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Barriers to Cement Industry Towards Circular Economy

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Abstract
Cement, as the main component of concrete, is a crucial industrial product for economic development and civilization. Nevertheless, its production is highly energy-intensive, environmentally polluting, and a source of extreme CO_2 emissions. For success in the transition to the circular economy and accelerating sustainable manufacturing in the cement industry, understanding and addressing the main barriers are essential. Using the above point of view, this study intends to address the challenges and barriers of the cement industry in the transition to a circular economy, define the causal relationships between these barriers, and determine the necessary practical implications to overcome the barriers. Systematic literature review and focus group study results enable a holistic model that integrates research results and business practical criteria. The DEMATEL method is used for the clarification of causal relations between factors. A total of 18 barriers in 6 clusters have been revealed to be used for managerial implications to speed up the transition to CE applications in the cement business. Out of 18 barriers, 6 were effect groups, which were the outcomes due to the remaining 12 causing barriers. The top three cause factors are an unstable waste market, lack of management competencies, and unstable macroeconomic conditions, while the leading three effect factors are revealed as giving priority to other issues, insufficient organisational structures, and deviations in product quality. Although there are many studies on CE in cement, they are concentrated on technical and laboratory studies enabling the use of different alternative materials as inputs to the cement process. Studying and revealing the barriers holding back the cement sector in the transition to CE is this study's core contribution, making it novel and unique.

Keywords- Sustainability, Circular economy, Cement, Barriers, Challenges.

1. Introduction

In recent years, circular economy (CE) has gained popularity among scholars and practitioners as an alternative model against the existing old linear economy model, mainly due to the uncontrolled passion of linear economy for the consumption of insufficient resources (WBCSD, 2010; Gonzalez et al., 2019). CE is a new concept that pushes for innovative solutions to increase efficiency, close the loop by using waste as resources, and employ new consumption and production routines. Such improvements are argued to create an economic ecosystem that is more resistant, more sustainable, and more competitive at the micro, meso, and macro levels. (Lewandowski, 2016; D'Amato et al., 2017; Avdiushchenko and Zajac, 2019).

The circular economy finds its position in profit- and growth-driven business life by ensuring that environmental constructiveness comes with related economic benefits (e.g., using other business wastes as resources). Social benefits like employment or a better living ecosystem are natural outcomes (Lee et al., 2009; Dawei et al., 2015). These benefits are forecasted to reach $4,5 trillion by 2030 and $25 trillion by 2050 as a global economic benefit while achieving a 63% decrease in global greenhouse gas reduction due to low carbon and resource-efficient strategies of CE (Sehnem et al., 2019).

All the figures relating to the expected increase in global population and the corresponding increase in consumption and post-production routines of human beings should also be interpreted with the rise of urbanisation, which results in detrimental environmental effects (Govindan, 2018). Besides, these changes are elevating the consumption of raw materials for new residential areas through the construction of roads, bridges, buildings, dams, sewage systems, etc. (Bastein et al., 2013).

Cement, as the main component of concrete, is a critical industrial product for economic growth and civilization. However, its production is highly energy-consuming, environmentally polluting, and a source of high CO_2 emissions (Uwasu et al., 2014). Especially with the reality that 36% of total CO_2 emissions in the world are created by industry (Tonelli et al., 2013), and the cement industry is considered one of the primary industries adversely affecting the environment (Fard et al., 2016).

The sustainable manufacturing concept of integrating social, environmental, and economic positive outcomes comes alive with the circular economy model. It offers various commercial and business opportunities to members of the cement industry (Supino et al., 2016). But all these opportunities come with substantial challenges and barriers. For success in the transition to the circular economy and accelerating sustainable manufacturing in the cement industry, understanding and addressing the main barriers is essential (Salas et al., 2016).

Although there is an increasing interest in the CE concept and its active implementation on the micro- to macro-level, there are still limited studies on CE in the cement business. Also, existing limited studies are mostly focused on technical solutions for alternative materials from waste, but barriers to the transition to CE in the cement business have not been studied in the literature. Literature published within the last five years regarding the circular economy and cement has been reviewed. Resulting in 344 research articles, they were distributed as alternative raw material (68%), alternative fuel sources (3%), analysis studies (13%), and systematic literature review (6%). No research has been conducted on barriers, especially those related to the cement business. These outcomes from the existing literature are the trigger point for our study, which also creates the uniqueness and novelty of the study.

Using the above point of view, this study intends to address the challenges and barriers of the cement industry in the transition to a circular economy. This research aims to fill the gap in the scientific arena by providing a list of barriers specific to the cement sector, which will help policymakers gain additional insights and practitioners with CE implementation. Hence, the research questions answered in this study are:

RQ1. What are the main barriers to progress towards CE in the cement business?
RQ2. What are the relationships among barriers to CE transition in the cement business?
RQ3. What are the practical implications of overcoming these barriers?

Under this umbrella, the research's motivation and purpose depend on providing a list of barriers specific to the cement sector, which will help policymakers gain additional insights and help practitioners with CE implementation. The concerned objective finds its roots in the research gap in existing studies. A growing number of research is developed in CE. But relating to the cement business, most of the studies are connected to alternative raw materials from waste. Although there are studies on some specific sectors/business models, barriers in the cement business have not been studied in the literature.

The DEMATEL method is used in the study because of its strength in validating the interdependencies of factors. It is essential to understand that the barriers should not be interpreted individually but must be analyzed together. One improvement or setback in one barrier cannot be commented on as progress or degradation in overall CE performance. For example, using less raw material for production but a shorter-life product cannot be assessed as an improvement from a CE point of view (Avdiushchenko, 2021). Hence, the DEMATEL method is used, as it gives a chance to map the relative relations of the factors. Besides, its usefulness in clarifying the cause-and-effect relations between factors helps reveal the answer to RQ3.

The paper consists of six sections. A literature review is first mentioned in Section 2 to reveal the cement industry's historical and theoretical background and sustainability effects. In this section, the motivation of the study is clarified by defining the research gap and emphasizing the need to study the cement industry. In Section 3, the research model is identified, and a barriers list is created. The cause-and-effect relations between the barriers are explained after mentioning the findings from running the DEMATEL method. The top three causes and effects are also discussed in this section. In Section 4, the discussion and implications section, the main outcomes are discussed and validated with some alternative researchers from the literature. In Section 5, the conclusion section, the limitations of the study, and the future scope of the study are shared.

2. Literature Review

As long as concrete keeps its strong position, the cement continues to be the key building material for today's growing housing and infrastructure requirements without an alternative. This reality makes the cement industry a crucial consumer of natural resources, energy sources, and CO_2-emitting sources on a global scale (Schneider et al., 2011). Cement consumption, which has a stable increase pattern, is forecast to be more than 5 billion tonnes globally by 2050. Due to fossil fuel burning for the endothermic reaction of the clinker process and mainly as the result of the chemical reaction of clinker formation, approximately 0,9 tons of CO_2 per tonne of cement is emitted to the atmosphere, which accounts for around 5-8% of man-made CO_2 emissions globally. With these forecasted enormous volumes of cement consumption, it will have a drastic effect on greenhouse gas emissions overall (Cai et al., 2016; Cembureau, 2019).

The next crucial point relating to cement production is the consumption of natural resources such as raw materials and heat energy sources. The production process needs limestone as a critical raw material component, but besides that, clay, iron ore, bauxite, and gypsum are also required as supplementary materials, which is necessary to a level of 1,65–1,75 tons of raw material per 1 ton of clinker (app. per 1,2 ton of cement). Also, for creating the needed heat energy of 750 to 850 kcal/kg clinker for an endothermic chemical reaction in the kiln for clinker production—the semi-product of cement—approximately 0,20-0,25 kg of coal are consumed for 1kg of clinker. Decreasing reserves of these raw material resources and the decline in the quality of existing resources in some areas globally are creating a sustainability problem (Naik, 2005; Potgieter, 2012).

According to Summerbell et al. (2016) and Naik (2005), the electrical energy consumption for cement production is approximately 2% of the world total and 5% of the industry total, with unitary consumption of 90-120 kWh/ton of cement production.

In light of the above figures for cement production, cement producers are under pressure to align their processes with sustainability in the long term (Bataille, 2020). According to Potgieter (2012), achieving sustainability in the cement industry is highly dependent on innovative solutions in production processes relating to waste and pollutant reduction by using waste and/or by-products from other industries.

The above-explained major figures of the cement industry relating to natural resource consumption, energy consumption, and environmental impacts (mainly dust, CO_2, and NOx emissions), when combined with global consumption and production figures of cement, put the industry at a significant sustainability threat. Therefore, studying and defining the barriers for the cement industry towards a circular economy is crucial for improving the industry's sustainability measures.

Cement producers are trying to adapt their processes to sustainability by introducing additional loops in their process flows and linking back resources from other industries' end-of-life products, waste, and by-products. These activities are related to recycling loops, which create less value compared to inner loops such as reuse or remanufacture. But when the cement industry is concerned, due to its nature of high energy consumption, any slight improvement in fuel mix or raw material by substituting wastes or by-products has the potential to create significant benefits for the environment, economy, and society (Ramsheva and Remmen, 2018). Replacing wastes and by-products creates the opportunity to decrease CO_2 emissions in the overall cement industry. Due to the limits of raw materials and energy, the business search is for value creation regarding closing loops, which has a background in systems theory. This approach helps with waste minimization (Miller et al., 2017). These loops are shown in Figure 1.

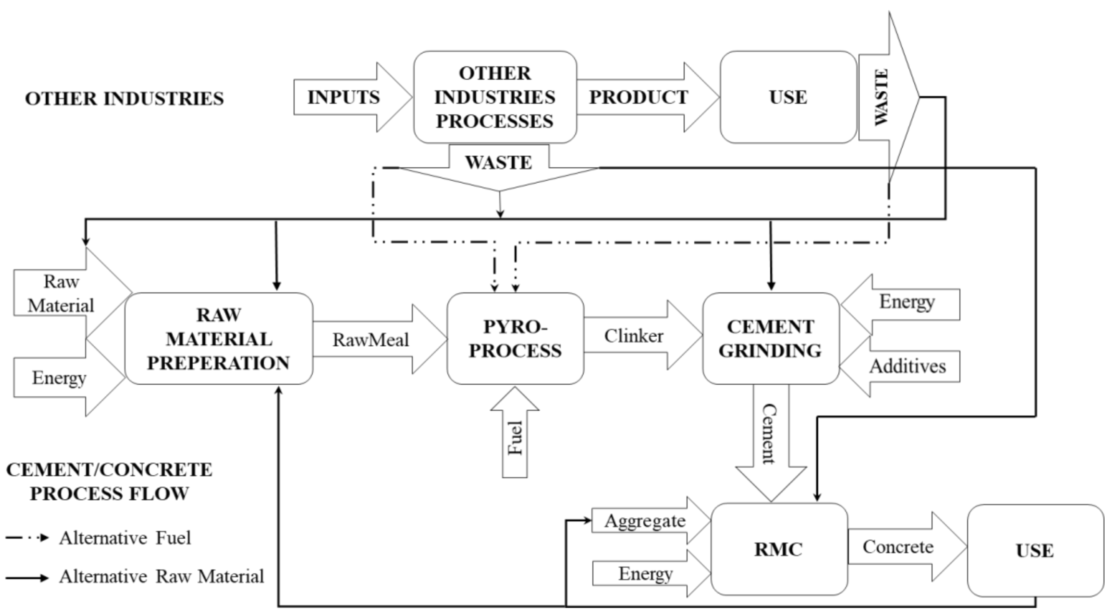

Figure 1. Closing loops in the cement process.

Realization of this approach depends highly on building a network of diverse organizations which share mutually profitable transactions. The search is for the industry's wastes or by-products to become the cement industry's raw material or energy source (Tsiliyannis, 2017). Cooperations between companies depending on industrial symbiosis enhance the ability to reach waste as alternative inputs of raw materials and fuels, which also creates the waste, by-product, and information exchange platform for a diversity of industries (Chertow, 2004; Hashimoto et al., 2010).

In this section, the research gap on the barriers of the cement industry towards the transition to CE will be validated by the summary of earlier circular economy studies in the literature.

While justifying the research gap, the WOS search has been achieved by keywords such as "cement, barriers, circular economy" without a time limit. The papers published are given in Table 1.

Table 1. Summary of literature.

Title	Author/Year	Summary
Complete reutilization of waste concretes	Villagran-Zaccardi et al. (2022)	End-of-life concrete to be used as a resource in construction and infrastructure
Achieving net zero greenhouse gas emissions in the cement industry via value chain mitigation strategies	Miller et al. (2021)	Considering the emission reduction challenges of industries from cement producers to end users, the study is based on proposals for reducing emissions through the value chain.
Industrial Symbiosis and Energy Efficiency in European Process Industries	Branca et al. (2021)	Industrial Symbiosis and energy efficiency practices are analyzed for evaluation depending on energy and material flows throughout European process industries.
State of the art review on Supplementary Cementitious Materials in India	Gupta and Choudhary (2020)	A literature review that analyses the effect of legal issues on using cementitious materials as an alternative raw material.
Developing advanced techniques to reclaim existing end-of-service life (EoSL) bricks	Zhou et al. (2020)	Proposal of some techniques for end-of-life bricks in construction and demolition waste to make them reused.
Fostering Circular Economy Through the Analysis of Existing Open Access IS Databases	Jato-Espino et al. (2020)	Analyses of databases that are open to the public are validating the relationship between the steel and cement industries.
Scrap happens: A case of industrial end-users, component remanufacturing outcome	Diener et al. (2019)	Reveal the systemic nature of component remanufacturing outcomes in paper, steel, and cement factories.
Recycling of MSWI Bottom Ash	Verbinnen et al. (2017)	Chemical laboratory study results for using the bottom ash of MSW incineration in the cement industry.

The literature in Table 1 has been published within the last five years and focuses mainly on using alternative materials from other industries or end-of-life materials in the cement process.

To enlarge the search borders to secure all information, keywords have been relaxed as "cement, circular economy" to investigate all studies on cement relating to the circular economy, and 344 articles have been found in the literature. All articles have been subgrouped into seven categories depending on their research topic. These groups are listed in Table 2.

Table 2. Article category.

Category	Explanation
ARM (Alternative Raw Material)	Lab. Studies to reveal the effect on cement/concrete physical and chemical quality parameters
AF (Alternative Fuel)	Lab. Studies to reveal the effect on cement/concrete physical and chemical quality parameters
Analysıs	Network Analysis, MFA, LCA, Performance Analysis, Emergy Analysis, Exploratory Analysis
New Tech./Product	Sulfobelite cement, 3D printing, Phase change materials
Polıcy/Regulatıons	Health, GHG emissions, Quality control
Lıterature Revıew	Supplementary cementitious material utilization (alternatives, quality)
Modellıng	Quantifying ARM types, Comparing the efficiency and performance of different AF/ARM

The distribution of these 344 articles on a category base is shown in Figure 2.

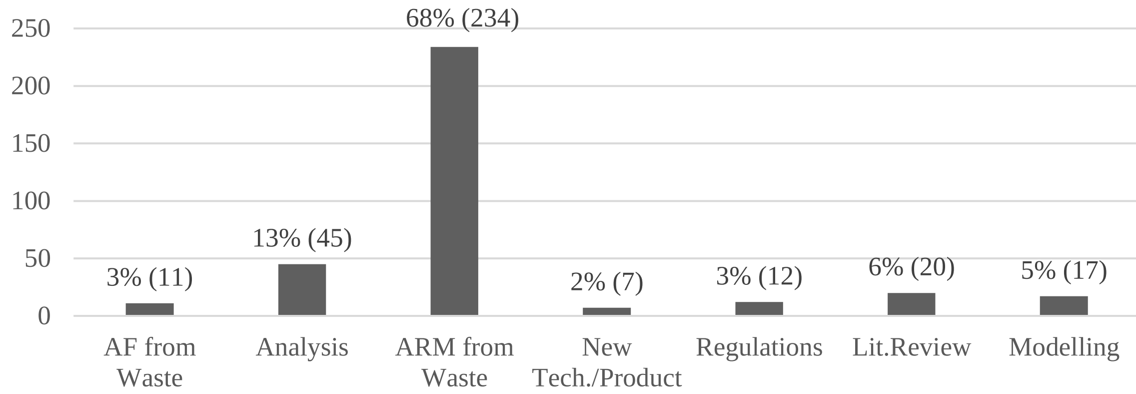

Figure 2. Distribution of papers by category.

There is no study found in the literature that searches the barriers to a circular economy specific to the cement business with a holistic view. Most studies' interest is in the circular economy in general and mainly focuses on individual applications on the path to CE. The main focus of research on cement and CE is the feasibility of alternative materials to be used in the cement process, substituting traditional raw materials and fossil fuel resources. Although the studies mentioned above in the literature are opening the way for a circular economy in cement, they do not study the barriers. Hence, the focus of this research remains novel and unique.

3. Methodology

3.1 Research Model

To speed up the transition of the cement business to CE, a comprehensive plan and holistic approach are needed. A holistic model which integrates both research results and business practice criteria related to cement business barriers is rational (Kazancoglu, 2018). This study is an effort to create such a model based on former scientific research and business criteria validated by experts. For this reason, the research model shown in Figure 3 has been used.

A group of 7 experts from cement organizations has been established to run the research model, including the vice president, director, plant manager, and process manager. The selection criteria for experts were their seniority level to have high experience in the cement business, their organizational status to secure their involvement in executive decisions, their companies to be a part of a multinational group to have the perspective of global and local dimensions, and their companies to be already involved in some of the CE applications. Information about the expert group is mentioned in Table 3.

Table 3. Expert group.

Expert's Position	Expert's Company	Seniority in Cement Business	Profession
Env.&Sust.Director	Group of 7 Cement Plants, Multinational	25 Years	Env.Eng., MSc
Sustainability Director	Group of 5 Cement Plants	18 years	Env.Eng.
Bus.Dev.R&D Director	Group of 5 Cement Plants	17 years	Chem.Eng., MSc
Technical Director	Group of 4 Cement Plants, Multinational	20 years	Mech.Eng., MSc
Plant Manager	Multinational Group	22 Years	Chem. Eng.
Plant Manager	Multinational Group	20 Years	Elect.Eng.
Vice President	Group of 6 Cement Plants	24 Years	Elect.Eng.

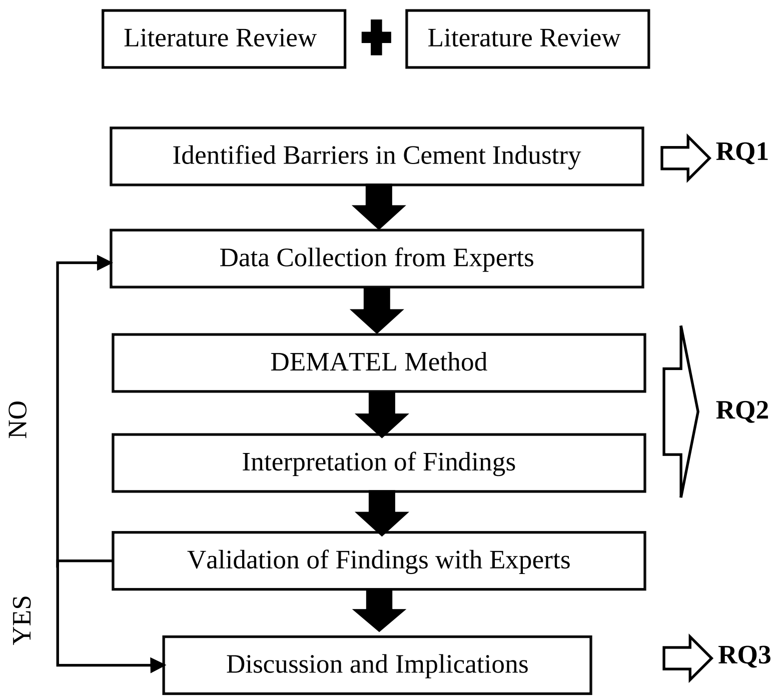

Figure 3. Research model.

The companies of the experts are all using circular economy applications to a limited level, mainly for alternative raw materials and alternative fuels to decrease their natural resource consumption of limestone, clay, iron ore, and coal. Their efforts are mostly incorporated with industrial symbiosis theory by building networks with other industries' wastes or by-products. Also, due to the intensive energy-consuming characteristic of the industry, as a traditional mindset, the management is always focused on continuous improvement of energy consumption figures. Their motivation for these efforts is mainly driven by cost advantage.

3.2 Barriers Against Circular Economy in Cement Business

Many studies related to circular economy implementation challenges and drivers show that they are mainly divided into two groups: external factors and internal organizational factors. But Ritzen and Sandstrom (2017), Govindan and Hasanagic (2018), and Morel and Charef (2019) came up with subgroups of barriers depending on their model after an extensive literature review. The main subgroups, or clusters, of CE implementation challenges are defined below.

Governmental/Regulatory issues: this group of barriers is mainly related to coordination and/or support insufficiency of existing legislation. Besides, it also consists of legislative incompatibility with changing global conditions.

Economic issues: this cluster of barriers is related to factors that affect organizations' financial situation when moving towards CE implementation.

Technological issues: constraints created because of the existing technical level create problems with product quality, design, etc.

Knowledge and skill issues: a group of factors relating to a lack of reliable information and data for implementing innovative CE implementations. Also, insufficient or wrong skills about CE create opposition to CE implementation.

Management issues: this group is related to managerial mistakes that block or slow down the movement towards CE in organizations.

Circular economy framework issues: this cluster includes the circular economy framework issues; other solutions might be more favorable than the circular economy framework.

Culture and social issues: this cluster refers to the lack of enthusiasm towards enacting the circular economy, consumer perception towards reused products, and the thrill of purchasing a new product.

Market and Social issues: societal oppositions to circular economy applications and consumer behaviors to products from CE applications.

The resulting barrier list to be used in research and the answer to RQ1 are in Table 4. The column "literature background" is used to reveal the related supporting studies in the literature. As the main focus is to use the experts' evaluations, although some barriers have limited background in the literature, all expert evaluations have been used in the list.

Table 4. Barriers list.

BARRIERS		**LITERATURE BACKGROUND**	**DESCRIPTION**
Governmental/Regulatory			
B1	Lack of Policies on the Quality of Recycled Material	de Man and Friege (2016); Mahpour (2018); Seth et al. (2016)	As the regulatory base has no relation to the quality of traded waste material, suppliers ignore the quality of waste material in market conditions with less supply than demand.
B2	Lack of Policies on Promoting CE	Pan et al. (2015); Hart et al. (2019); Seth et al. (2016)	Regulations are concentrated mainly on the security of transportation, handling, and storage of waste material. Lack of direction to control the market on quality, process types, manufacturing conditions, and competition is slowing the conditions towards CE.
B3	Lack of Rules Forcing the Implementation of CE	Li et al. (2009); Mahpour (2018); Isaksson (2016); Seth et al. (2016)	Industrial CE implementation practices are totally on management decisions. No regulatory practices are forcing the organizations to move towards CE.
B4	Waste Import Restrictions-ETS(CBAM)	Pan et al. (2015)	Collected wastes are not sufficient in quantity, quality, and diversity. Import opportunities will force the waste market into competition. Especially existing bioenergy local sources are shifting to energy producers as they are paid better. Referring to the ETS (Emissions Trade System), the newly introduced CBAM (Carbon Border Adjustment Mechanism) will introduce additional costs on exporters to the EU.
Economic Issues			
B5	Unstable Macroeconomic Conditions		Uncertainty on revenue, cost of inputs, and new project feasibility are forcing short-term decisions rather than medium- and long-term strategic changes.
B6	Insufficient Internalization of External Costs (env. costs are not considered)	Lieder and Rashid (2016); Hart et al. (2019)	Moving towards CE is only promoted if actions create an advantage in production costs. As there is no internalization of environmental costs, the production cost advantage becomes the only advantage and decision criteria. Most of the time, creating unfair competition conditions.
B7	High Investment Costs for Implementation	Pan et al. (2015); Hart et al. (2019)	Mainly for using the waste of other industries, new technological infrastructure (machinery) is capital intensive.
B8	Production Costs are Increasing by refuse-derived inputs	Palm et al. (2016); Shahbazi et al. (2016); Chatziaras et al. (2016)	Due to humidity, unwanted chemical ingredients, and fluctuations in physical and chemical compositions, it adversely affects the process and costs.

Table 4 continued...

Technological Issues			
B9	Maintaining Product Quality is a Challenge	Singh and Ordonez (2016); Ghisellini et al. (2016); Hart et al. (2019); Mahpour (2018); Chatziaras et al. (2016)	The down-cycling characteristics of wastes (calorific value, chlorine content) have a negative effect on products.
B10	Insufficient Technology for Multiple and Quality Variable Waste Inputs	Hart et al. (2019); Seth et al. (2016)	Cement plants prefer to use a variety of ARM and/or AF, but the machinery needed to use ARM and/or AF is mostly for one or several types of waste. Lack of technological infrastructure (homogenizing, laboratory) in waste preparation is a source of quality fluctuation.
Knowledge and Skill			
B11	Limited Historical Data	Andrew (2018)	In the status quo, predicting the future is simpler with enough extensive historical data. Transitioning to CE means limited historical data for predicting the future.
Management			
B12	Lack of Top Management Competencies	Hart et al. (2019); Seth et al. (2016)	Shifting towards CE needs to make changes in the entire value chain, with managers having creativity, capacity, and commitment.
B13	Existing Organisational Structures are Challenge on Coprocessing	Liu and Bai (2014); Seth et al. (2016)	Organizational change is needed. Conflicts of interests between departments should be resolved through the sharing of responsibilities and risks.
B14	Higher Priority on Other Issues	Hart et al. (2019)	Managers' main approach is mostly short-term gains due to pressures from the BoD, which results in a current-year EBITDA focus.
B15	Lack of a Standard System for Measuring CE	Su et al. (2013); Li et al. (2009); Geng (2012)	Managing without measuring is impossible.
B16	Plant Locations are Close to the Public	Ekinci et al. (2020)	Some cement plant locations are close to residential areas. Besides other disturbing issues, using waste material as an alternative raw material and/or alternative fuel is becoming an additional problem (smell, increased traffic, risk of environmental accidents, etc.).
B17	Unstable Waste Market	Hart et al. (2019)	Waste dependency on the existence of industrial zones creates problems with availability, quality, and price in different locations.
B18	Consumers Perceptions	Mahpour (2018); Seth et al. (2016)	Consumers' approach is suspicious about products with ARM orAF.

3.3 Methodology: DEMATEL Method

The Decision Making Trial and Evaluation Laboratory (DEMATEL) technique was first developed by the Geneva Research Centre of the Battelle Memorial Institute to visualize the structure of complicated causal relationships through matrixes or digraphs (Si et al., 2018). It is a structural modeling method and is especially used for defining the cause-and-effect relationships between factors by analyzing the components of a system. By using the DEMATEL method, it is possible to validate the interdependency of factors; hence, it gives a chance to map the relative relations among factors. The use of a map creates the possibility of investigating complicated problems. Besides its usefulness in clarifying the cause-and-effect relations between factors, it is also powerful to sort by impact and define critical factors.

The steps of running the classical DEMATEL can be formulated as follows (Si et al., 2018).

Step 1 (Generating the Group Direct Influence Matrix, Z_d)

The first step is to create an integer scale of 5 levels from 0 to 4, as shown in Table 5, to be used by experts to evaluate the relations between factors.

Table 5. Comparison scale.

Integer Value	Definition
0	No Influence
1	Low Influence
2	Medium Influence
3	High Influence
4	Very High Influence

For assessing relationships between n criteria $C = \{C1, C2, \ldots, C_n\}$, experts are asked to evaluate the pairwise effect of each criterion on each other criteria, which means to give an integer value from scale in Table5 for the influence of C_i on C_j. The result is an individual direct relation matrix for each expert. Individual direct relation matrixes are each expert's judgment of the influences of factors on other factors in a matrix having a principal diagonal value of zero. By aggregating all experts' judgments, group direct relation matrix $\boldsymbol{Z}$ is obtained by

$$Z = \frac{1}{n} \Sigma Z_{ij} \quad i, j = 1, 2, \ldots.., n \tag{1}$$

Step 2 (Normalized Direct Influence Matrix, X)

By using group direct relation matrix, $\boldsymbol{Z}$, formula (2) and (3), normalized direct influence matrix, $\boldsymbol{X}$, is obtained as

$$X = \frac{Z}{s} \tag{2}$$

$$s, \max_{1 \leq i \leq n} \sum_{j=1}^{n} Z_{ij} \tag{3}$$

Step 3 (Total Relation Matrix, T)

Total relation matrix means actually to sum up all direct and indirect effects; hence it is determined as follows where I represents the identity matrix

$$T = X + X^2 + X^3 + \ldots + X^h = X\,(I - X)^{-1}, \text{ when } h \rightarrow \infty \tag{4}$$

Step 4 (Influential Relation Matrix, IRM)

As the experts' evaluations are completed depending on the intensity of influence of a factor in a row on all other factors in the columns, summing up the values in a row means the total effect being distributed from C_i to all other factors. Summing up the values in a column by the same approach means the total effect C_j receives.

The vectors of R and C are formulated as follows, which depict the sums of rows and sums of columns of the total relation matrix

$$R = [r_i]_{n\text{x}1} = \left[\sum_{j=1}^{n} tij\right]_{n\text{x}1} \tag{5}$$

$$C = [c_j]_{1\text{x}n} = \left[\sum_{i=1}^{n} tij\right]_{1\text{xn}} \tag{6}$$

Hence the sum of these two vectors (R+C) is called *prominence*. It depicts the information about the strength of effects that a factor is giving and receiving, which can be articulated as putting the factors into importance order in the system. Alike, the difference of vectors (R-C) is called *relation* and depicts the information about the net effect of a factor, which means the positive valued factors affect the others (cause group). Negative valued factors are the ones that are being affected (effect group).

As a result, the graph of prominence and relation becomes a valuable tool to make evaluations and analyses for decision-making and define cause and effect relations between the factors in a system.

3.4 Implementation and Findings

Eight experts from leading companies in the cement sector participated in the study for implementation. As experts working in group companies, they represent 36 plants, and 13 are part of a group that acts as a global cement producer. And all experts' companies are realizing CE practices in their processes at varying scales (Table 3). Also, the experience level of respondents in the cement business varies between 17 and 25 years, with an average of 20 years. The diversity of experts, combined with their seniority in the cement sector, creates the reliability and representativeness of the focus group.

18 factors have been used for experts to make their judgements (Table 4), and for solving matrixes, Microsoft Excel is used. To give some insight, one of the experts' judgements is shown as a matrix in Table 6.

After collecting the evaluations of 7 experts, the group direct-influence matrix was obtained by aggregating the seven experts' opinions. When the group direct-influence matrix is acquired, the normalized direct-influence matrix has been achieved using Equations (2) and (3), which indicate the overall evaluation of the experts. The total relation matrix is created using Equation (4) and presented in Table 7.

Table 6. Assessment of an expert.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18
B1	0	3	3	1	0	2	2	4	4	0	1	0	0	2	1	0	3	2
B2	3	0	3	2	0	2	2	3	0	0	1	0	0	2	2	0	2	2
B3	3	3	0	2	0	3	0	0	0	0	1	2	2	4	3	0	2	2
B4	0	0	0	0	0	3	2	3	3	0	0	0	0	2	0	0	4	1
B5	2	2	2	0	0	3	4	3	3	0	1	3	3	4	0	3	4	0
B6	2	2	1	1	0	0	0	3	0	1	1	3	2	3	3	2	1	1
B7	3	2	3	0	0	0	0	3	3	0	1	2	2	3	0	0	3	1
B8	0	0	3	0	0	0	3	0	0	0	0	1	4	4	2	0	1	0
B9	0	0	1	0	0	1	2	4	0	2	0	0	4	4	1	0	2	4
B10	2	1	2	0	0	1	3	3	3	0	1	0	2	1	0	0	1	0
B11	3	3	3	1	0	2	0	1	2	2	0	3	3	1	3	0	0	1
B12	2	2	2	2	0	1	1	2	2	2	1	0	3	4	1	0	1	2
B13	0	0	0	0	0	0	0	1	2	0	1	0	0	3	2	0	2	2
B14	2	2	2	1	0	1	0	1	1	0	2	3	3	0	3	0	1	2
B15	2	4	3	2	0	1	0	0	0	1	1	3	3	2	0	0	2	1
B16	1	1	1	0	0	0	3	0	0	0	0	0	0	2	0	0	1	4
B17	0	0	0	3	0	0	3	2	3	0	1	1	2	2	0	0	0	1
B18	0	0	0	0	0	0	2	0	2	0	0	2	2	3	0	0	0	0

As a final step, to show the structural model, Equation (5) is used to determine *D*+*R* and *D*-*R* values and presented in Table 7. A summary of numerical results is shown in Table 8. The resulting causal diagram depending on these values is shown in Figure 4.

Table 7. Total relation matrix.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18
B1	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0197	0,0066	0,0000	0,0099	0,0000
B2	0,0000	0,0000	0,0263	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0300	0,0180	0,0000	0,0137	0,0000
B3	0,0128	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0210	0,0119	0,0000	0,0082	0,0000
B4	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0226	0,0204	0,0000	0,0000	0,0000	0,0000	0,0238	0,0000	0,0000	0,0000	0,0000
B5	0,0000	0,0000	0,0000	0,0000	0,0000	0,0221	0,0247	0,0172	0,0144	0,0000	0,0000	0,0000	0,0195	0,0483	0,0000	0,0103	0,0263	0,0000
B6	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0125	0,0000	0,0000	0,0000	0,0157	0,0000	0,0262	0,0000	0,0000	0,0067	0,0000
B7	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0186	0,0000	0,0000	0,0000	0,0000	0,0210	0,0000	0,0000	0,0000	0,0000
B8	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0098	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
B9	0,0000	0,0000	0,0000	0,0000	0,0000	0,0064	0,0000	0,0234	0,0000	0,0071	0,0000	0,0000	0,0227	0,0288	0,0000	0,0000	0,0000	0,0000
B10	0,0087	0,0088	0,0064	0,0000	0,0000	0,0000	0,0179	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0177	0,0000	0,0000	0,0000	0,0000
B11	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0066	0,0058	0,0103	0,0000	0,0000	0,0000	0,0000
B12	0,0000	0,0000	0,0000	0,0000	0,0000	0,0066	0,0000	0,0123	0,0145	0,0000	0,0000	0,0000	0,0201	0,0348	0,0000	0,0000	0,0000	0,0000
B13	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0182	0,0000	0,0042	0,0000	0,0000	0,0135	0,0000	0,0000	0,0088	0,0000
B14	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0101	0,0000	0,0067	0,0000	0,0000	0,0000
B15	0,0074	0,0088	0,0126	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0105	0,0000	0,0000	0,0000	0,0080	0,0000
B16	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
B17	0,0000	0,0000	0,0000	0,0118	0,0000	0,0000	0,0000	0,0244	0,0242	0,0000	0,0031	0,0071	0,0220	0,0364	0,0000	0,0000	0,0000	0,0000
B18	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0156	0,0000	0,0000	0,0000	0,0000

Table 8. *D+R* and *D-R* dataset.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18
D+R	0,065	0,106	0,099	0,079	0,183	0,096	0,092	0,122	0,199	0,067	0,030	0,118	0,155	0,364	0,091	0,010	0,211	0,016
D-R	0,007	0,070	0,009	0,055	0,183	0,026	0,013	0,103	0,022	0,052	0,015	0,059	0,066	0,330	0,004	0,010	0,047	0,016

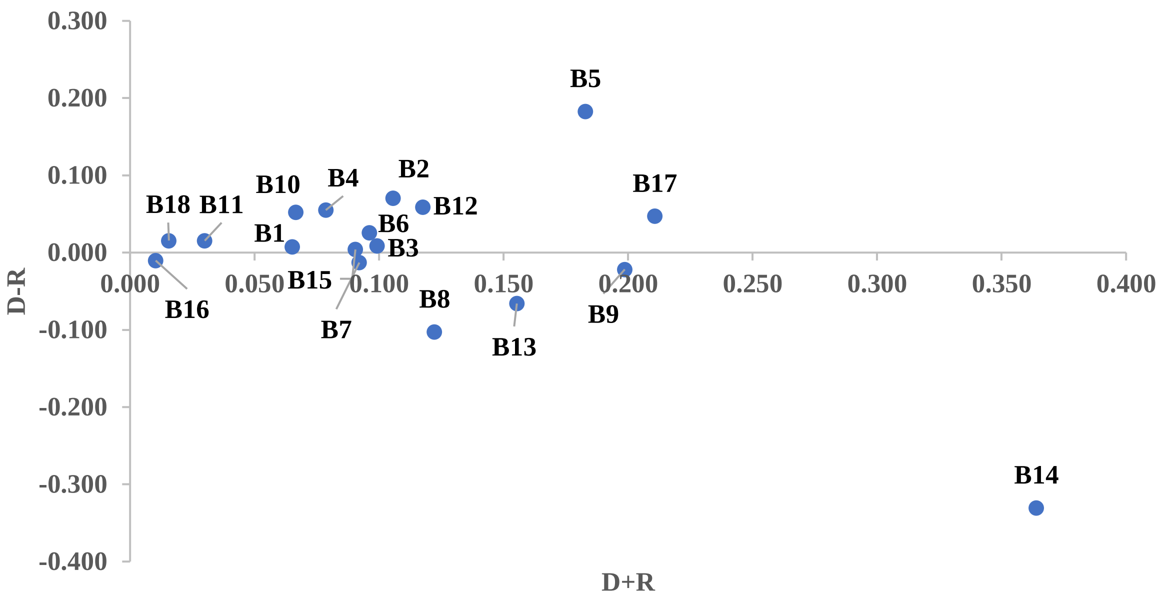

Figure 4. Causal diagram.

Depending on the numerical findings listed in Tables 7 and 8, a summary in Table 9 has been prepared to be used for managerial implications. Table 9 shows the importance order besides the cause and effect groups of factors relating to CE barriers in the cement business. D+R values are used to identify the importance of the criteria, as a higher value gives greater importance to the concerned factor.

Table 9. Summary of numerical findings.

	Importance Order (Influence on Other Factors)	Cause Group	Effect Group
B14	Higher Priority on Other Issues		✓
B17	Unstable Waste Market	✓	
B9	Maintaining Product Quality is a Challenge		✓
B5	Unstable Macroeconomic Conditions	✓	
B13	Existing Organisational Structures are Challenge on Coprocessing		✓
B8	Production Costs are Increasing by refuse-derived inputs		✓
B12	Lack of Top Management Competencies	✓	
B2	Lack of Policies on Promoting CE	✓	
B3	Lack of Rules Forcing the Implementation of CE	✓	
B6	Insufficient Internalization of External Costs	✓	
B7	High Investment Costs for Implementation		✓
B15	Lack of a Standard System for Measuring CE	✓	
B4	Waste Import Restrictions-ETS(CBAM)	✓	
B10	Insufficient Technology for Variable Waste Inputs	✓	
B1	Lack of Policies on the Quality of Recycled Material	✓	
B11	Limited Historical Data	✓	
B18	Consumers Perceptions	✓	
B16	Plant Locations are Close to the Public		✓

Referring to Table 9, the factors affecting the others as causes and affected factors are clear, but factors with reasonable relationships should be revealed to reach practical implications. Hence, in Figure 5, factor relationships with a higher value than the average value of the total relation matrix are presented (Kazancoglu et al., 2019).

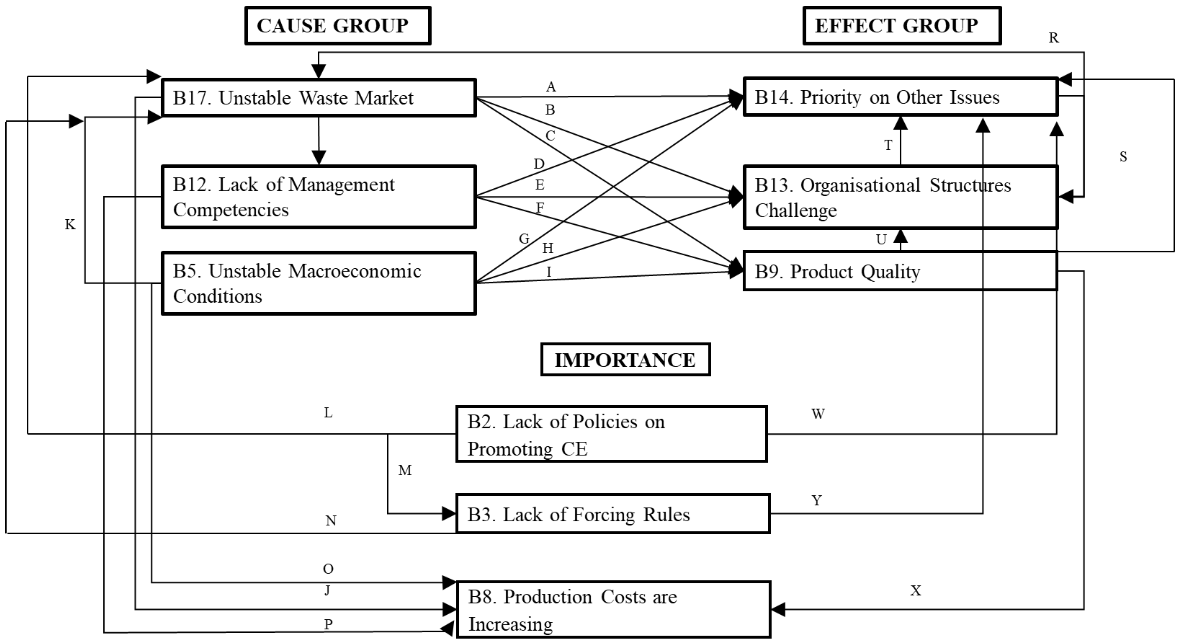

Figure 5. Factor relationship map.

Depending on the numerical results of the DEMATEL study, the top three cause factors are an unstable waste market (B17), a lack of management competencies (B12), and unstable macroeconomic conditions (B5), while the top three effect factors are management priority on other issues (B14), organisational structures challenges (B13), and challenges on keeping the product quality (B9). Below are the explanations for managerial implications regarding factor relations shown in Figure 5, which also answers RQ2.

A-B-C(B17 to B14, B13, B9)**:** Unstable conditions in the waste market relating to fluctuations in physical, chemical, and calorific values mainly affect product quality. Because the waste from the market is being used as an alternative raw material and/or alternative fuel source, which in turn is being bonded into the product during the reactions of the production process (B9). Also, fluctuations in these materials' availability create uncertainty in securing the supply amount and price. Under the existing organizational structures, it becomes tough to cope with these challenging conditions (B13). As a result, under challenging business conditions (competition, market, economic conditions, etc.), management's preference becomes to search for more secure operational decisions (B14).

D-E-F(B12 to B14, B13, B9)**:** Adapting the organization to circular economy applications versus traditional linear economy requires more flexible production processes, reshaped organizational structures to improve coprocessing through the value chain, and a focused vision on the triple bottom line for sustainability. Inadequate managerial skills and competencies to increase awareness of the topic and properly manage needed changes naturally become a cause.

***G-H-I(B5 to B14, B13, B9)*:** Uncertainties in economic conditions, high rates of inflation, currency, and interests; recession, inflation, stagflation, political risks, etc. are sources creating unstable macroeconomic conditions. Under these kinds of uncertain situations, management's decisions become to survive versus sustain, forcing them to change their priorities (B14). Due to more limited resources or changes in resource allocation criteria, needed actions are postponed, resulting in product quality problems.

***K-L-N-R (Causes of B17)*:** Wastes to be used in the cement business as alternative raw material and alternative fuel are produced from individual consumption and/or from industrial processes whose amount and quality are affected by challenges in macroeconomic conditions (K). These outcomes are even used directly or after being processed by a supplier in the value chain. Promotions and/or limitations become moderating rules for market regulations under extraordinary conditions. Hence, deficiencies in promoting and forcing rules, especially under unstable macroeconomic conditions, are causes for disrupting the stability of the waste market (L, N). The dynamic nature of waste coprocessing coming from the industrial symbiosis concept requires continuous alignment between the parties in the value chain of the cement business. Its contradictory nature with the traditional supply chain requires more dynamic and engaged relations between supplier and user. Alternative materials in cement are a part of the process input that has to be controlled within specification limits, while they are the outcomes of another industry. Hence, organizational structures have to be modified to keep this value flow in symbiotic form (R).

***J-O-P-X (Causes of B8)*:** For keeping the product quality and production cost at the desired level, the input (wastes are also input) and process parameters are set to targets. These targets are defined based on technical and economic feasibility studies. Any fluctuations in price, quality, and amount of waste in the negative direction of set targets have the same negative effect on production costs, which raises the importance of stability in the waste market (J). The same conclusions are also triggered by adverse and/or unstable macroeconomic conditions (O). Lack of any needed managerial competencies as a result of a deficiency in fulfilling the management functions creates a production cost increase, which is only one among many. But especially under extraordinary or newly adaptive conditions, additional competencies (creativity, flexibility, agility, assertiveness, etc.) are becoming necessary. The team must adapt to a new way of doing business by moving out of their comfort zone, which is exactly the move towards CE (P). In the cement process, under extraordinary conditions to maintain the final product's quality according to standards and customers, sacrifice is made in the process before the final step, which results mostly in rework and scrap, or on the final process step (cement grinding), which results in more consumption of electricity, chemicals, and material (clinker). These extraordinary conditions are triggered by the price, amount, and quality (chemical, physical, calorific) of wastes integrated into the cement process (X).

***V-W-Y (Causes of B14)*:** Although lack of promoting and forcing rules are tools to moderate the industry and market conditions, its implication on prioritizing other issues than CE is more dependent on a lack of management competencies. The same implication is also valid for product quality.

4. Discussion and Implications

This study uses literature background and expert opinions to determine 18 factors related to barriers to cement business in the transition to CE, which answers RQ1. These factors are evaluated by the same experts, and the DEMATEL method is employed to reveal the interrelations of the factors to define causal relations. As an answer to RQ2, it is revealed at the end of the findings sections. The resulting findings are also shared by the same experts for validation. The outcomes of the methodology have implications. In this section, discussion on implications is shared as an answer to RQ3. Hence, the answers to three RQs have been succeeded by the methodology.

The top three cause factors influencing the other determined barriers are defined using the numerical results of the DEMATEL method. Outcomes reveal the fact that the most influencing factor is waste market stability, which overlaps with Chatziaras (2016) arguments that physical, chemical, and calorific properties, availability (amount per time), and stability of these properties are crucial for process control and operations management in the cement industry. Hence, as an industry's waste becomes the cement process's input, deviations from specification limits in this symbiotic relationship cause risks to production continuity, cost, and quality in the cement business. The second important influencing factor is related to macroeconomic conditions. Adverse conditions in macroeconomic parameters (high inflation, currency fluctuations, recession, etc.) affect the supply, demand, and supply chain figures, as directly affecting the overall market conditions also affects the sales, production, and financial figures of waste suppliers, dealers, and users.

These adverse conditions will affect overall market conditions; when having a different impact on different business segments, the cement business's waste inputs from various sources are adversely affected by supplying the needed waste amount. Quality fluctuations in waste inputs simultaneously follow up on this availability problem. Besides adverse effects on availability and quality, management is also forced to change their business priorities to survival mode, which paves the way to limiting expenses by shifting to less risky and shorter payback decisions. Management competencies and commitment are found to be the third important influencing factor, which has also been emphasized by de Jesus (2018) as hard and soft barriers for any industry on the way towards CE applications. Hard barriers should be solved by forcing the needed changes using technical or economic tools. But soft barriers are the ones to be overcome by means of values and institutional tools to reshape the attitudes and behaviors of people (Marsh et al., 2022). Hence, shifting from a traditional linear economy to a circular economy concept requires managerial effort and experienced competencies.

Interrelationships between factors also have substantial implications for improving the transition of the cement sector to CE. The lack of forcing rules and policies on promoting CE strongly influences the main causal factor of the unstable waste market. An unstable waste market, adverse macroeconomic conditions, and limited management competencies are creating a strong influence on production cost increases and management priorities on other issues. Therefore, it is possible to make an argument that governmental forcing of rules and promoting policies will have a positive effect on the stability of the waste market, and when supported by committed and competent management, the production costs will not increase, and priority will be given to CE rather than other short-term issues even in adverse macroeconomic conditions.

Hence, all three RQs are answered as above. Moreover, regarding the managerial implications depending on the DEMATEL results of the study, we would like to make additional suggestions for improving the CE concept in the cement business:

- Improving the data network between cement companies supported by management information systems will improve the traceability of the alternative materials used in the sector.
- Regular meetings with policymakers and cement sector representatives will be a powerful tool for improving communication. Policymakers will be more aware of the needs and problems of the sector, while the sector will remain updated and ready regarding the existing and upcoming regulations.
- Because they are working as a bridge between industries and cement plants, an association of waste dealers should be encouraged to improve communication on all supply chain levels.
- Standards, especially on alternative fuels, should be employed to regulate refuse-derived fuel product quality and market conditions.

5. Conclusion

This study aims to define barriers to progress towards CE in the cement business using the DEMATEL approach to reveal the causal relationship among the defined barriers. Proposals on practical implications have been determined with a holistic view to overcome the effects of concerned barriers. The DEMATEL structural modeling method has been used to visualize the structure of complicated causal relationships and to define the cause-and-effect relationships between factors.

In total, 18 barriers have been revealed by experts in the cement industry as answers to RQ1. Causal relationships have been revealed to classify the barriers as causes and effects, which was the source of the answer to RQ2. Out of 18 barriers, 6 were effect groups which were the outcomes due to the remaining 12 causing barriers. The interpretation of causal relationships is shared by experts and has been validated by them. Implications are shared mainly at the end of the findings sections and summarized in the discussion section as an answer to RQ3. Moreover, these results have been validated by the same participant experts when shared and discussed.

The main outcomes of the study show that fluctuations in alternative materials quality (physical, chemical, calorific) and amount directly cause a negative effect on the control of cement quality and product cost. Due to its dynamic nature, coping with this challenge requires adopting the behaviors of the organization; hence, existing organisational structures are becoming a barrier, along with insufficient management competencies. Inappropriate macroeconomic conditions, as one of the strong causes of barriers, are directing the decisions to a survival mode and forcing the focus on short-term solutions. Also, due to more limited resources or changes in resource allocation criteria during adverse macroeconomic conditions, needed actions are postponed, resulting in product quality problems.

Although there are many studies on CE in cement, they are concentrated on technical and laboratory studies enabling the use of different alternative materials as inputs to the cement process. Studying the barriers holding back the cement sector in the transition to CE is the first contribution of this study and makes it novel and unique. The second contribution is revealing the causal relationship among barriers by analyzing the interrelationships between factors. The third contribution is to mention the practical implications, which will be supportive of solving the adverse effects of the barriers in the cement business.

Even though the global acting companies are kept within the scope of the study, the rater experts are located in Turkey, which increases the probability of having a Turkey-based mindset among the raters, which is the study's limitation. For the future scope of the study, comparative studies can be conducted in different countries to map the location and cultural effect of barriers. Also, conducting future studies to drill down on each barrier will encourage creative solutions.

Conflict of Interest

No potential conflict of interest was reported by the authors.

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