elaborate their preferences and objectively the relationships between the criteria.

In addition, the proposed mathematical model can be used to simultaneously define the weight coefficients of experts, attributes, and alternatives. In contrast, the AHP and BWM (the Best Worst Method) models can only be used to determine the weight coefficients of criteria/alternatives. Furthermore, in the OPA-I method, a mathematical model for aggregating expert preferences is implemented, so it does not require the additional application of other models for averaging the results.

It should be noted also that the linear model of the OPA-I method is adaptive so that it can be used without additional modifications in group and individual decision-making. At the same time, other traditional methodologies such as AHP and BWM require the engagement of mathematical aggregators for the fusion of expert preferences.

The other advantage is that the OPA-I algorithm has flexibility and enables the processing of uncertain and unspecified information. For example, if the expert cannot rank certain alternatives concerning a certain attribute due to a lack of knowledge, the algorithm enables the definition of weight coefficients. This property of the OPA-I algorithm is essential for application in a dynamic and uncertain environment. Ultimately, the OPA-I model allows decision makers to present their preferences through a logical algorithm when prioritizing criteria. Furthermore, by applying the OPA-I model, optimal values of the weighting coefficients are obtained with a simple mathematical apparatus that eliminates inconsistencies in the case of expert preferences, which are tolerated in specific subjective models (BWM and AHP).

According to the results obtained in the previous section, technology and policy are the most critical barriers in converting agricultural residues into building material. Similar results reported by Liu et al. [10] that mentioned some major barriers in development of bio-insulations as technology level, economic conditions, and policies. Technology barriers were defined as lack of advanced and updated engineering systems in implementing the tasks, measurement, material characterization, and data analysis. These barriers existed in different dimensions from technical to organizational aspects. For instance, not all countries have proper access to advanced engineering systems to measure the properties of agricultural residues. Although several technical properties of processed agricultural residues were reported in the literature review, there might be a need to test these materials for additional parameters in the future. In this regard, it is still unclear which corresponding technology should be applied [10]. Digitalization and data management is another important factor in the field that still needs more research. In addition, it is not clear at what extent the system in those involved sectors should be updated and/or upgraded. This can be further complicated by the fact that multiple stakeholders must be synchronized at the same time. In this context, Industry 4.0 pillars can support the required technologies to establish such coordination between different sectors. As far as policy is concerned, the big issue is to fit biological products into business models developed recently for CE. The future policies should encourage the proper management of agricultural residues, and on the other side put limitations on burning the residues. Proper management of the residues may have an impact on other sectors, for instance in their transport and storage. This will finally have an impact on the supply chain of these materials. Such effects should be reflected in the future policies. Another challenge is to define a comprehensive policy, which will have enough influence on the collaboration level between different actors of the network now and in the future. In this regard, an investigation on the effectiveness of current regulations is needed to see how much and in what areas change should be made.

In estimation of the feasibility level to overcome the barriers, the lowest feasibility is reported in the operation and construction phases in the building sector. This means the experts are more concerned with agricultural residues' application rather than their supply chain. In the most critical one, operation and maintenance, one of the biggest challenges is the performance of these materials. Although some residues have shown promising performance, there is little information in testing them in practice, in particular their adaptability level in different geographical conditions. The other challenges, such as their water absorption tendency, stability, durability, and safety issues as resistance to fire should address this sufficiently [11]. Additionally, there is little eagerness among building managers to consider these new materials in practice. No incentives or support were considered to change the current situation and the roles of stakeholders in different sectors and phases have not been defined properly.

The multidimensionality of the issue of converting agricultural residues into building materials and the existence of numerous barriers and stakeholders in all sectors increase the importance of creating an integrated framework. In such framework, it is important to address the main actions to overcome barriers and enhance the feasibility level. The proposed integrated framework includes several key components as follows:

- **Localization**: parameters that can have a considerable environmental impact, in a positive manner, for instance minimum transportation, transportation mode, loading and unloading the products, storage mode and utilizing local available agricultural residues [11,40,46]. Transport may have an impact on final price of the product as shown in other applications such as biomass transport. Localization can be measured either by numerical indicators of cost, energy, and emissions or in an expert-based model in transportation and other sectors [40]. The other important action is to optimize the building construction in early stage such as design process. The application of technical tools that can reflect the socio-economic profile of local communities such as multi-objective optimization, Building Information Modeling (BIM), and Life Cycle Cost (LCC) analysis is encouraged [46].
- **Prevention** (of putting pressure): The proposed business should not put pressure on air, water, and land use and food security [21]. It should not negatively affect human resources working in different sectors (social dimension). In other applications, for instance in biomass energy, Switzerland does not apply the policy of growing energy crops or energy wood [40]. The potential of similar action should be further investigated in Chile in case of application of agricultural residues in building construction. Tools such as Life Cycle Analysis (LCA) and Material Flow Analysis (MFA) are recommended in this section to identify the resource efficiency, and to investigate potential impacts of any action on the environment.
- **Collaboration**: There are many tasks that need strong connections between different stakeholders. Sharing and exchanging information and knowledge seem necessary in the different activities of production, supply chain, marketing, and design, to name a few. On the other side, the benefits for such collaboration between stakeholders should be considered, for instance accessing information and knowledge, interactive learning forms, and networking opportunities [21]. A value for a network of stakeholders should be created and sharing the information and market competition should be decoupled [16,23]. It is also important for stakeholders to present their commitment and responsibility to maintain the collaboration [21]. Stable relationships between different stakeholders in the long term is of vital importance. In this context, having new stakeholders with the role of keeping the connection between different actors is suggested [20]. Collaboration is essential to overcome several distinct barriers, for instance standardizations and codes in the knowledge barrier, resistance to change due to lack of trust in the cultural barrier, and promoting innovative business models

to overcome the cost and infrastructure barriers, to name a few. In this context, a collaboration tool that has been already developed should be brought into practice [16].

- **Digitalization**: Localization as explained above does not mean to isolate local activities from other regions. Some actions such as sharing information, knowledge on common practices and standardization, developing tools and material passports are dependent on large-scale collaborations worldwide. These types of actions are constructed on the basis of digital data and traceability [20]. The other main action in this part is platformization [20,47]. A multi-stakeholder platform that can play role of a consultation body may facilitate the collaboration [21].

Given the fact that the most critical sectors are construction and operation, a new practical implication should be considered as suggested in Figure 3. In this context, we suggested the actions in each pillar of integrated framework as an option to facilitate the solutions in the construction and operation phase in the building sector.

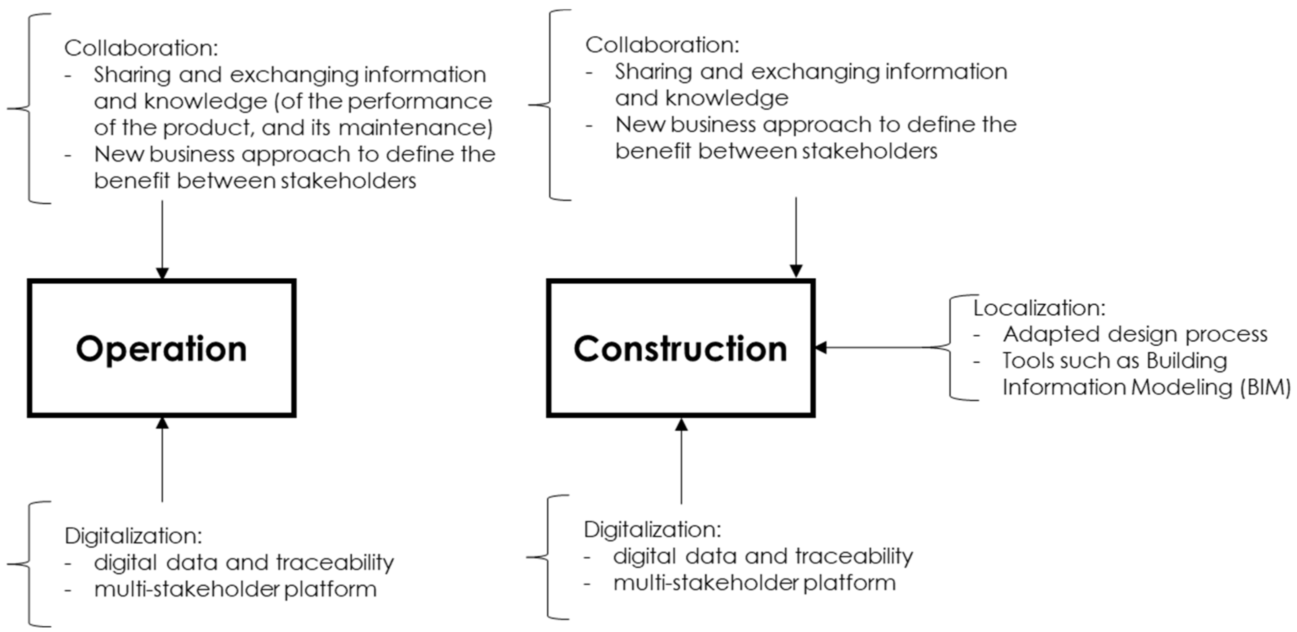

Figure 3. Practical implications taken from the proposed integrated framework in the most two critical sectors.

4. Concluding Remarks

This research studied common barriers in developing projects in converting agricultural residues to building material and products. In terms of identifying barriers, involved sectors and phases, and the feasibility level of overcoming the barriers, this study is comprehensive, and therefore can be considered as a basis for other research studies dealing with biological products in building construction. In this context, not only were the barriers evaluated, an integrated framework based on four pillars of localization, prevention, collaboration, and digitalization was proposed to enhance the feasibility level to overcome the barriers in the field. Due to the importance of biological products in the circular economy and multi-sector concept, it is suggested to form a consultation body for greater coordination between different sectors and stakeholders in particular public and private sectors, and monitoring the progress considering those aforementioned pillars to overcome the barriers.

Chile has recently initiated its CE roadmap, which has 27 initiatives. Converting agricultural residues to building products, identifying barriers, and proposing an integrated framework of localization, prevention, collaboration, and digitalization to overcome the barriers are linked to several initiatives as listed below:

- “Initiative 5: Scale-up of high potential circular solutions,

- Initiative 6: Information systems for modelling the local environmental impact of goods and services,
- Initiative 7: Technical standards for the CE,
- Initiative 13: Transparency and traceability for the CE
- Initiative 14: Monitoring progress towards a CE
- Initiative 25: Regenerative production Systems
- Initiative 26: Local infrastructure and equipment for the CE
- Initiative 27: Incorporation of a circularity focus in the planning of regional and communal development" [36]

The theme is highly relevant to the CE roadmap of the country and its future vision. Therefore, it is highly recommendable to consider similar projects to enhance the potential to reach the goals assigned in the roadmap, in particular monitoring CE progress, reducing environmental pressure existing in the current waste management model, and finally provide CE opportunities in the long run [36].

This work contains a few limitations that should be considered in future studies. It would be an asset to break down the sectors and phases to more involved stakeholders to consider their viewpoint for future policy implications. The consultation body should form in close collaboration with all stakeholders in multiple sectors. The other limitation is related to expert participation, in particular their number and viewpoints. Due to limited time and resources, we have consulted one expert in each sector, but more can be consulted. This in particular will result in better policy design and implications if more experience is put together. On the other side, subjectivity always exists in experts' opinions, which should be completely assessed in future works in the form of comprehensive sensitivity analysis. The other solution would be to use quantitative data instead of experts' opinions to receive reliable conclusions in terms of the real impact of practices [18].

In addition, one of the proposed methodology's limitations is the computational complexity of the model and the inability to address information neutrality adequately. Therefore, it is necessary to direct future research toward creating user-oriented software and improving the proposed methodology's performance by applying other tools for processing uncertainty, such as intuitionistic fuzzy sets and picture fuzzy sets.

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