Modeling Barriers to a Circular Economy for Construction Demolition Waste in the Aysén Region of Chile

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ABSTRACT

An increasing rate of urbanization, lack of knowledge, low willingness to pay for sustainable waste management, and absence of legal landfills inhibit the rate at which Circular Economy (CE) is implemented. The successful CE adoption for construction and demolition waste (CE-CDW) involves navigating a complex tapestry of interconnected factors that enable or inhibit CE-CDW success. We used a participatory system thinking and modeling approach to analyze the interaction of *inhibiting* factors that impact CE-CDW in Aysén, Chile. Barriers to CE-CDW were identified in the literature and modeled in a workshop with experts from different areas of construction industry, policy, and academia. The emerging CE-CDW system model was analyzed using structural factor and network analysis techniques to identify leverage points for policy and practice. Findings pointed to limited strategic vision of policy and regulation as a key barrier impacting the necessary financial and technical elements needed to implement and scale-up CE-CDW.

Keywords: Circular Economy; Construction and Demolition Waste; Stakeholders; Systems Thinking; Systems Modeling

1. Introduction

A circular economy (CE) seeks to foster an efficient use of resources, and a reduction of waste and environmental impacts of production cycles (Aslam et al., 2020; Bao and Lu, 2020). The opportunities that CE offers for re-thinking the waste generating processes associated with construction, rebuilding and infrastructure demolition is even more significant given the fast rate of urbanization (UN, 2019), and its derived higher CO2 emissions (Chen et al., 2013; Erlandsson and Levin, 2004). Construction and demolition waste (CDW) refers to materials such as, concrete, brick, tiles, ceramics, wood, plaster and plastic (Véliz et al., 2022) and currently CDW accounts for 30-40% of total solid waste, being the largest contributing sector (Jin et al., 2019; López Ruiz et al., 2020). Proper CDW management of these practices are important for reutilization of surplus materials in the building industry enabling it to flow in a closed loop in which waste is converted into a resource (Bao and Lu, 2020; Ghaffar et al., 2020).

The Ellen MacArthur Foundation describes the concept of CE based upon the principles of elimination of waste, circulation of products and materials at their highest value, and the regeneration of nature, all three with the potential of decoupling the economy from the use of finite resources (EMF, 2022). Accordingly, the dissemination of innovative business initiatives that foster circularity within the economy can help to achieve current sustainable development goals (SDG) (Ghisellini et al., 2016; Kirchherr et al., 2017; Murray et al., 2017; Naustdalslid, 2014; Suárez-Eiroa et al., 2019). However, the most recent Circularity Gap Report (2021) states that our current economy is only 8.6% circular, leaving space for CE policies that, combined with the climate agenda, can foster a path towards sustainable use of resources globally.

CE principles adoption to CDW, from here on referenced as CE-CDW, is a complex and interconnected challenge that is most appropriately studied from a systems perspective. Systems modeling and analyses consist of an integrative approach to comprehend the multiple, nonlinear, dynamic and interconnected relationships within a broader system in which an organization operates (Pesce et al., 2020), helping to understand how to inform holistic decision leverage points for the policy and practice required for CE-CDW (Chaudhari et al., 2021; Matlin et al., 2016; Summerton et al., 2019). Leverage points represent places to intervene in a system to transit from one equilibrium to another (Meadows, 2009,1999), defined as points of power in the system (whether factors, pathways or processes), where a small change could lead to a large shift in the equilibrium.

Past research has used system dynamics to study CE strategies for sustainable development, aiming to identify the primary drivers of change that are influenced by these strategies (Bassi et al., 2021). In particular, material flow analysis and system dynamics, which study a system's behavior through system feedback, have been integrated into CE to develop strategic recommendations for long-term sustainability (Gao et al., 2020).

Contributions related to effectively closing resource loops in the supply chain of a CE (Franco, 2019) and with revenue, cost, and strategic-regulatory decisions (Alamerew and Brissaud, 2020) have also been analyzed with system dynamics simulations. In addition, system thinking has offered solutions in the determination of how resource recovery systems operate to promote transformational changes towards circularity (Iacovidou et al., 2021), and in the assessment of carbon emissions of building refurbishment CDW (Ma et al., 2022). However, there is no single study analyzing the interconnected barriers influencing CE-CDW.

At a local geographical level, very little work has been conducted on CE-CDW in Chile and this study contributes with a novel systems perspective to close the circularity gap in buildings and construction focusing this study on the Aysén region of Chile. The following research questions (RQs) guided this research:

RQ1: What are the barriers to implementing CE-CDW in Aysén?

RQ2: How do these barriers interact as a system?

RQ3: How does an analysis of these interactions inform policy and practice for CE-CDW in Aysén

In addressing these research questions, our study sought to propose policy interventions and practices through the systematic identification and modeling of barriers inhibiting CE-CDW based on local expert perception, with application to other regions in Chile.

2. Background of CE-CDW in Chile and Aysén

The current roadmap for a CE created by the Ministry of the Environment in Chile, aims for a regenerative circular economy for Chile towards a sustainable and equitable development (MMA, 2021), including waste management as a priority and the construction sector as a main responsible (MMA, 2020) given its contribution to greenhouse gas emissions (23% according to CChC, 2019). Nonetheless, population and urbanization are growing at a fast rate, making it difficult for widespread adoption of CE-CDW. Nearly 88% of the Chilean population lives in urban areas (CIA, 2022), expecting it to increase over time.

The current legal framework established under the Waste Management, Extended Responsibility of the Producer and Promotion of Recycling Law (NCL, 2016), indicates that all recoverable waste should be destined for this purpose, avoiding its disposal. However, this regulatory scheme has not translated into real changes for CDW management (Véliz et al., 2022), mainly because 58% of people do not know this waste management law nor the sanctions for waste transportation to clandestine landfills (Sanguinetti et al., 2019); NCL, 2015). Among the Chilean construction industry, only 30% declare they know how to deal with material and waste management with CE criteria in mind (Véliz et al., 2022). In addition, construction companies are often not willing to improve current management practices as long as this leads to higher CDW classification, collection and disposal costs (Véliz et al., 2022). These current CDW management and disposal practices are responsible for the 3,735 illegal disposal sites in the country, from which 46 sites are located in the Aysén Region without meeting the requirements of engineered sanitary landfills (Ossio and Faúndez, 2021).

Aysén is a remote area in Chile’s southern Patagonia witha sparse population, complex access routes and elevated transportation, products and service costs (Bachmann-Vargas and van Koppen, 2020) given its large distance from the highly socio-economical centralized Chilean capital (Espinoza et al., 2019). The construction sector generates 11,459 m^3/year in this region, with Coyhaique city, the regional capital, as the biggest contributor (55% of this regional total) (Ossio and Faúndez, 2021). Aysén does not have legal CDW final disposal sites within its geographical borders (Bezama et al., 2013; Ossio and Faúndez, 2021), nor a significant history of CE implementation. However, its low population makes it an interesting case of analysis since its potential for collaboration and coordination among relevant stakeholders. Additionally, by 2030, the regional goals include a substantial improvement of waste management to become an international sustainable tourism destination that will benefit from CE actions (ILPESCEPAL/DIPLADE Aysén, 2009).

3. Methods

This section presents the mixed-method process (Fig. 1) we used to identify and analyze the interaction between barriers to CE-CDW.

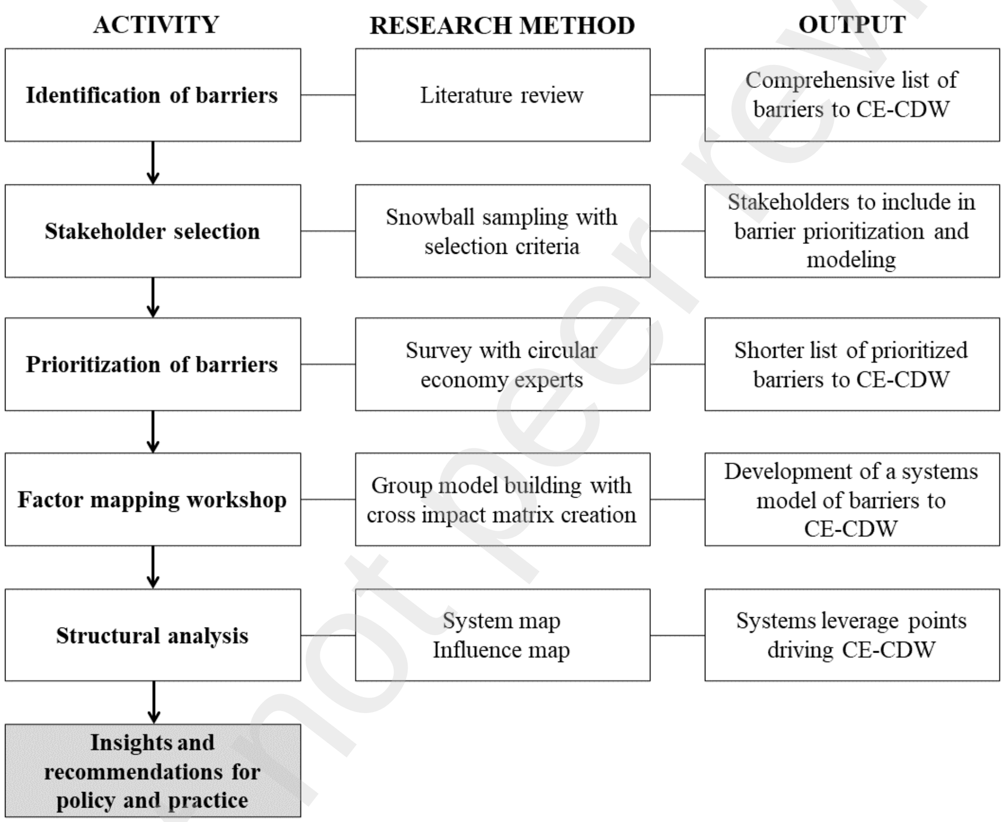

Fig.1. The multi-step research method.

3.1. Identification of Barriers

To identify barriers to CE-CDW a literature review of articles obtained from the Web of Science platform was performed. This review began with the combination of all the keywords previously chosen in the reading and familiarization phase of the research objective, specifically, “CDW”, “Circular Economy”, “Construction”, “Debris” “Barriers”, and “Limitations” or “Challenge”. In total, 977 articles were identified. Next, we proceeded to identify papers that studied topics related to barriers to CE-CDW. This step resulted in the selection of 40 papers, from which 14 articles were eliminated because they did not meet the selection criteria (Fig. A.1), providing us a total of 26 articles to perform an in-depth review. These articles were used to systematically identify and categorize difficulties the construction sector has experienced in implementing CE-CDW in different regions of the world. A raw list of barriers identified through this process were then vetted and scored by local stakeholders to provide a refined list of barriers for the CE-CDW system model, described in Section 3.3.

3.2. Stakeholders Selection

A key part of the data collection process entailed engaging local stakeholders in a systematic discussion of the interaction that exists between barriers to CE-CDW. A stakeholder was considered as any individual or group that could affect or be affected by practices, actions and operations of CE-CDW (Freeman et al., 2020; 1984; Parmar et al., 2010). Stakeholders' selection process began reviewing organizations listed among the socio-environmental conflicts connected to CE-CDW in Chile (INDH, 2021). The alliance established with the Ministry of the Environment and the Ministry of

Housing and Urban Planning allowed us to contact additional stakeholders and implement a snowball selection strategy (Taylor et. al 2015).

For stakeholder selection criteria, we first established a general classification considering organizations from five areas of expertise. The first area was the public sector (executive branch), which was subdivided into three groups of authorities; central/national (mainly state departments); regional (regional divisions of state departments) and local (four municipalities of Aysén). The second group included NGOs and organizations from civil society specialized in CE and recycling, while the third group was the private sector, including construction firms that operate in Aysén. The other stakeholders´ represented the political sector, including parliament members engaged in environmental aspects as well as local political authorities, and the academia, incorporating local universities and think tanks. Using these selection criteria, we engaged with stakeholders belonging to organizations such as the above-mentioned ministries and Ministry of Public Works, Coyhaique Regional Directorate of Roads, Center for Research in Patagonian Ecosystems, Chilean Chamber of Construction and representatives belonging to other relevant organizations.

3.3. Prioritization of Barriers

Barriers found in the selected articles were presented to the stakeholders in an online survey. In this questionnaire, stakeholders were asked to evaluate the relevance of barriers within a Likert scale from 1 to 7 (where 1 is the lowest relevance to achieve the objectives of a CE-CDW and 7 represents the highest relevance). The barriers were then prioritized from most to least influential based on a combination of the average and summed Likert scores, which allowed for a selection of the most relevant CE-CDW barriers to include in the model. Identification of barriers in this way helped us address our first research question (RQ1) regarding the key barriers influencing CE-CDW.

3.4. Barrier Mapping Workshop

Stakeholders were engaged in a remote modeling workshop held on Zoom and facilitated with the use of the online whiteboard software, Miro, to consider the potential interactions that exist between the prioritized CE-CDW barriers. The process of engaging stakeholders in a virtual model building session followed adaptations of practices outlined by (Wilkerson et al., 2020), while the form of participatory systems mapping within the workshop followed a structured model-building process described by Walters et al. (2018). Given the lengthy process of considering all pairwise interactions between barriers, stakeholders were divided into four breakout groups. We posit that working with groups of fewer stakeholders had benefits beyond expediency and participant fatigue, such as the ability to facilitate diverse perspectives and minimize biases from group think (MacDougall and Baum, 1997).

Discussion on pairwise barrier interactions entailed asking stakeholders to consider how one barrier influenced another barrier (e.g. Barrier A >> Barrier B). If the group decided that an interaction existed, stakeholders were then asked to indicate the strength of interaction as either 1 weak, 2 moderate or 3 strong. If no interaction was observed, influence was evaluated with 0. Consensus on barrier existence and strength was said to be achieved if the majority (over 50%) of stakeholders agreed on both the existence of an interaction and the strength of interaction. This process took the group approximately 2 hours to complete and resulted in an $n \ x \ n$ matrix known as a '*cross impact matrix*' (hereon referenced as simply 'matrix'), which houses all of the interactions agreed upon by the experts. In effect, the matrix represents the stakeholders' combined conceptualization of the CE-CDW system. Once each group was finished discussing barrier interactions, they were reconvened to briefly discuss the preliminary findings from analysis of this matrix, explained below. This systematic elucidation of barrier interactions helped us address our second research question (RQ2) regarding how CE-CDW barriers interact as a system.

3.5. Structural Analysis

The matrix resulting from the previous step was analyzed to evaluate system leverage points. Leverage points were based on the quantitative and visual evaluation of a *barrier influence map* and a *barrier system map* complimented by an eigenvector centrality comparison between barriers (Walters et al., 2022). These analyses are described below.

3.5.1. Barrier Influence Map

A barrier influence map was created using the Lipsor structural analysis software (EPITA, 2002) to provide a two-dimensional analysis of the *roles* barriers play within the CE-CDW system (Godet, 1976). Past CE assessments and mitigation framework for decision and policymakers for the building sector have also been analyzed with this structural analysis technique (Bilal et al., 2020). An influence map provides a two-dimensional display of each barrier's *influence* and *dependence* score within the network (Arcade et al., 2009). Influence scores for each barrier are calculated as the sum of connections and connection strengths each barrier has on other barriers (the summed row in the matrix), while dependence scores are calculated as the sum of connections and connection strengths on a particular barrier from the other barriers (the summed column in the matrix). Plotting barrier influence and dependence scores on an influence vs. dependence chart (Fig. 2 right) allows for the graphical analysis of the function barriers have in the system. Specifically: i) barriers to target with policy and practice due to their high influence and low dependence on other barriers (target barriers, quadrant I), ii) barriers to protect because of their high influence and high dependence (unstable barriers, quadrant II), iii) barriers to monitor and measure system health since they have low influence and high dependence (outcome barriers, quadrant III) representative of system outcomes and behavior and iv) barriers to analyze as that have low influence and low dependence (incidental barriers, quadrant IV), making them secondary on system outcomes.

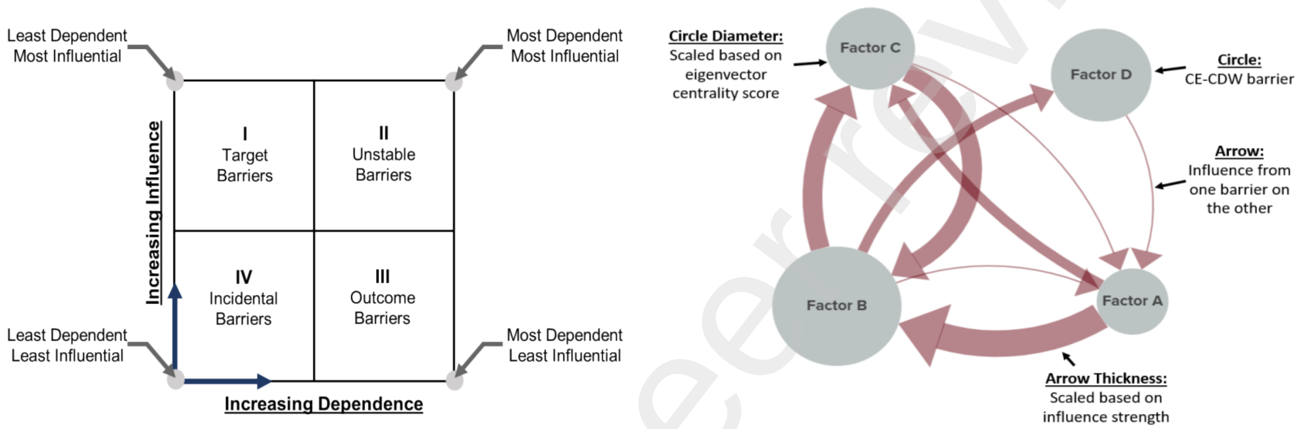

Fig. 2. The anatomy of an influence map (left) and a system map (right).

Further granularity and nuance into system behavior was found using a process called Cross Impact Matrix Multiplication Applied to Classification (MICMAC in its French acronym) (Godet, 2003). MICMAC entails performing various matrix multiplications of the matrix built from stakeholder perception (known as the 'direct' matrix) to infer barrier dynamics from both indirect interactions not considered or perceived by the experts as well as by stronger barrier interactions that are amplified by the multiplication process. The number of multiplications varies based on the size and complexity of the matrix, and is complete once subsequent multiplications yield the same rank of influence and dependence scores for the barriers - usually after approximately six or seven iterations (Arcade et al., 2009). Resulting from the multiple multiplication iterations of the direct matrix is the 'indirect' matrix, which houses interconnections and interconnection strengths based on the influence of indirect interactions. Analysis of influence, dependence and centrality of the indirect matrix adds granular and nuanced insight into system feedback dynamics and thus the overall evolution of the CE-CDW system. As the objective of this research was to provide a systems-focused assessment of leverage points for future CE-CDW policy and practice, the leverage point calculations were based on the barrier connection strengths from the indirect matrix.

3.5.2. Barrier System Map

A barrier system map, created in the network visualization software Kumu (Kumu, 2022) was used to visually evaluate which barrier links and pathways of links were the most prominent within the CE-CDW system (Walters et al., 2022). Within this map, prominent barrier links were represented by arrows between barriers, and are based on the influence scores from the indirect impact matrix. Presenting the relationship between barriers in this way enabled the visual identification of key barrier links, pathways, and dynamic feedback mechanisms. For this study, key barriers in the CE-CDW system were based on their relative level of interconnectivity, using weighted and directed eigenvector centrality (circle diameters in Fig. 2 left). Eigenvector centrality is a network analysis metric that iteratively evaluates a barrier's direct and indirect level of influence within a network by evaluating the number and strength of connections with other highly central barriers (Wasserman and Galaskiewicz, 1994). To enable the visual identification of key barrier connections and pathways we divided the connection strengths into five quantiles, very weak, weak, moderate, strong, and very strong, where the most important links of interest within the systems map would be the top 20% in connection strength.

Combining system and influence maps enabled the identification of key barriers, barrier interactions, and barrier pathways, inhibiting CE-CDW. Crucial barriers for policy and practice are considered those that have high influence on the CE-CDW system measured by high eigenvector centrality, and high connection strengths. With the help of the barrier system map, it was also possible to identify and characterize key causal pathways or “chains'' that exist between these most influential or interconnected barriers, by comparing and contrasting the summed influence strengths of barriers within pathways having the largest influence strength. These complementary structural analyses helped us address our final research question (RQ3) regarding the key CE-CDW system leverage points to influence with policy and practice.

4. Results

This section presents the outputs and findings for each step in the data collection and analysis process described in the previous section and summarized in Fig. 1.

4.1. Identification and Prioritization of CE-CDW Barriers

Forty potential barriers to CE-CDW were identified from the 26 selected papers published in the area of construction and the environment (Table A.1.), that were grouped into the following CE-CDW domains: Socio-Environmental: Focused on barriers that depend on the level of stakeholders' awareness and conceptions, as well as the characteristics of the project's physical environment; Technical, addressing barriers involving lack of experience, knowledge and technologies needed to promote sustainability; Financial, focused on barriers that result from challenges in the implementation of projects due to their complexity and financial scope; and Strategic-regulatory, barriers related to insufficient planning, management and regulatory gaps.

The process of selecting barriers explained in section 3.2 derived the barriers described in Table 1.

Table 1. Prioritized barriers and definitions used in the systems model, grouped into barrier category.

Barrier	Definition
	Socio-Environmental
Desire for Short-Term Profitability	Construction companies prioritize short-term monetary savings over environmental care, thus preferring the use of illegal landfills and unauthorized personnel to manage their CDW (Abarca-Guerrero et al.,

	2017; Blaisi, 2019; Chen and Lu, 2017; Hart et al., 2019; Liu et al., 2020; Menegaki and Damigos, 2018; Negash et al., 2021; Wu et al., 2017; Zhang et al., 2019).
Rapid Urban Growth	Population growth pressures companies to build, prioritizing rapid construction instead of sustainable waste management (Chen and Lu, 2017; Hart et al., 2019; Kabirifar et al., 2021; Menegaki and Damigos, 2018; Tam and Lu, 2016; Wu et al., 2016).
Natural Disasters	Lack of assignment of responsibility in the management of CDW in the face of natural disasters (Menegaki and Damigos, 2018; Scatolini and Bandeira, 2020).
Technical	
Lack of Infrastructure	Lack of adequate infrastructure, technology, and processes that allow classification, transport and recovery of CDW (Abarca-Guerrero et al., 2017; Ajayi et al., 2017; Aldana and Serpell, 2012; Blaisi, 2019; Chen et al., 2018; Díaz-López et al., 2021; Hart et al., 2019; Hossain et al., 2020; Huang et al., 2018; Kabirifar et al., 2021; Mahpour, 2018; Menegaki and Damigos, 2018; Oliveira Neto and Correia, 2019; Ossio and Faúndez, 2021; Tuan, 2018; Zhang et al., 2019).
Poor Knowledge of Technology	Stakeholders have inadequate technological knowledge and information along with a lack of experience in CE, which translates into traditional CDW management (Aldana and Serpell, 2012; Chen et al., 2018; Díaz-López et al., 2021; Hart et al., 2019; Huang et al., 2018; Kabirifar et al., 2021; Liu et al., 2020; Menegaki and Damigos, 2018; Negash et al., 2021; Oliveira et al., 2021; Zhang et al., 2019).
Lacking Certification of Recycled Materials	Lack of technical certification of waste quality leading to a low preference for recovered materials (Hossain et al., 2020; Huang et al., 2018; Mahpour, 2018).
Financial	
High Capital Investment	Difficulty and lack of budget for capital investment given its high value (Abarca-Guerrero et al., 2017; Kabirifar et al., 2021; Liu et al., 2020; Negash et al., 2021).
Low Demand for Recycled Materials	Willingness to pay for recycled materials less than their market price, leading to substitution for new materials (Ajayi et al., 2017; Liu et al., 2020; Menegaki and Damigos, 2018; Oliveira et al., 2021).
High Cost of Production	Production cost of recovered materials is greater than the market price, discouraging new supply of these materials (Huang et al., 2018; Liu et al., 2020; Menegaki and Damigos, 2018).
Strategic- Regulatory	
Limited Strategic Vision	Political priorities and state agents are not focused on strategic CE objectives for CDW, which increases uncertainty and demotivation for sustainable waste management (Díaz-López et al., 2021; Hart et al., 2019; Kabirifar et al., 2021; Liu et al., 2020; Wu et al., 2017; Yuan, 2017).
Absence of Incentives	Lack of incentives and supervision to recognize those who recirculate CDW and penalize those who manage CDW in non-authorized sites (Abarca-Guerrero et al., 2017; Aldana and Serpell, 2012; Blaisi, 2019; Chen et al., 2018; Chen and Lu, 2017; Díaz-López et al., 2021; Hart et al., 2019; Hossain et al., 2020; Huang et al., 2018; Kabirifar et al., 2021; Liu et al., 2020; Mahpour, 2018; Menegaki and Damigos, 2018; Negash et al., 2021; Oliveira et al., 2021; Tam and Lu, 2016; Tuan, 2018; Wu et al., 2017; Yuan, 2017; Zhang et al., 2019).

Limited Collaboration	Collaboration that maximizes social benefit between interest groups is hindered due to information asymmetries and lack of coordination systems at central and local levels (Blaisi, 2019; Hart et al., 2019; Hossain et al., 2020; Kabirifar et al., 2021; Menegaki and Damigos, 2018; Negash et al., 2021; Wu et al., 2016; Zhang et al., 2019).

4.2. Barrier and Interaction Strength: Barrier System Map of CE-CDW

Within the barrier mapping workshop, 13 participants were divided in four groups: one group per barrier domain. Stakeholders' expertise was taken into account to conform each subgroup, composed by three or four experts. Table A1 and A2 in the appendix present the direct and indirect matrices resulting from the barrier mapping workshop and MICMAC analysis, respectively. The direct matrix provides some high-level insight on the system of barriers as perceived by the stakeholders, while the indirect matrix will be used to discuss system leverage points and recommendations. The stakeholders identified 78% of the barrier connections as non-zero (n = 103), revealing their ability to consider a great level of nuance in the way these multidimensional barriers are interconnected. The most influential barrier in the direct matrix was *Limited Strategic* Vision (influence score of 28) (Table A1), and it was the only barrier that interacts with all other barriers in the direct matrix, depending only on five barriers, the strongest being *Limited Collaboration* (ranked 3-strong). Conversely, *Desire for Short-term Profitability* is influenced by (or dependent) on all 11 barriers, being the most dependent barrier of the system (dependence score of 31).

For the indirect matrix (Table A2), six multiplication iterations were necessary to reach stability in the rank of influence and dependence scores. Connection strength values in this are normalized for comparison, by dividing each connection strength by the largest connection strength in the matrix. The top three connection strengths in the indirect matrix are: *Limited Strategic Vision >> Desire for Short-Term Profitability* (1.0), *Limited Strategic Vision >> High Cost of Production* (0.9), *Limited Strategic Vision >> High Capital Investment* (0.86) and *Absence of Incentives >> Desire for Short-Term Profitability* (0.86).

Fig. 3 presents the system map for the CE-CDW system for top 29, 'very strong' connection strengths calculated in the indirect matrix. Fig. A1. present the complete systems map; considering very weak, weak, moderate, strong and very strong links. The system map also shows which barriers are the most interconnected using eigenvector centrality; scaled based on the radial sizing of the circles in the system map. Relative connection strengths are indicated in the system map based on line (connection) width. Findings from the eigenvector analysis show that *Desire for Short-term Profitability* is the most interconnected barrier, followed by *High Capital Investment*, *High Production Cost*, and *Low Demand for Recycled Material*. *Limited Strategic Vision*, while highly influential on other barriers, has the lowest level of connectivity, along with *Rapid Urban Growth* and *Natural Disasters*. We can see that while not having the lowest eigenvector centrality, *Natural Disasters* has no connections classified as 'very strong' and thus exists in isolation in the systems map. It may also be seen that the core drivers within the CDW-CE barrier system are within the Strategic-Regulatory barrier category, mostly targeting financial barriers, apart from the most central barrier *Desire for Short-Term Profitability*.

An obvious focal point in the CE-CDW system is the most interconnected barrier (highest eigenvector centrality score), *Desire for Short-term Profitability.* It can be seen that this barrier is not only the most interconnected within the "very strong" CE-CDW system map (Fig. 3), it also has the strongest three-barrier pathways between the most influential barrier, *Limited Strategic Vision*, and the other barriers. If we quantify pathway strength based on the sum of normalized connection strengths from the indirect cross matrix (Table A2), the top three causal pathways that emerge are: i.) Pathway 1: *Limited Strategic Vision* (1.0) >> *Desire for Short Term Profitability* (0.75) >> *High Cost of Production* (1.75 total), ii.) Pathway 2: *Limited Strategic Vision* (1.0) >> *Desire for Short Term Profitability* (0.70) >> *Low Demand for Recycled Materials* (1.70 total), and iii.) Pathway 3: *Limited Strategic Vision* (0.79) >> *Absence of Incentives* (0.86) >> *Desire for Short-Term Profitability* (1.65 total). It can be seen that Pathway 3 leads into Pathway 1 and 2 through *Absence of Incentives*, making it a core driver of the most influential barriers in the system; a barrier that is influenced most by *Limited Strategic Vision.* We also see a feedback loop (circular causality) exists between *Desire for*

Short-Term Profitability >> High Capital Investment >> Low Demand for Recycled Material. This feedback loop implies a vicious cycle exists between the willingness for companies to invest in CE-CDW and the reciprocal impact this has on and from the high investment costs needed to create a demand for materials or products created from recycled CDW.

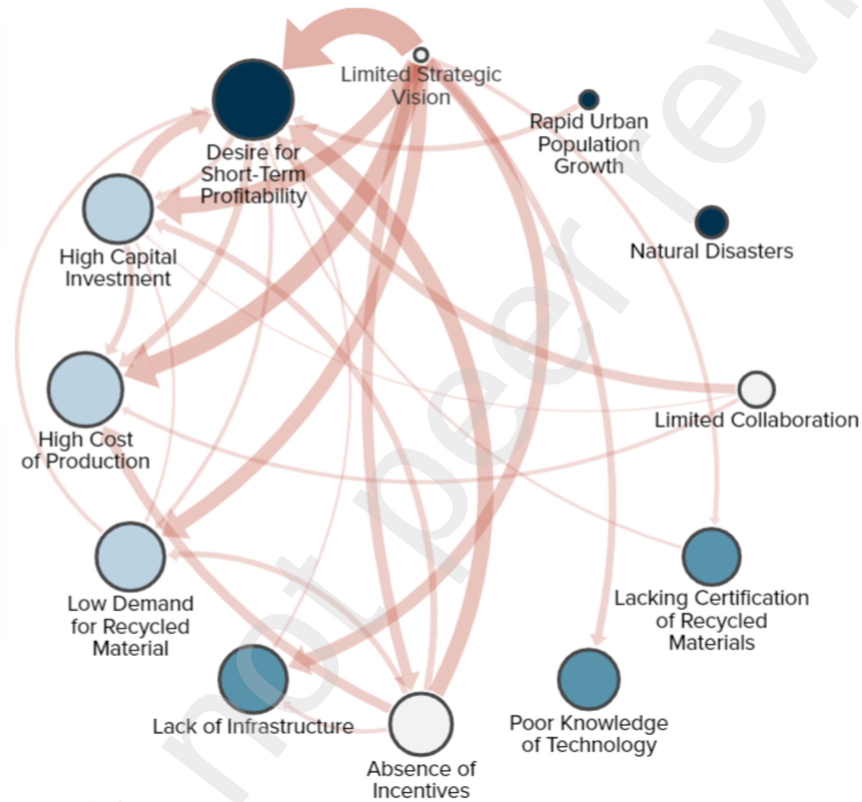

Fig. 3. Barrier map showing only 'very strong' connections in light red (top 29 connection strengths). Width of connection is scaled based on the strength of interaction from the indirect impact matrix for connections within the very-strong category. Size of node (circle) based on eigenvector centrality. Dark blue circles are Socio-Environmental barriers, teal circles are Technical barriers, light blue circles are financial barriers, and light gray circles are Strategic-Regulatory barriers.

4.3. Barrier Roles: Influence Map of CE-CDW barrier system

The results above highlight the impact *Limited Strategic Vision* and *Absence of Incentives* has on the *Desire for Short-Term Profitability* and the 'downstream impacts' this has on financial barriers. Analysis of the data using an influence map (Fig. 4) further reinforces these observations and provides further depth regarding key roles these barriers play within the CDW-CE barrier system. For example, barriers in the upper right quadrant (II) highlight barriers that are both influential and dependent on other barriers, making them highly and dynamically interconnected. This highlights the dynamics between *Desire for Short-Term Profitability* and *High Capital Investment*. It also points to the large influence (second highest overall) *Absence of Incentives* has on the system. Overall, this aligns with the analyses of the systems map, which identified these factors within key pathways and feedback loops. Unsurprisingly, we see *Limited Strategic Vision* (quadrant I) as the most influential barrier, with the lowest relative dependence on other barriers, making it a clear barrier to impact the system overall. We also see that *Limited Collaboration* has a moderate influence on the system and a low dependence on other barriers, making it a potential barrier to address in order to change the current dynamic in the system towards a faster CE-CDW. Barriers in the lower-right quadrant (III), *Low Demand for Recycled Materials*, *Lack of Infrastructure*, and *Poor Knowledge of Technology,* show that these barriers are an outcome of the previously mentioned high-influence barriers, and potential areas of the system to measure and monitor to evaluate progress within the CE-CDW system. This is particularly important for *Lack of Infrastructure* since still there is no clarity about when a legal landfill will be built in Aysén. Finally, we see *Natural Disasters*, *Lacking Certification of Recycled Materials*, and Rapid *Urban Growth* (quadrant IV) as incidental on the CE-CDW system.

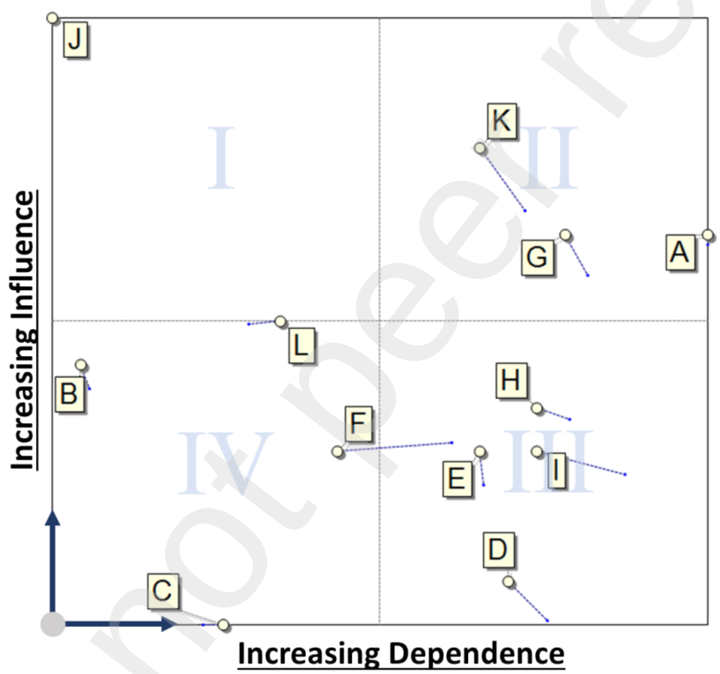

Fig.4. Influence map showing direct and indirect dependence and influence scores, created in the Lipsor MICMAC software. Quadrants are numbered in faded Roman numerals. Small light yellow circle for each barrier is the direct influence:dependence; the small blue dot is the indirect influence:dependence. The dashed line between small circle and dot shows the 'displacement' between direct and indirect influence and dependence scores from the direct and indirect matrix, respectively, inferring a shift over time from potential indirect influences and feedback between barriers.

Barrier names are shortened for clarity, with A: Desire for Short-Term Profitability; B: Rapid Urban Growth; C: Natural Disasters; D: Lack of Infrastructure; E: Poor Knowledge of Technology; F: Lacking Certification of Recycled Materials; G: High Capital Investment; H: Low Demand for Recycled Materials; I: High Cost of Production; J: Limited Strategic Vision; K: Absence of Incentives; L: Limited Collaboration.

Barrier displacements shown in Fig. 4 - calculated as normalized differences in influence and dependence scores from the direct and indirect matrices - indicate another important rationale about the barriers' dynamic behavior over time. That is, each displacement shows how each barrier evolves over the long-term until the system reaches a stable equilibrium, based upon indirect interaction and feedback among barriers. Here we see that most barriers become more dependent over time since their displacements occur to the right (Fig. 5). The only barrier that shifts towards more independence is *Limited Collaboration*, which makes it an attractive barrier to intervene towards an effective and sustainable CE-CDW program.

5. Discussion

The findings above point to four salient observations regarding the key systems-level barriers impeding CE-CDW: i) a lack of influence on public strategic vision, ii) a desire for short term profitability for CE-CDW, iii) a lack of incentives drives desire for short-term profitability, and iv) the incidental importance of technical barriers and natural disasters.

5.1. Lack of Influence on Public Strategic Vision

Findings from the impact matrices, barrier system map, and influence map, show that *Limited Strategic Vision* has the greatest overall impact on the CE-CDW system, making it a clear leverage point for policy and practice. The strategic vision of the Chilean government has a great influence on the spread of CE, but its low dependence implies that it is difficult to influence. Indeed, the state-level stakeholders are commonly inaccessible, and therefore additional mechanisms need to be created in order to have an impact on their decisions and actions. In Chile, there is low partnership between people and organizations (Valenzuela and Cousiño, 2000), therefore instances to improve collaboration networks are important to decrease information asymmetries among agents in these markets. These results also imply that legitimacy of CE implementation is relevant for companies, who need to be protagonists of CE initiatives and not passive agents who leave significant actions to the state.

5.2. Desire for Short-Term Profitability Drives CE

Desire for *Short-Term Profitability* emerges as a core barrier within the most significant causal pathways and feedback mechanisms and key to target 'downstream' from *Limited Strategic Vision*. Currently, it is difficult for Chilean companies to implement CE-CDW on a massive scale since bidding conditions do not state specific requirements with CE criteria. Bidding conditions that address CE aspects would provide certainty to quantify costs, and to assess correct procedures for CDW management. It is challenging to change the preconception of high costs associated with the CE in the short-term for the concept of savings in the long-term when the total social benefits and costs of a project are analyzed. However, the barrier system map (Fig. 3) shows that improving action (vis a vis eliminating barriers) from the State (*Limited Strategic Vision*) could have a multi-pronged effect of mitigating the financial barriers (High Capital Investment, *Lack of Incentives*, *High Production Costs*), all 'upstream' barriers that in-turn impact *Desire for Short Term Profitability*.

5.3. Absence of Incentives Impacting Desire for Short-Term Profitability

Limited Strategic Vision was seen in the barrier system map to have an upstream influence on *Absence of Incentives* which in turn have a large upstream influence on *Desire for Short-Term Profitability* - inciting all subsequent interconnections and dynamics involving investment in technology and processes to promote CE, and the impact this has on the company and user demand for recycled CDW. Further incentives to encourage CE development should be given to stakeholders to promote closed-loop material processes, recycled products certification, sustainable consumption patterns, and a resource reutilization culture in these markets. On the one hand, policies such as subsidies can financially support firms who conduct on-site sorting by increasing revenues, and, on the other hand, measures such as the reinforcement of the supervision by municipalities might discourage illegal dumping by reducing profits since production costs rise. The combined impact of multiple incentives can encourage sustainable CDW considerations by contractors and society and help to reduce the *Desire for Short-Term Profitability*.

5.4. A lesser importance of technical barriers and natural disasters

A lesser importance of *Poor Knowledge of Technology*, *Natural Disasters* and *Rapid Urban Growth*, implies that technical solutions, while not insignificant, are not the core barriers driving CE-CDW. *Natural Disasters* might be less prevalent in Aysén because historically no major disasters have been reported in the area, so the perception of their relevance in the implementation of the CE is not obvious (Iribarren Anacona et al., 2014). Additionally, it is noted that technical barriers (*Lack of Infrastructure*, *Poor Knowledge of Technology*) have relatively less influential, and perhaps are indicators of the progress of the systems that support the development of the CE, given their placement in the lower right (III) quadrant of the influence map.

5.5. Policy Recommendations

Overlaying policy recommendations on the barrier system map, offers insights into the impacts these policies can have on addressing key barriers inhibiting CE-CDW (Fig. 5). These recommendations are presented below.

5.5.1. Engage International Law and International Agreements:

The clear leverage point barrier for CE-CDW policy and practice in Aysén is *Limited Strategic Vision*, due to its extremely high level of influence and low level of dependence. However, its low level of dependence implies that it is hard to adapt to a strategic vision which considers CE as a relevant element for economic development. The engagement and reinforcement of international law and international agreements related to CE might help to influence *Limited Strategic Vision,* and accordingly all other barriers in the system. From the perspective of social systems theory, this outcome would result from the structural coupling between the legal and societal systems (Luhmann, 2004), and also a consequence of globalization and internationalization of worldwide expectations (Neves et al., 2013). An example of these is the United Nations Sustainable Development Goals (SDGs) 9 (Industry, development and infrastructure), 11 (Sustainable cities and communities), 12 (Responsible consumption and production), and 13 (Climate action) that impact CE (UN, 2018) - all having the potential to impact CE policies in Chile.

The Chilean state has a long history of adjustment to and respect for international law since its ability of applying pressure and inciting local legal changes (Nye, 2004). We can find many examples of this in Chile in diverse contexts, such as the establishment of laws against domestic violence after the ratification of the convention of the rights of the child by the UN General Assembly in 1989 (Couso, 2003) or the signing of the ILO Convention 169 in 1989 on Indigenous and Tribal People to facilitate the dialogue between governments and people. Although some of these ratifications result in rapid and long-term changes in local law like the example of child rights, others are implemented slowly and in a conflictive manner due to the processes within the legislative system. These precedents and interactions with international stakeholders might help to include legal modifications in the Chilean CE-CDW context consistent with the current SDGs.

Limited Collaboration among stakeholders is one of the few barriers that was found to have a strong influence on *Limited Strategic Vision* (Fig. 3). One of the comments raised by a stakeholder in the barrier mapping workshop indicated that without the push from organizations such as academia or NGOs towards the state, measures around CE would probably not be discussed, particularly in Aysén. Accordingly, the alliances between stakeholders to press for changes to the current system could have a significant impact to increase the elements present in the strategic visioning and action for CE-CDW (Benn et al., 2009; Edelenbos and Klijn, 2006), which is why we propose facilitating positive synergies among aligned organizations by promoting collaboration. In addition, interaction platforms, social networks and a gradual empowerment of different civil society actresses and actors could be tools to facilitate collective action (PNUD, 2020).

5.5.2. Promoting Scientific Innovation

We propose that scientific innovation might influence *Limited Collaboration*, *Lack Certification of Recycled Materials* and *Poor Knowledge of Technology* (Fig. 4). Scientific innovation might encourage collaborative partnerships among supply chain representatives that can enhance CE adoption among beneficiaries and parties involved in the business cycle (Gupta et al., 2019), and mechanisms such as contracts that protect the interests of parties involved and a transparent information sharing platform can foster these partnerships (Bao et al., 2019). The coordination of activities and responsibilities among key stakeholders entails an increase of circular CDW investment initiatives and CE practices for CDW management (Lockrey et al., 2018).

Technological innovation can also help to raise the value of recycled products in CE businesses, through a higher environmental awareness on the supply of raw materials, increase in sales of remanufactured products and the improvement of regulations and legislations (Liu et al., 2020), and lead to the implementation of a recycled product certification system that would allow a long-run market in which certificated materials are traded like virgin ones (Bao and Lu, 2020). In addition, significant new knowledge can emerge from technological innovations, which can facilitate a decrease in the quantity of waste produced and therefore efforts to manage it (Swetha et al., 2022). Currently, the construction sector is adopting innovative manufacturing processes and technologies related with eco-materials (Sierra-Pérez et al., 2016), that have implied an efficient use of natural resources, a lower production of by-products waste (Minunno et al., 2018). More efficient buildings designed and constructed with CE criteria might generate environmental and long-term financial benefits of reuse, recovery, and recycling (Song and Wang, 2018; Zhang et al., 2019).

5.5.3.Increase the Value of Recycled Products

An *Increased Value of Recycled Products* might influence Desire for *Short Term Profitability*, *Limited Strategic Vision* and *Lack of Infrastructure* (Fig. 4). To boost the market value of recycled products, construction companies need to increase their relatively low willingness to pay for CDW disposal. Recently, personnel from Chilean private construction firms have declared that their willingness to pay might change as access to knowledge about CE, CDW management, and productivity improves, and an official register with authorized transport for CDW exists (Véliz et al., 2022). In the long-run, all these incentives might help to sustain a market of recycled products created from CDW. In addition, the establishment of protocols to count, segment and assess materials quality (Kabirifar et al., 2021), the efficient planning and logistics of material, the implementation of legal requirements for materials reuse in new projects, and the rise of legal deposit areas (Oliveira Neto et al., 2017) might be effective instruments to help to make CDW recycled products price competitive substitutes of virgin ones.

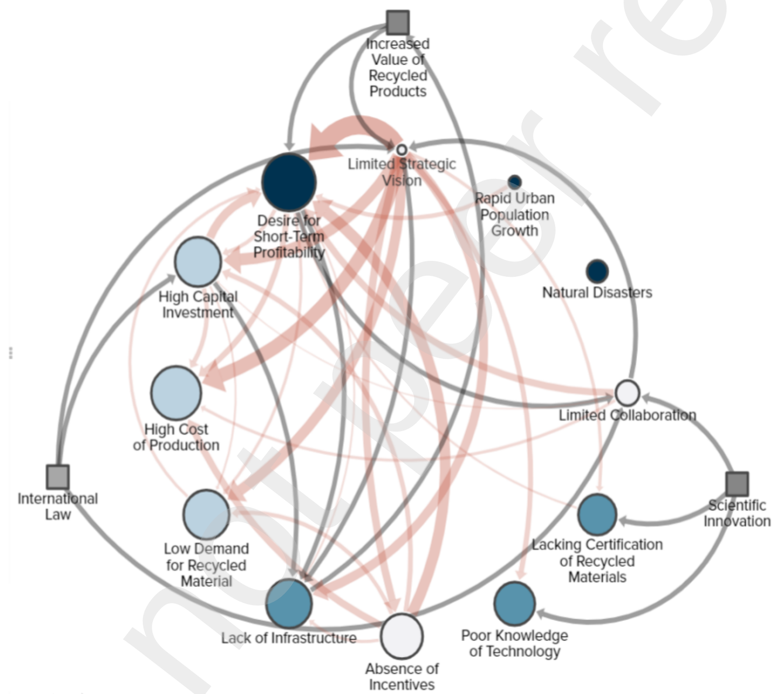

Fig.5. Policy recommendations overlaid on the CE-CDW system map. Red lines represent the interaction between barriers based on the indirect impact matrix. Dark blue circles are Socio-Environmental barriers, teal circles are Technical barriers, light blue circles are Financial barriers, light gray circles are Strategic-Regulatory barriers, and dark gray boxes are policy recommendations. Gray arrows represent the interaction between policy recommendations and the CE-CDW barriers.

Conclusions:

Our study sought to gain insight on the interconnected barriers that inhibit circular economy adoption in the construction sector, applied to a regional case study in Aysén, Chile. Through the complementary pairing of the literature with local stakeholder knowledge, we identified key CE-CDW barriers (RQ1), characterized the interaction and roles of these barriers using system and influence maps (RQ2), and used these maps to highlight systems-level leverage points for minimizing these barriers and promoting widespread and successful implementation of CE-CDW (RQ3). Study findings revealed that the refinement of governance strategy is a clear leverage point to achieve this end goal. Bolstering strategic vision can have downstream effects that ameliorate financial barriers (i.e., high capital and production costs and a lack of incentives) that exacerbate the desire for short-term profitability of companies and stakeholders. Additionally, the findings inform a two-pronged approach is needed to simultaneously pair long-term visioning and policy with innovation that improves the processes needed to create high-value products from recycled CDW.

While all CE-CDW systems will be context-specific, we believe that many of these findings and recommendations are generalizable to CE-CDW in other regions in Chile, given the country's consistent geopolitical context. Potential future research can inform more generalizable insights through the use of quantitative models that further characterize and elucidate the interconnection between the barriers identified in this study and promote what-if scenarios and simulation.

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Appendix

Table A1: Direct matrix; presenting values gathered from barrier mapping workshop. Highest influence (summed along the row) and dependence (summed down the column) are highlighted in **bold underline**.

	A	B	C	D	E	F	G	H	I	J	K	L	∑
A	0	2	2	2	1	3	2	3	3	2	3	0	23
B	3	0	2	2	3	0	2	1	2	1	1	3	20
C	3	0	0	0	1	0	3	2	2	1	1	1	14
D	3	1	0	0	3	0	3	2	3	0	0	0	15
E	3	0	0	3	0	2	3	3	3	1	0	0	18
F	3	0	0	0	2	0	3	3	3	0	3	1	18
G	3	2	2	3	2	2	0	1	3	0	3	2	23
H	3	0	0	2	2	3	2	0	2	0	3	2	19
I	3	0	0	3	2	2	2	2	0	0	3	1	18
J	3	3	3	3	2	1	3	3	1	0	3	3	**<u>28</u>**
K	2	0	3	3	2	3	3	3	3	0	0	3	25
L	2	1	2	3	3	2	0	2	0	3	3	0	21
∑	**<u>31</u>**	9	14	24	23	18	26	25	25	8	23	16	

A: Desire for Short-Term Profitability; B: Rapid Urban Growth; C: Natural Disasters; D: Lack of Infrastructure; E: Poor Knowledge of Technology; F: Lacking Certification of Recycled Materials; G: High Capital Investment; H: Low Demand for Recycled Materials; I: High Cost of Production; J: Limited Strategic Vision; K: Absence of Incentives; L: Limited Collaboration

Table A2: Normalized indirect matrix, the top-3 strongest connection strengths are presented in **bold underline**. Values normalized based on the highest connection strength from 6 matrix multiplication iterations.

	A	B	C	D	E	F	G	H	I	J	K	L
A	0.83	0.24	0.35	0.68	0.62	0.59	0.71	0.70	0.75	0.20	0.66	0.39
B	0.72	0.21	0.30	0.59	0.54	0.51	0.62	0.61	0.65	0.18	0.57	0.34
C	0.55	0.16	0.23	0.44	0.41	0.38	0.47	0.46	0.49	0.13	0.43	0.26
D	0.55	0.16	0.23	0.45	0.41	0.39	0.47	0.46	0.50	0.13	0.43	0.26
E	0.65	0.19	0.27	0.53	0.48	0.46	0.56	0.55	0.59	0.16	0.51	0.31
F	0.68	0.20	0.28	0.56	0.51	0.48	0.59	0.57	0.62	0.17	0.54	0.32
G	0.81	0.23	0.34	0.66	0.60	0.57	0.69	0.68	0.73	0.20	0.64	0.38
H	0.70	0.20	0.29	0.57	0.52	0.49	0.60	0.59	0.63	0.17	0.55	0.33
I	0.66	0.19	0.27	0.54	0.49	0.46	0.57	0.55	0.60	0.16	0.52	0.31
J	**<u>1.00</u>**	0.29	0.42	0.82	0.74	0.71	**<u>0.86</u>**	0.84	**<u>0.90</u>**	0.24	0.79	0.47
K	**<u>0.86</u>**	0.25	0.36	0.70	0.64	0.60	0.74	0.72	0.77	0.21	0.68	0.40
L	0.77	0.22	0.32	0.63	0.57	0.54	0.66	0.65	0.70	0.19	0.61	0.36

A: Desire for Short-Term Profitability; B: Rapid Urban Growth; C: Natural Disasters; D: Lack of Infrastructure; E: Poor Knowledge of Technology; F: Lacking Certification of Recycled Materials; G: High Capital Investment; H: Low Demand for Recycled Materials; I: High Cost of Production; J: Limited Strategic Vision; K: Absence of Incentives; L: Limited Collaboration