




Article

Evaluation of Carbon Emission Factors in the Cement Industry: An Emerging Economy Context

Mohammad Zahirul Khaiyum ¹, Sudipa Sarker ² and Golam Kabir ^{1,*}

¹ Industrial Systems Engineering, Faculty of Engineering and Applied Science, University of Regina, 3737 Wascana Parkway, Regina, SK S4S 0A2, Canada; mzk777@uregina.ca

² The Business School, Edinburgh Napier University, Edinburgh EH14 1DJ, UK; s.sarker@napier.ac.uk

* Correspondence: golam.kabir@uregina.ca

Abstract: The cement industry is a major contributor to carbon emissions, responsible for 5–8% of global emissions. This industry is expanding, particularly in emerging economies, and it is expected that CO₂ emissions will rise by 4% by 2050. To address this critical concern, this paper identifies ten factors that contribute to carbon emissions in the cement production process through an extensive literature review and prioritises these factors using the Bayesian best–worst method. The data was gathered by conducting a methodical online survey with seven cement industry professionals in Bangladesh, with the aim of gaining insights into the emerging economy. The results illustrate that fuel burning and electricity consumption are the two greatest contributors to CO₂ emissions in the cement production process. This research provides guidelines for cement industries in emerging economies on how to reduce CO₂ emissions as well as suggesting areas of future research for sustainable cement production.

Keywords: decarbonization; cement industry; CO₂ reduction; sustainable practices; environmental sustainability



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1. Introduction

Carbon dioxide (CO₂) is the most problematic greenhouse gas (GHG) and contributes significantly to global warming. The global cement industry is responsible for 27% of total direct CO₂ emissions, making it the second-largest CO₂ producer of the industrial sectors [1]. The cement industry is expected to grow between 12 and 23% from 2005 to 2050, a disproportionate amount of this growth occurring among non-OECD countries, which could increase total global CO₂ emissions by 4% in that time [2]. The updated synthesis report of nationally determined contributions reveals a worrying trend of a GHG increase of about 16% as opposed to a 45% reduction by 2030 [3]. The reduction target of 45% for CO₂ emissions, keeping the global temperature increase below 2 degrees, and net-zero emissions cannot be achieved if a highly energy-intensive sector such as cement does not take measures to reduce CO₂ emissions [4].

Cement is used as glue in concrete, a building material that is second only to water in the total annual volume of consumption [5]. The International Energy Agency (IEA) has predicted annual cement production to be 4.4 billion tonnes in 2050. In reality, however, global cement production was already 4.1 billion tonnes in 2020 [6]. The cement production and processing industry is the second-largest energy-intensive sector after heating and cooling, and thus contributes significantly to GHG emissions. In the cement sector, the direct emissions from energy and other sources account for 20% of total emissions, while the indirect emissions from the production of electricity and heat together with the fuels purchased and used account for 40–50% of total emissions [4]. Moreover, the calcination of limestone in cement production also triggers large amounts of CO₂ emissions [7]. It is therefore of utmost importance that the cement industry adopts decarbonisation strategies and reduces CO₂ emissions in their production processes.

Carbon emissions in cement production can be reduced in several ways, including increasing the use of renewable energies to reduce energy-related emissions, improving clinker production efficiency to reduce process emissions, and developing carbon capture–utilisation–storage mechanisms [8,9]. Another effective path to CO₂-emissions reductions is to replace cement with alternative materials, such as geopolymers, which uses waste materials and by-products and contributes less to global warming [7]. However, the actual practice of carbon reduction in cement production is limited due to the reluctance of the industry to compromise on clinker quality and the performance characteristics of cement [8].

Although China is the biggest producer and user of cement, the high growth of other developing countries means that they are also consuming large quantities of cement to build infrastructure [10]. Increasing cement consumption is also referred to as a development indicator [11,12]. Consequently, Bildirici [13] purports that cement production has a critical impact on CO₂ emissions and economic growth. Comparatively, CO₂ emissions from cement production are greater in developing countries than in developed countries because of greater reliance on nonrenewable energy sources (e.g., oil, coal, gas) [2]. For instance, China's CO₂ emissions have decelerated due to the country's commitment towards low-carbon transitions [14]. While CO₂ emissions in advanced economies are projected to decline steadily by about one-third between 2020 and 2050, CO₂ emissions are expected to grow in emerging economies by almost 20% by the mid-2040s. This is because of increased population, economic growth, rapid urbanisation, and infrastructure expansion [4]. Consequently, there is a need to learn about CO₂-emission-reduction potentials in emerging economies.

This paper answers the following research questions (RQs) to address the aforementioned issues:

RQ1: What are the CO₂ emission factors of the cement manufacturing process in the context of an emerging economy?

RQ2: What are the most important factors that influence the CO₂ emissions in the cement manufacturing industries in an emerging economy?

To answer RQ1, an extensive literature review is conducted using the Scopus and Web of Science databases. RQ2 is answered using the Bangladesh cement industry as a case study. This study considers the Bangladeshi cement industry for several reasons. To begin, cement manufacturing in Bangladesh constitutes a noteworthy source of the country's total carbon emissions. In recent years, there has been significant expansion in both the local and international cement markets [15]. The compound annual growth rate for the past seven years has reached approximately 11.5%, indicating promising prospects for potential investments and business expansion in the future [16]. In 2018, the per capita cement usage stood at 184 kg, almost twice the per capita consumption recorded in 2011 [17]. Sunny et al. [18] found that within the Dhaka division in Bangladesh, the cement sector was a primary source of soil pollution due to the release of dust particles containing heavy metals and air pollution. Additionally, according to Rasul et al. [19], cement industries in Bangladesh were ranked as the second-largest contributor to air pollution and ninth in terms of chemical pollution. As a result, the cement industry is now compelled to explore sustainable approaches to mitigate its adverse effects on the environment in Bangladesh. Furthermore, the Bangladeshi cement manufacturing sector is under significant international scrutiny to achieve economic, social, and environmental sustainability in alignment with the United Nations' Sustainable Development Goals [20]. Therefore, the determination of CO₂ emission factors can play a crucial role in this endeavour.

This research identifies ten CO₂ emission factors from the literature and ranks them by applying the Bayesian best–worst method (BWM). The Bayesian BWM is a new benchmarking and multicriteria decision-making (MCDM) method based on various performance indicators [21]. Compared to widely used MCDM procedures, such as the analytic hierarchy process, the BWM offers fewer pairwise evaluations but more consistent calculations of subcriteria and main criteria [22,23].

The rest of the paper is structured as follows. Section 2 reviews and identifies CO₂ emission factors in the cement industry. The following section presents the methodology and model implementation. Section 4 presents the results and discusses the findings. Section 5 highlights the theoretical, managerial, and policy implications of the study. The final section summarises the study, highlights limitations, and provides direction for future research.

2. Literature Review

This section summarises the CO₂ emission factors and studies in the cement industry. Cement production comprises three main steps: kiln feed preparation, clinker production, and cement manufacturing [24]. Figure 1 shows the cement production process along with sources of CO₂ emissions.

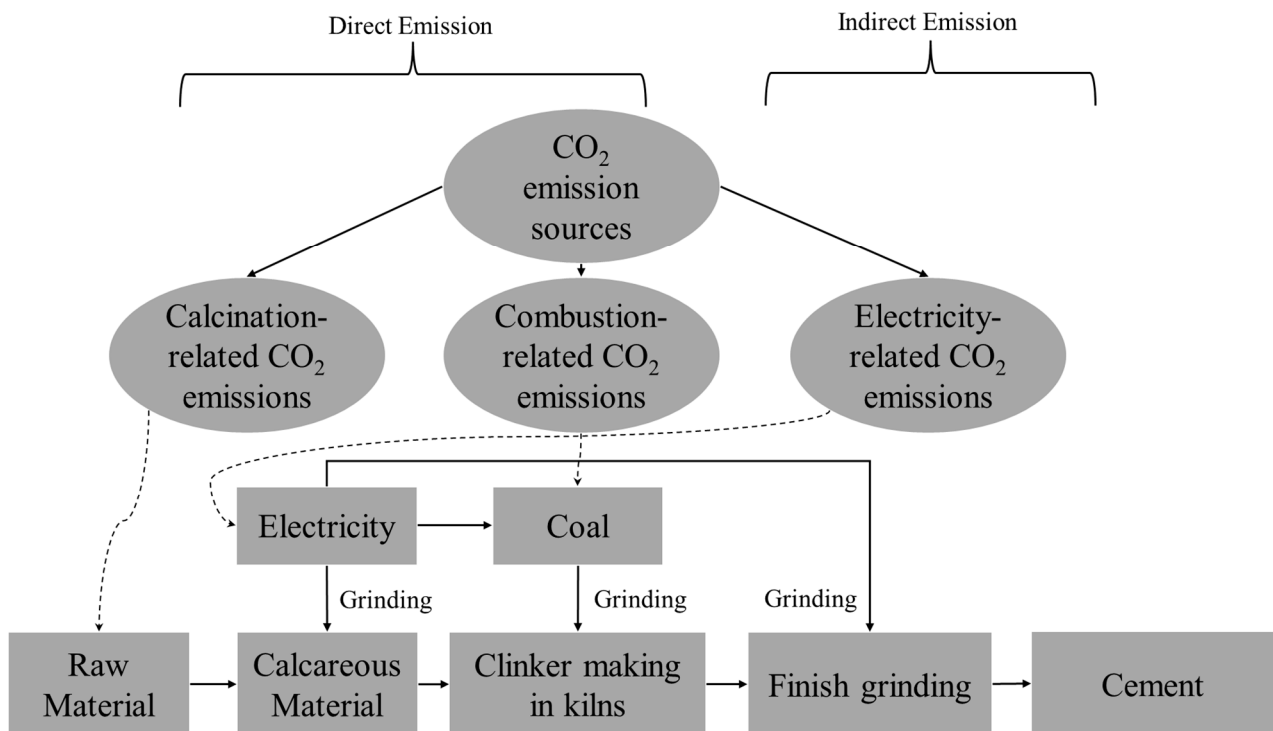


Figure 1. Cement production processes and CO₂ sources (adapted from [25]).

During cement production, CO₂ is released from four different sources: emissions from the calcination of calcium carbonate, combustion of fossil fuel, electricity usage for transporting raw materials, and operation of electrical motors and facilities [26,27]. The calcification of calcium carbonate and combustion of fossil fuels are considered direct emissions and account for 90% of total emissions. A large part of the emissions (nearly 50–60%) result from the breakdown of limestone (CaCO₃), which yields lime (CaO) as the vital element in cement formulations [28]. Burning fossil fuels in high-temperature processing units (preheaters, calciners, furnaces) accounts for 30–40% of the overall CO₂ [28]. Electricity-related emissions are referred to as indirect emissions and represent 10% of total emissions [29,30]. Emissions from the calcification of calcium carbonate are also considered process emissions and consist of raw-material drying and pyroprocessing, whereas combustion-related emissions include the burning of coal, coke, petroleum, and solid and liquid waste fuels. In contrast, electricity-related emissions are generated by the operation of motors, blowers, and fans for rotating kilns, heating, drying, and the grinding of materials and clinkers [31].

Several mechanical inadequacies in the traditional cement manufacturing process led to additional CO₂ emissions. Such inadequacies reduce plant performance, result in additional fuel and power consumptions, produce more waste heat, and increase CO₂ emission levels. According to Benhelal et al. [28], the leading reasons for excess CO₂

emissions from the cement industry are (a) using inefficient systems, (b) losing heat through the exhaust streams, (c) utilising poor quality raw materials and carbon-extensive fossil fuels, (d) producing cement with a high percentage of clinker, and (e) using inefficient and outdated types of machinery.

Multiple factors contribute to the carbon emissions in the cement industry. The importance and priority of these factors may vary according to the manufacturing process of the particular cement industry. Based on the literature, ten carbon emission factors for the cement industry are identified and summarised in Table 1.

Table 1. Carbon emission factors in the cement industry.

Sl.	Parameters	Description	Reference
1.	Raw materials (RM)	CO ₂ emissions from raw materials arise when limestone (CaCO ₃) is transformed into lime (CaO) through decomposition.	[10,27,28]
2.	Chemical reaction (CR)	CO ₂ is also emitted during the chemical reaction stage while the raw materials as carbonates are decomposed into oxides.	[28,32,33]
3.	Clinker quality (CQ)	Clinker is CO ₂ -intensive and formed by burning a mixture of primary limestone, silicon oxide, aluminium oxide, and iron oxide. The higher the clinker quality, the greater the CO ₂ emissions.	[27,31,34]
4.	Heating the raw ingredients (HTRI)	One of the significant sources of CO ₂ emissions is the preheating of raw materials, which must be heated well over 1000 °C.	[9,28,33]
5.	Organic and inorganic carbon in the fuel (OICITF)	The more inorganic carbon in the fuel, the greater the carbon emission due to the combustion of that fuel.	[34,35]
6.	Fuel burning (FB)	CO ₂ emissions from fossil-fuel burning in the cement kiln at temperatures ranging from 1400 to 1500 °C. Such emissions, referred to as direct emissions, are mainly due to preheating, precalcinating, and pyroprocessing kilns.	[24,34,36]
7.	Electricity consumption (EC)	CO ₂ emissions come from power usage in the various stages of cement production, including crushing of raw materials, pulverisation, and cement manufacturing.	[30,37]
8.	External production of electricity (EPE)	Many countries purchase electricity from other countries to produce cement, resulting in indirect CO ₂ emissions.	[27,33,38]
9.	Transport of raw materials and finished products (TRMFP)	The transport of raw materials and finished products indirectly contributes to CO ₂ emissions.	[39–41]
10.	Cement crushing (CC)	Cement grinding is one of the three stages of cement production. The crushing, grinding, and drying of cement relies heavily on electricity.	[32,42]

3. Methodology

This paper adopts a mix-method methodology to identify and rank the most significant carbon emission factors in the cement industry. Figure 2 explains the step-by-step procedure adopted in the article. Ten CO₂ emission factors were initially identified, scrutinising the literature and followed by feedback from the industry experts. Ten factors were then extracted and classified into direct and indirect emission factors, and the Bayesian BWM was utilised to specify the position of the emission factors and rank them according to importance. The BWM allows decision-makers to determine the best (i.e., the most essential and desirable), and worst (i.e., the least necessary and desirable factors). The BWM also requires the performance of a pairwise evaluation between best–worst factors and other factors. The rationale for using the BWM is its superior performance when prioritising strategies with incomplete and ambiguous information [22,23].

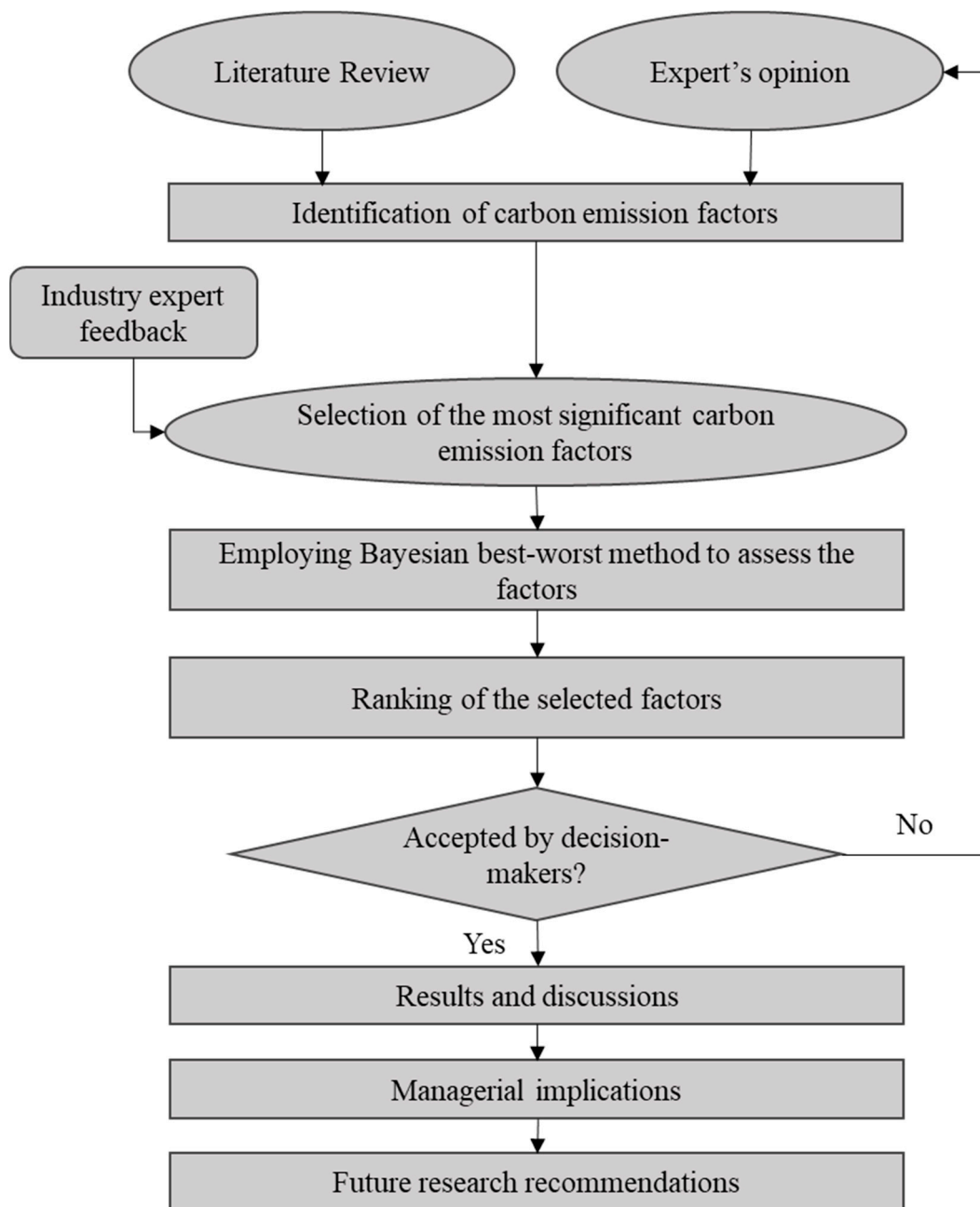


Figure 2. Methodology flow chart.

3.1. Expert Selection

This section evaluates the CO₂ emission factors for Bangladesh cement manufacturing with the proposed methodology. Data for the model were collected from seven experts working for seven local and multinational cement companies in Bangladesh. The names of the companies are not disclosed to protect privacy and maintain confidentiality. The criteria for selecting an expert encompassed familiarity with the cement industry, possession of a minimum of a bachelor's degree, proficiency in carbon-emission matters, and a minimum of five years experience in the pertinent field. A seven-respondent sample is deemed sufficient for three reasons [43]. First, MCDM research is not based on statistical inferences. Consequently, it is not necessary to have many respondents. Second, the quality of the information is more important than is the quantity, and it is ensured by selecting respondents with more than ten years of experience and university education. Third, data

saturation in the MCDM study is typically achieved using a small number of interviewees. Table 2 reports the demographic profile of the seven respondents.

Table 2. Expert's profile.

Decision-Maker (DM)	Designation	Experience (Years)	Education
No. 1	Chief Engineer and Head of Plant	18	Bachelor (Mechanical)
No. 2	AGM—Quality Assurance	23	Master (Chemistry)
No. 3	Environment Manager	15	MSc. in Env. Sc.
No. 4	Assist. GM—QC	22	MSc. (Applied Chemistry)
No. 5	Assist. GM	14	Bachelor (Civil)
No. 6	DGM (QC)	21	Master (Applied Chemistry)
No. 7	DGM (Engineering and Operation)	20	Bachelor (Mechanical)

3.2. Model Development

In this study, the Bayesian BWM is utilised to determine the most important direct and indirect CO₂ emission factors. The Bayesian BWM is applied in the following six stages [21,44]:

Step 1: Understanding the specific decision factors

In this step, based on the existing literature and interviews with numerous experts, the 10 most significant sources of cement industry carbon emissions are identified. These factors are divided into direct and indirect CO₂ emission factors: raw materials (RM), clinker reaction (CR), clinker quality (CQ), heating the raw ingredients (HTRI), organic and inorganic carbon in the fuel (OICITF), fuel burning (FB), cement grinding (CG), transport of raw materials and finished products (TRMFP), electricity consumption (EC), and external production of electricity (EPE).

Step 2: Identifying the worst (W) and best (B) decision factors and sub-factors

In this step, the best (B) and worst (W) direct and indirect CO₂ emission factors are identified based on feedback from the experts or respondents [21].

Step 3: Evaluating the best factor (B) with other factors (j)

Once the best direct and indirect CO₂ emission factors (B) are identified, the respondents compare them (B) with the remaining factors on a nine-point scale presented in Table 3. One on a nine-point scale means a factor is as essential as the other, whereas nine means a factor is more important than the other. The outcome of this step is the best vector (BO) or $A_B = (a_{B1}, a_{B2}, a_{B3}, \dots, a_{Bn})$, where a_{Bj} illustrates the favourite of the best factor B over factor j, and $a_{BB} = 1$. A similar approach was applied for both direct and indirect CO₂ emission factors [21].

Table 3. Ratings of the BWM [45].

Dialectal Variable	Crunchy Value
Equally important	Value 1
Equal to moderately more important	Value 2
Moderately more important	Value 3
Moderately to strongly more important	Value 4
Strongly more important	Value 5
Strongly to very strongly more important	Value 6
Very strongly more important	Value 7
Very strongly to extremely more important	Value 8
Extremely more important	Value 9

Step 4. Evaluation of worst factor (W) with other factors (j)

After identifying the worst direct and indirect CO₂ emission factors (W), the respondents may be asked to compare other factors (j) with the worst factor (W) using the same 1–9 scale. Similarly, 1 indicates equal priority over the worst, while 9 indicates that another factor has the greatest importance over the worst [21].

The result was the other-to-worst (OW) vector, as given below:

$Aw = (a_{1W}, a_{2W}, \dots, a_{nW})^T$, where a_{jW} illustrates the priority of j over the worst factor W , and $a_{WW} = 1$.

The same approach was applied for both direct and indirect CO₂ emission factors.

Step 5. Calculate weights based on optimal group

The optimal weight for each respondent or expert (w^k) is dependent on the two sets of vectors: A_B^k and A_W^k . The group optimal weight w^* is also dependent on the optimal weight for each respondent or expert (w^k) [21].

The calculation of the optimal weights for each respondent w^k , $k = 1, 2, \dots, K$ and the aggregated weights for all respondents $w^* = w_1^*, w_2^*, \dots, w_k^*$, are performed using the Bayesian BWM, as follows [21]:

$$A_B^k | w^k \sim \text{multinomial} \left(\frac{1}{w^k} \right), \forall k = 1, 2, \dots, K \quad (1)$$

$$A_W^k | w^k \sim \text{multinomial} \left(w^k \right), \forall k = 1, 2, \dots, K \quad (2)$$

$$w^k | w^* \sim (\gamma \times w^*), \forall k = 1, \dots, k \quad (3)$$

$$\gamma \sim (0.1, 0.1)$$

$$w^* \sim (1)$$

where multinomial and Dir denotes a multinomial and Dirichlet distribution, respectively. Gamma (0.1, 0.1) indicates a gamma distribution with the shape parameters of 0.1. Markov-chain Monte Carlo (MCMC) sampling is required to estimate the solution of the probabilistic model.

Step 6. Credal ranking

In this step, the credal ranking is determined to indicate the level to which one CO₂ emission factor is superior to another factor [46]. The distribution of weights can guide us to assess the reliance on different factors. The confidence of these relationships among different factors can be analysed using the subsequent distribution in the weights (i.e., the Dirichlet distribution of w^*) [44].

For example, there is a set of factor c_i and c_j being measured. It is essential to understand whether the ranking outcomes of the group weights are consistent with the evaluation of all respondents or experts. To analyse the confidence of this assessment, the concept of credal ranking is used. The probability of c_i being better than c_j can then be expressed as [21]:

$$P(c_i > c_j) = \int I(w_i^* > w_j^*) P(w^*) \quad (4)$$

where $P(w^*)$ is the posterior probability of w^* and I is a conditional parameter, which can be measured if $(w_i^* > w_j^*)$; otherwise, it is 0. The number of samples Q obtained by MCMC sampling is used to calculate the confidence and the posterior distribution [21,44].

$$P(c_i > c_j) = \frac{1}{Q \sum_{q=1}^Q I(w_i^{*q} > w_j^{*q})} \quad (5)$$

$$P(c_j > c_i) = \frac{1}{Q \sum_{q=1}^Q I(w_i^{*q} > w_j^{*q})} \quad (6)$$

where w^* represents q w^* 's from MCMC samples. When $(c_i > c_j) > 0.5$, it implies that factor i is valued higher than factor j , and the confidence is represented by the probability. Moreover, the total probability $(c_i > c_j) + (c_j > c_i) = 1$.

4. Results and Discussion

This section reports the results and discussion of the study.

4.1. Results

Tables 4 and 5 illustrate the relative importance of carbon emission factors for direct emissions and indirect emissions. Tables 6 and 7 represent other vectors regarding the least important vectors for direct and indirect emissions, respectively.

Table 4. Most important factors with respect to others factor for direct emissions.

Respondents	Direct Emission Factors						
	Best	RM	CR	CQ	HTRI	OICIF	FB
1	FB	6	4	3	5	2	1
2	CR	7	4	1	5	3	2
3	CQ	9	4	1	4	5	2
4	FB	4	5	9	2	3	1
5	HTRI	4	7	5	1	3	2
6	FB	5	3	4	3	2	1
7	CQ	8	2	1	4	5	5

Table 5. Most important factors with respect to other factors for indirect emissions.

Respondents	Indirect Emission Factors				
	Best	CG	TRMFP	EC	EPE
1	EPE	2	4	3	1
2	CG	1	4	6	2
3	TRMFP	4	1	2	7
4	EC	8	9	1	9
5	EPE	9	3	5	1
6	EPE	3	4	2	1
7	EC	2	7	1	5

Table 6. Other factors with respect to the least important factors for direct emissions.

Respondent	Direct Emission Factors						
	Worst	RM	CR	CQ	HTRI	OICIF	FB
1	RM	1	3	4	2	5	6
2	FB	6	5	8	4	3	1
3	RM	1	3	9	5	2	6
4	CQ	3	2	1	5	4	9
5	CM	3	1	2	7	4	5
6	RM	1	3	2	8	9	9
7	RM	1	7	8	3	5	6

Table 7. Other factors with respect to the least important factors for indirect emissions.

Respondent	Indirect Emission Factors				
	Worst	CG	TRMFP	EC	EPE
1	TRMFP	3	1	2	4
2	EPE	9	5	6	1
3	EPE	6	3	5	1
4	EPE	2	3	9	1
5	CG	1	6	4	9
6	TRMFP	3	1	3	8
7	TRMFP	5	1	7	4

The total weights of the total baseline and subfactor levels estimated using the Bayesian BWM are reported in Table 8 and Figure 3. Table 8 and Figure 3 also compare the weights of the BWM methods with those of the Bayesian BWM methods for both direct and indirect emissions.

Table 8. Average evaluation of the BWM and the Bayesian BWM.

Emission Type	Factors	BWM	Factors	Bayesian BWM
Direct Emissions	FB	0.245	FB	0.243
	CQ	0.221	HTRI	0.178
	HTRI	0.173	OICIF	0.177
	OICIF	0.163	CQ	0.169
	CR	0.131	CR	0.136
	RM	0.067	RM	0.097
Indirect Emissions	EC	0.332	EC	0.309
	EPE	0.262	EPE	0.251
	CG	0.232	CG	0.246
	TRMFP	0.173	TRMFP	0.195

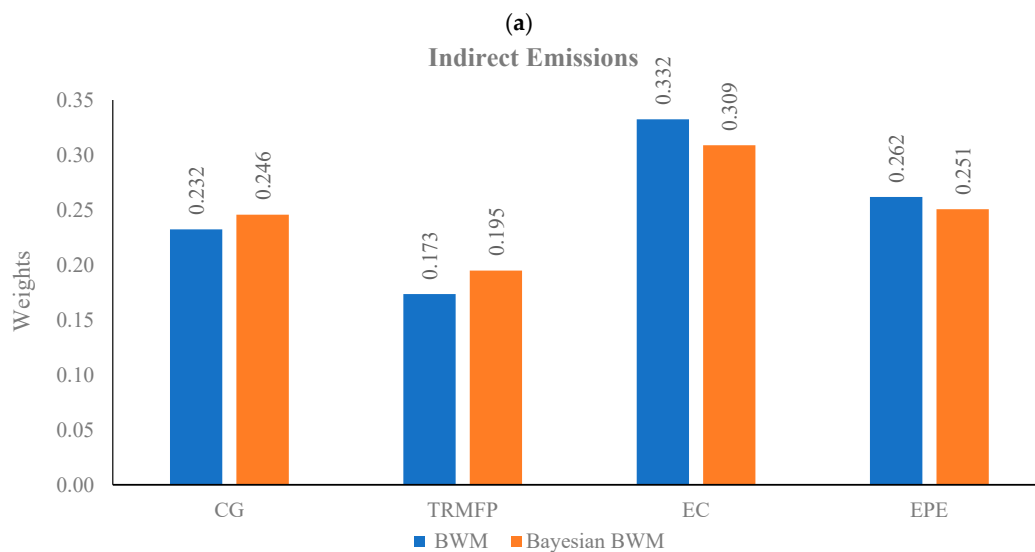
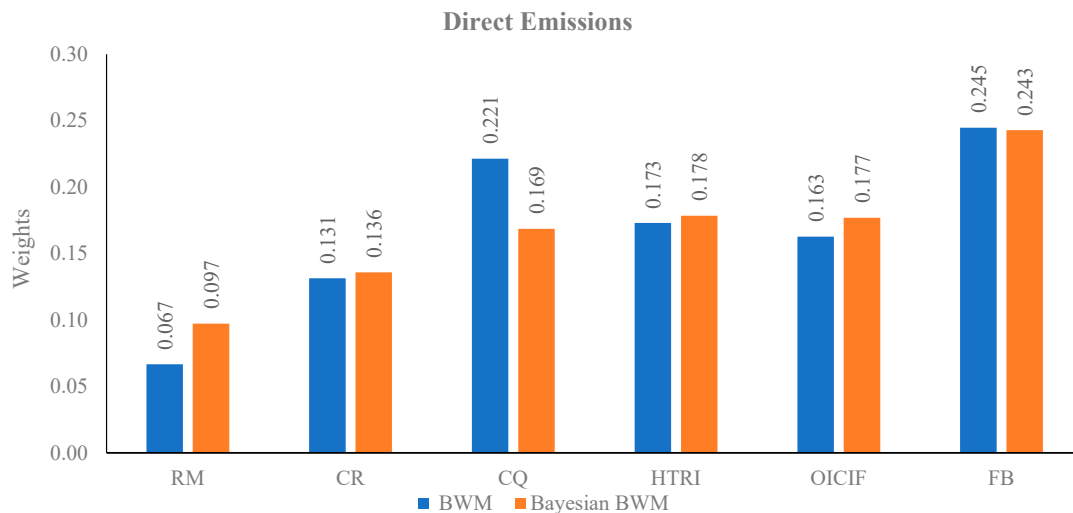


Figure 3. Weights of carbon emission factors in the cement industry: (a) direct emissions. (b) indirect emissions.

To determine the credal rankings, all the pairs of factors are compared, and the results are visualised using a centre-of-gravity graph (see Figure 4). Figures 4 and 5 show the credal ranking of factor for choosing the direct carbon emission and indirect carbon emission factors. Each factor is indicated by a separate colour.

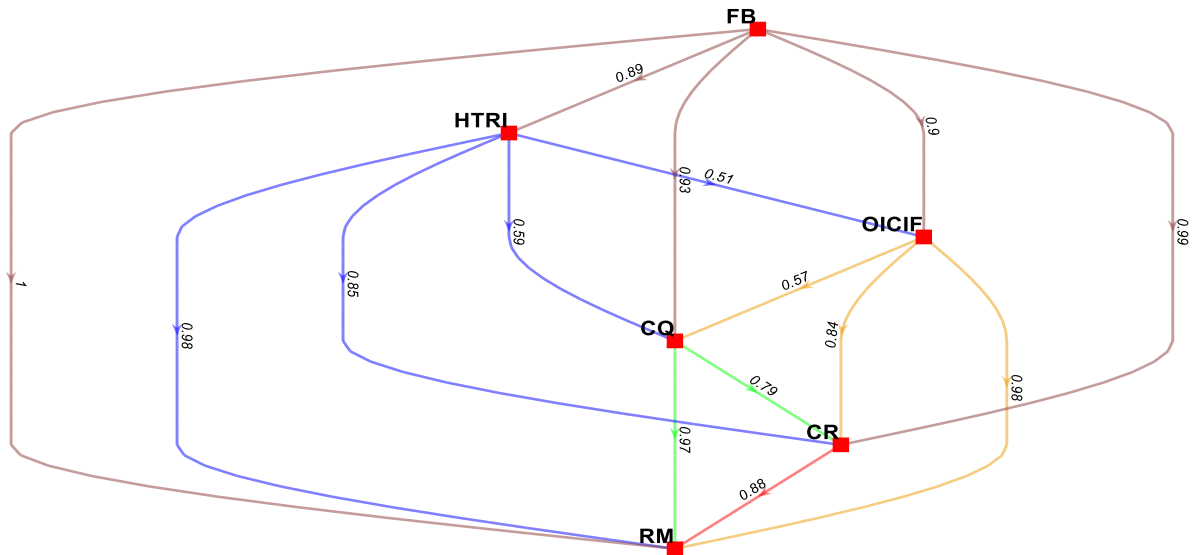


Figure 4. Credal ranking for choosing direct carbon emission factors.

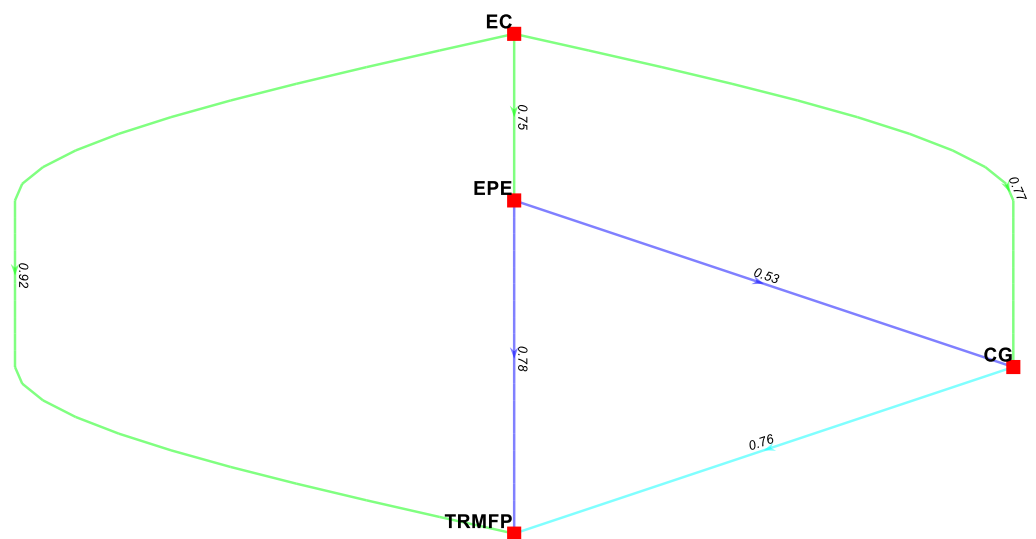


Figure 5. Credal ranking for choosing indirect emission factors.

4.2. Discussion

According to the Table 4, three of the seven respondents reported fuel burning (FB) and clinker quality (CQ) as essential factors. In contrast, only one respondent noted that raw material heating was the most critical factor for direct emissions. For indirect emissions (Table 5), three of the seven respondents reported the external production of electricity (EPE) as the best factor. Table 6 shows that four of the seven respondents reported that raw materials were the least important factor for direct emissions. Table 7 indicates that the external production of electricity was the least essential factor.

The nodes in Figure 3 represent the average weight of the factor using the Bayesian BWM. According to the Figure 3, fuel burning (0.245) is the most important on the factor level, and raw materials (0.097) the least important for direct carbon emissions in the

Bangladesh cement industry. Again, during the indirect carbon emissions, electricity consumption (0.309) is the most preferred factor for the cement industry.

In Figures 4 and 5, a node represents a direct or indirect carbon emission factor and each edge $A \rightarrow B$ indicates that factor A is more important than B, and the confidence of this relationship is represented by d . Based on Figure 4, fuel burning (FB) is the most crucial factor based on the opinions of all participants. The other extreme case is the composition of the raw materials (RM), which is the least desirable feature for choosing direct carbon emission factors. From Figure 4, the confidence about the relationship of the factors can also be read. For example, heating the raw ingredients (HTRI) is more important than raw materials (RM), and it is more desirable than organic and inorganic carbon in the fuel (OICITF), with a confidence of 0.51. As shown in Figure 5, electricity consumption (EC) is the most critical factor based on expert opinions for indirect emissions. On the other extreme, transport of raw materials and finished products (TRMFP) and cement grinding (CG) are the least critical factors.

A comparative study was conducted to assess the robustness of the suggested approach [47]. This analysis included a comparison of the Bayesian BWM alongside the traditional BWM. According to Table 8 and Figure 3, fuel burning (FB) ranks high in both the Bayesian BWM and BWM methods for direct emissions. Similarly, electricity consumption (EC) tops the chart in both methods for indirect emissions. The ranking of the BWM, as can be seen in the table, is $FB > CQ > HTRI > OICIF > CR > RM$, whereas the standing of the factors using the Bayesian BWM is $FB > HTRI > OICIF > CQ > CR > RM$. Both methods rank raw materials as the least important factor for controlling direct carbon emissions. Both methods provided the same rankings for indirect emissions (i.e., $EC > EPE > CG > TRMFP$).

Although the outcomes exhibit a certain degree of proximity, variations are present. The analysis also encompasses an assessment of the correlation between the priority values of both direct and indirect emissions factors generated by the Bayesian BWM and the traditional BWM. Figure 6 highlights that the correlation values are above 95%. This suggests that, despite certain variances among the models, their outcomes closely align, and the Bayesian-based BWM model proposed is likewise viable.

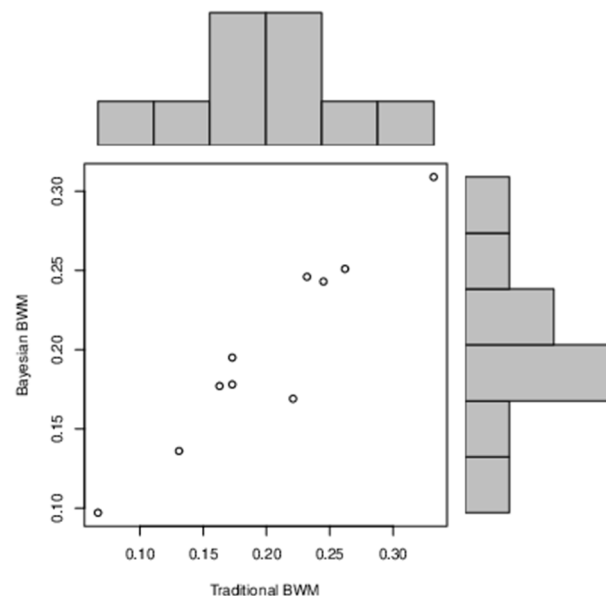


Figure 6. Pearson correlation analysis results.

In contrast to the proposed Bayesian BWM, in the classical BWM, the assessment scores of individual experts were addressed as distinct models, and the ultimate result vectors were derived by computing the arithmetic mean of the evaluations provided by each expert [47]. The Bayesian BWM overcomes the shortcoming of the BWM, which calculates an arithmetic average of weights for a group of decision-makers [44].

5. Implication of This Study

One-third of the global CO₂ emissions result from energy usage in the industrial sector [39]. Evaluating carbon emission factors in the cement industry is a fundamental tool to identify the CO₂ reduction efforts and establish prospective CO₂ reduction targets for the cement industry [34]. Hence, several implications can be drawn from this study.

Environmental and sustainable issues are major concerns for businesses, governments, and international organisations. Corporate organisations readily strive for sustainable practices as a part of their corporate social responsibility [48]. CO₂ emission factors increase the adverse environmental impact of industrial activities. Therefore, it is elemental to comprehend the effects of carbon emission factors in the cement industry so that appropriate interventions can be designed to counteract its detrimental impact on the environment. Emerging economies such as Bangladesh are expected to consume large quantities of cement because of their need for infrastructure development during the growth phase.

GHG accumulation in the atmosphere is currently posing a serious environmental threat. CO₂ emissions are the most harmful of the GHGs, and the cement industry is one of the high GHG emitters [28]. It is therefore of utmost importance that managers working in the cement industry recognise the emission factors and make decisions, taking action accordingly to reduce GHG emissions as much as possible. This research not only identifies the principal emission factors of CO₂ but also ranks the most critical ones. For instance, fuel burning is clearly the highest contributor to the cement industry GHG emissions. Consequently, using high quality fuel can reduce cement industry emissions significantly [34].

Moreover, using alternative fuels such as biomass and municipal or industrial waste can further reduce CO₂ emissions [41]. Heating the raw material ingredient is another significant contributor to CO₂ emissions. A massive amount of thermal loss occurs during raw material heating, and such losses can be minimised by improving the cement industry production process [28]. The use of thermal energy recovery can accomplish much to reduce CO₂ emissions in the cement industry [39].

In comparison, the transport of the raw materials and finished goods and cement grinding contribute less to CO₂ emissions, meaning that these two factors can be tackled after other critical factors are addressed. Understanding CO₂ emission factors in the cement industry can help policy-makers devise suitable policies for CO₂ reduction, which will help the industry become more climate-friendly [36].

6. Conclusions

GHG emissions from the cement industry deserve special attention. This paper identifies ten critical carbon emission factors for emerging economies and ranks them using the Bayesian BWM. Fuel burning and heating the raw material ingredients have been found to be the most dominant carbon emission factors among direct emission factors. Among the indirect emission factors, electricity consumption and external production of electricity are the most critical. Emerging economies such as Bangladesh invest heavily in infrastructure, resulting in disproportionate cement consumption. Because of the high energy usage in the cement industry combined with the significant release of CO₂ from the raw materials, governments and policy-makers in emerging economies must scrutinise the emission factors. Unless proper policies are implemented, high economic growth accompanied by increased consumption of cement will substantially damage the climate.

The contribution of this study can be summarised as follows:

1. This research identifies ten carbon emission factors in the cement industry through an extensive literature review.
2. The study then verifies these carbon emission factors using expert opinions.
3. It also ranks the factors using the Bayesian BWM.
4. The research then compares the Bayesian BWM with the BWM and demonstrates how the Bayesian BWM produces superior results.
5. The study also illustrates the relative importance of the factors using credal diagrams.

Despite the valuable contributions of this study, it does come with certain limitations. Firstly, in the Bayesian BWM approach, the participating experts who provide evaluations are not assigned experience coefficients and are considered equally important. While the inclusion of seven experienced experts is typically sufficient for a multicriteria decision-making model of this kind, future researchers may consider obtaining feedback from a larger pool of experts to enhance the generalisability of the findings. Another limitation is the potential for the results of this research to be specific to the geographical context of this study. However, the methodology employed in this study is generic and can be replicated in other emerging economy settings like China, India, Brazil, and Pakistan. Future research can validate the findings reported here in these contexts.

This research can benefit substantially from future research. For instance, CO₂ emission factors for other energy-intensive industries, such as steel and iron, can be studied. Methodologically, it will be interesting to explore and compare results with those from the fuzzy grey theory. Future research can also examine the CO₂ emission factors for other high-emission sectors, such as the electricity, heat, and transport sectors. In the future, efforts are needed to find alternative materials to cement, such as cementitious tile adhesive [49], recycled clay-brick waste [50], circulating fluidised bed combustion ash, and rice-husk ash [51] to reduce the use of cement in the construction industry. This is because energy consumption is the fundamental cause of greenhouse gas emissions [52]. Because the cement industry is a high-energy-intensive industry, reducing the use of cement as a construction material will reduce the overall cement production worldwide. Furthermore, in the future, developing countries such as Bangladesh may introduce green tax policies, which are helping countries like China to reduce CO₂ emissions substantially [53].

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References

1. Zhaurova, M.; Soukka, R.; Horttanainen, M. Multi-criteria evaluation of CO₂ utilization options for cement plants using the example of Finland. *Int. J. Greenh. Gas Control.* **2021**, *112*, 103481. [CrossRef]
2. IEA (International Energy Agency) Statistics. CO₂ Emissions from Fuel Combustion Highlights. 2019. Available online: www.iea.org/CO2highlights (accessed on 20 July 2020).
3. UN Climate Press Release. Updated NDC Synthesis Report: Worrying Trends Confirmed. UNFCCC, 25 October, p. 1. 2021. Available online: <https://unfccc.int/news/updated-ndc-synthesis-report-worrying-trends-confirmed> (accessed on 2 January 2022).
4. IEA. Net Zero by 2050 A Roadmap for the Global Energy Sector, International Energy Agency. 2021. Available online: <https://www.iea.org/reports/net-zero-by-50>. (accessed on 29 October 2021).
5. *International Energy Agency Cement Technology Roadmap: Carbon Emissions Reductions up to 2050*; Organization for Economic Co-Operation and Development (OECD): Paris, France, 2009; ISBN 9789264086340.
6. US Geological Survey. Cement Production Worldwide from 1995 to 2020 (in Billion Tons), Statista. 2021. Available online: <https://www.statista.com/statistics/1087115/global-cement-production-volume/> (accessed on 2 January 2022).
7. Abdulkareem, M.; Havukainen, J.; Horttanainen, M. How environmentally sustainable are fibre reinforced alkali-activated concretes? *J. Clean. Prod.* **2019**, *236*, 117601.

8. Habert, G.; Billard, C.; Rossi, P.; Chen, C.; Roussel, N. Cement production technology improvement compared to factor 4 objectives. *Cem. Concr. Res.* **2010**, *40*, 820–826. [[CrossRef](#)]
9. An, J.; Middleton, R.S.; Li, Y. Environmental Performance Analysis of Cement Production with CO₂ Capture and Storage Technology in a Life-Cycle Perspective. *Sustainability* **2019**, *11*, 2626. [[CrossRef](#)]
10. Shen, L.; Gao, T.; Zhao, J.; Wang, L.; Wang, L.; Liu, L.; Chen, F.; Xue, J. Factory-level measurements on CO₂ emission factors of cement production in China. *Renew. Sust. Energy Rev.* **2014**, *34*, 337–349.
11. Ali, A.A.M.; Negm, A.M.; Bady, M.F.; Ibrahim, M.G.E.; Suzuki, M. Environmental impact assessment of the Egyptian cement industry based on a life-cycle assessment approach: A comparative study between Egyptian and Swiss plants. *Clean Technol. Environ. Policy* **2016**, *18*, 1053–1068. [[CrossRef](#)]
12. Song, M.; Wang, S.; Yu, H.; Yang, L.; Wu, J. To reduce energy consumption and to maintain rapid economic growth: Analysis of the condition in China based on expended IPAT model. *Renew. Sustain. Energy Rev.* **2011**, *15*, 5129–5134. [[CrossRef](#)]
13. Bildirici, M.E. Cement production, environmental pollution, and economic growth: Evidence from China and USA. *Clean Technol. Environ. Policy* **2019**, *21*, 783–793. [[CrossRef](#)]
14. Zheng, J.; Mi, Z.; Coffman, D.M.; Shan, Y.; Guan, D.; Wang, S. The Slowdown in China’s Carbon Emissions Growth in the New Phase of Economic Development. *One Earth* **2019**, *1*, 240–253. [[CrossRef](#)]
15. Hossain, S.R.; Ahmed, I.; Azad, F.S.; Hasan, A.M. Empirical Investigation of Energy Management Practices in Cement Industries of Bangladesh. *Energy* **2020**, *212*, 118741.
16. Ahmed, M.; Bashar, I.; Alam, S.T.; Wasi, A.I.; Jerin, I.; Khatun, S.; Rahman, M. An overview of Asian cement industry: Environmental impacts, research methodologies and mitigation measures. *Sustain. Prod. Consum.* **2021**, *28*, 1018–1039. [[CrossRef](#)]
17. EBL Securities Ltd. Cement Industry of Bangladesh, EBL Securities Ltd. 2015. Available online: https://www.researchpool.com/download/?report_id=1537474&show_pdf_data=true (accessed on 2 January 2022).
18. Sunny, F.A.; Karimanzira, T.; Huang, Z. Environment security: An empirical study of industrialization and the impact on environment in the Dhaka division, Bangladesh. *Environ. Dev. Sustain.* **2012**, *14*, 885–900. [[CrossRef](#)]
19. Rasul, M.G.; Faisal, I.; Khan, M.M.K. Environmental pollution generated from process industries in Bangladesh. *Int. J. Environ. Pollut.* **2006**, *28*, 144. [[CrossRef](#)]
20. Dhar, B.K.; Sarkar, S.M.; Ayithey, F.K. Impact of social responsibility disclosure between implementation of green accounting and sustainable development: A study on heavily polluting companies in Bangladesh. *Corp. Soc. Responsib. Environ. Manag.* **2022**, *29*, 71–78. [[CrossRef](#)]
21. Mohammadi, M.; Rezaei, J. Bayesian best-worst method: A probabilistic group decision making model. *Omega* **2020**, *96*, 102075. [[CrossRef](#)]
22. Rezaei, J. Best-worst multi-criteria decision-making method. *Omega* **2015**, *53*, 49–57. [[CrossRef](#)]
23. Rezaei, J. Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega* **2016**, *64*, 126–130. [[CrossRef](#)]
24. Mossie, A.T.; Khatiwada, D.; Palm, B.; Bekele, G. Investigating energy saving and climate mitigation potentials in cement production—A case study in Ethiopia. *Energy Convers. Manag.* **2023**, *287*. [[CrossRef](#)]
25. Wei, J.; Cen, K.; Geng, Y. Evaluation and mitigation of cement CO₂ emissions: Projection of emission scenarios toward 2030 in China and proposal of the roadmap to a low-carbon world by 2050. *Mitig. Adapt. Strateg. Glob. Chang.* **2019**, *24*, 301–328. [[CrossRef](#)]
26. Brown, D.; Sadiq, R.; Hewage, K. A health-based life cycle impact assessment (LCIA) for cement manufacturing: A comparative study of China and Canada. *Clean Technol. Environ. Policy* **2017**, *19*, 679–687. [[CrossRef](#)]
27. Gao, T.; Shen, L.; Shen, M.; Chen, F.; Liu, L.; Gao, L. Analysis of differences of carbon dioxide emission from cement production and their major determinants. *J. Clean. Prod.* **2015**, *103*, 160–170. [[CrossRef](#)]
28. Benhelal, E.; Shamsaei, E.; Rashid, M.I. Challenges against CO₂ abatement strategies in cement industry: A review. *J. Environ. Sci.* **2021**, *104*, 84–101. [[CrossRef](#)]
29. Mikulčić, H.; Vujanović, M.; Duić, N. Reducing the CO₂ emissions in Croatian cement industry. *Appl. Energy* **2013**, *101*, 41–48. [[CrossRef](#)]
30. Sousa, V.; Bogas, J.A.; Real, S.; Meireles, I.; Carriço, A. Recycled cement production energy consumption optimization. *Sustain. Chem. Pharm.* **2023**, *32*, 101010. [[CrossRef](#)]
31. Chaudhury, R.; Sharma, U.; Thapliyal, P.; Singh, L. Low-CO₂ emission strategies to achieve net zero target in cement sector. *J. Clean. Prod.* **2023**, *417*, 137466. [[CrossRef](#)]
32. Yang, Y.; Wang, L.; Cao, Z.; Mou, C.; Shen, L.; Zhao, J.; Fang, Y. CO₂ emissions from cement industry in China: A bottom-up estimation from factory to regional and national levels. *J. Geogr. Sci.* **2017**, *27*, 711–730. [[CrossRef](#)]
33. Andrew, R.M. Global CO₂ emissions from cement production. *Earth Syst. Sci. Data* **2018**, *10*, 195–217. [[CrossRef](#)]
34. Cao, Z.; Shen, L.; Zhao, J.; Liu, L.; Zhong, S.; Sun, Y.; Yang, Y. Toward a better practice for estimating the CO₂ emission factors of cement production: An experience from China. *J. Clean. Prod.* **2016**, *139*, 527–539. [[CrossRef](#)]
35. Geng, Y.; Wang, Z.; Shen, L.; Zhao, J. Calculating of CO₂ emission factors for Chinese cement production based on inorganic carbon and organic carbon. *J. Clean. Prod.* **2019**, *217*, 503–509. [[CrossRef](#)]
36. Wang, Y.; Zhu, Q.; Geng, Y. Trajectory and driving factors for GHG emissions in the Chinese cement industry. *J. Clean. Prod.* **2013**, *53*, 252–260. [[CrossRef](#)]

37. Shen, W.; Cao, L.; Li, Q.; Zhang, W.; Wang, G.; Li, C. Quantifying CO₂ emissions from China's cement industry. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1004–1012. [[CrossRef](#)]
38. Zhou, C.; Xuan, D.; Miao, Y.; Luo, X.; Liu, W.; Zhang, Y. Accounting CO₂ Emissions of the Cement Industry: Based on an Electricity–Carbon Coupling Analysis. *Energies* **2023**, *16*, 4453. [[CrossRef](#)]
39. Anand, S.; Vrat, P.; Dahiya, R.P. Application of a system dynamics approach for assessment and mitigation of CO₂ emissions from the cement industry. *J. Environ. Manag.* **2006**, *79*, 383–398. [[CrossRef](#)] [[PubMed](#)]
40. Aruda, E.S.A., Jr.; Braga, N.T.d.S.; Barata, M.S. Life cycle assessment to produce LC³ cements with kaolinitic waste from the Amazon region, Brazil. *Case Stud. Constr. Mater.* **2021**, *18*, e01729. [[CrossRef](#)]
41. Summerbell, D.L.; Barlow, C.Y.; Cullen, J.M. Potential reduction of carbon emissions by performance improvement: A cement industry case study. *J. Clean. Prod.* **2016**, *135*, 1327–1339. [[CrossRef](#)]
42. Zheng, C.; Zhang, H.; Cai, X.; Chen, L.; Liu, M.; Lin, H.; Wang, X. Characteristics of CO₂ and atmospheric pollutant emissions from China's cement industry: A life-cycle perspective. *J. Clean. Prod.* **2021**, *282*, 124533. [[CrossRef](#)]
43. Munim, Z.H.; Sornn-Friese, H.; Dushenko, M. Identifying the appropriate governance model for green port management: Applying Analytic Network Process and Best-Worst methods to ports in the Indian Ocean Rim. *J. Clean. Prod.* **2020**, *268*, 122156. [[CrossRef](#)]
44. Liu, P.; Hendarlianpour, A.; Hamzehlou, M.; Feylizadeh, M.R.; Razmi, J. Identify and rank the challenges of implementing sustainable supply chain blockchain technology using the bayesian best worst method. *Technol. Econ. Dev. Econ.* **2021**, *27*, 656–680. [[CrossRef](#)]
45. Yang, J.J.; Chuang, Y.C.; Lo, H.W.; Lee, T.I. A two-stage MCDM model for exploring the influential relationships of sustainable sports tourism criteria in Taichung City. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2319. [[CrossRef](#)]
46. Mohammadi, M.; Rezaei, J. Evaluating and comparing ontology alignment systems: An MCDM approach. *J. Web Semant.* **2020**, *64*, 100592. [[CrossRef](#)]
47. Yanilmaz, S.; Baskak, D.; Yucesan, M.; Gul, M. Extension of FEMA and SMUG models with Bayesian best-worst method for disaster risk reduction. *Int. J. Disaster Risk Reduct.* **2021**, *66*, 102631. [[CrossRef](#)]
48. Bacinello, E.; Tontini, G.; Alberton, A. Influence of corporate social responsibility on sustainable practices of small and medium-sized enterprises: Implications on business performance. *Corp. Soc. Responsib. Environ. Manag.* **2021**, *28*, 776–785. [[CrossRef](#)]
49. Bin Mobarak, M.; Hossain, S.; Mahmud, M.; Ahmed, S. Redispersible polymer powder modified cementitious tile adhesive as an alternative to ordinary cement-sand grout. *Heliyon* **2021**, *7*, e08411. [[CrossRef](#)]
50. He, Z.; Shen, A.; Wu, H.; Wang, W.; Wang, L.; Yao, C.; Wu, J. Research progress on recycled clay brick waste as an alternative to cement for sustainable construction materials. *Constr. Build. Mater.* **2021**, *274*, 122113. [[CrossRef](#)]
51. Phuoc, H.T.; Hung, V.V.; Tuan, B.L.A.; Giang, P.H.H. Development of a cementless eco-binder as an alternative to traditional Portland cement in construction activities. *J. Sci. Technol. Civ. Eng. (STCE) NUCE* **2020**, *14*, 40–52. [[CrossRef](#)]
52. Bildirici, M.; Ersin, Ö.Ö. Nexus between Industry 4.0 and environmental sustainability: A Fourier panel bootstrap cointegration and causality analysis. *J. Clean. Prod.* **2023**, *386*, 135786. [[CrossRef](#)]
53. Zhou, Y.; Lv, S.; Wang, J.; Tong, J.; Fang, Z. The Impact of Green Taxes on the Carbon Emission Efficiency of China's Construction Industry. *Sustainability* **2022**, *14*, 5402. [[CrossRef](#)]

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