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Modeling Challenges for Improving the Heat Rate Performance in a Thermal Power Plant: Implications for SDGs in Energy Supply Chains

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Abstract: Rapid industrialization and the increased use of consumer electronic goods have increased the demand for energy. To meet the increasing energy demand, global nations are looking for energy from renewable sources rather than non-renewable sources, to adhere with the sustainability principle. As energy from renewable sources is still in the experimental stage, there is a need to use available energy sources optimally. Considering this, the present study aims to identify, evaluate, and reveal the interrelationship among critical challenge factors in improving the heat rate performance of coal-fired thermal power plants. The study identifies twenty critical challenges through a comprehensive literature review. Then, to evaluate the identified critical challenges, the grey-DEMATEL (Decision Making Trial and Evaluation Laboratory) technique is used. For evaluating the challenges, this study conducts an empirical analysis in a thermal power plant in India. The findings reveal that air preheater leakage, coal flow balancing, and air heater air outlet temperature are the top three critical challenges hampering the thermal power plant's performance. Additionally, fourteen challenges come under the cause group, while eight challenges come under the effect group. The findings of the study can assist industrial managers in overcoming problems in their thermal power plants. The results can also guide the development of a robust and reliable framework for mitigating these challenges.

Keywords: decision making; thermal power plant; grey-DEMATEL; renewable energy source; sustainability

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1. Introduction

An ever-increasing population and continuous industrial expansion has increased the demand for energy in an exponential manner. Energy is an essential commodity for economic and technological developments; it is one of the necessities of the modern day-to-day routine. Globally, 41% of electricity is generated through coal-based thermal power plants (CBTPPs) [1]. The need for energy production arises due to an aspiration for development, including industrialization and urban societal needs. Similarly, smartphones, computers, household equipment, such as refrigerators, air conditioning equipment, and televisions, have raised the need for electrical energy. In India, CBTPPs are the major energy generation source and account for 60% of the energy generated. Coal is primarily used as a resource for energy generation as it very cheap in terms of cost [1]. In India, coal reserves are so plentiful that they can be used for the next 50 years to produce electricity; 80% of the coal produced in India is utilized for energy generation [2]. As of 31 August 2020, India has an installed capacity of 199,594.50 megawatts for coal-based energy generation (Central Energy Authority India, 2020), amounting to 58% of the total installed thermal energy. Although the CBTPPs play a significant role in meeting the energy demand of the nations, they are also subjected to a lot of criticism [2]. The waste produced by the CBTPPs are directly disposed into the environment, thereby increasing environmental pollution. CBTPP waste results in water pollution, air pollution, and land pollution.

CBTPP waste, such as filter cakes, oil sludge, waste industrial oils, and heavy coal–tar products, are directly discharged into the environment, thus accruing the level of environmental pollution [3]. Countries, such as China, India, Japan, Russia, the USA, and Australia, are registering an increased level of air pollution every year. CBTPPs not only produce energy, but also produce hazardous anthropogenic emissions, such as CO_x, NO_x, SO_x, and fly ash wastes [4]. Although some portion of the fly ash emitted by the CBTPPs is utilized in the production of bricks and blocks used in the construction industry, the majority of the fly ash is disposed openly into the environment [5]. These emissions enhance the chance of the occurrence of the greenhouse effect resulting in drastic climate change. According to Zaman et al. [6], CBTPPs account for nearly 15% of environmental problems in Colombia and Russia. To maintain the global temperature by 2 °C, as indicated by the Intergovernmental Panel on Climate Change (IPCC), global countries have to reduce their coal consumption by 73% [7]. It is obvious that there has been an urgent need to cut the rate of coal usage; however, in meeting the energy demand, the role of coal is inevitable.

As a result of its concern for the adverse environmental impact of industrialization, the United Nations (UN) has listed a set of seventeen goals, called sustainable development goals (SDGs), and appealed to global nations to take action in the attainment of these goals. The attainment of SDGs requires holistic and comprehensive strategies. Among the 17 SDGs proposed by the UN, both goal 7 (affordable and clean energy) and goal 13 (climate action) require immediate action; each goal helps to achieve SDGs for individual nations and for the earth [8,9]. Furthermore, the dependence on non-renewable resources (coal) for energy demand places an enormous burden on the ecosystem. To minimize the burden and attain sustainability, alternative energy resources (wind and hydroelectricity) have been developed and are preferred. However, the efficiency of energy from alternative energy resources is not up to the level of energy efficiency from non-renewable energy resources [10]. Under such circumstances, the efficient and optimal usage of the available energy source will reduce the over-exploitation of non-renewable resources and help in moving towards sustainability.

From the above information, it is clear that India largely relies on CBTPPs for energy demands, but the efficiency of CBTPPs has not been fully utilized. Additionally, adequate steps were not taken to lower the adverse environmental impact. Taking adequate steps to improve the efficiency and lower the emissions produced from CBTPPs is essential to attain SDGs. Hence, there is a need to improve the optimal use of CBTPPs.

In this connection, this study analyzes the various challenges in improving the efficiency of CBTPPs. This paper contributes to a thorough explanation of the thermal efficiency of CBTPPs in many ways; we curate the main factors that serve as a critical challenge. The challenges that are presented in the present study act as controls to optimize and improve the efficiency of thermal plants. In this study, a coal-based thermal power plant located in India is considered as it is the largest consumer of coal and also accounts for high emissions. In relation to this notion, this study raises the following questions for the purpose of analysis:

- What are the challenges affecting the heat rate performance in thermal power plants?
- How does one reveal the causal interrelationship among the identified challenges affecting the heat rate performance in thermal power plants?

The purpose of this study is to identify the challenges affecting the heat rate performance in thermal power plants through a literature review and interaction with industrial management, and reveal the causal interrelationship among the identified challenges using the Multi-Criteria Decision Making (MCDM) technique. In the present paper, the Decision Making Trial and Evaluation Laboratory (DEMATEL) technique is used to evaluate the challenges. The DEMATEL technique, introduced by Gabus and Fontela [11], can be used to reveal the causal interrelationship of the challenges affecting the heat rate performance in thermal power plants. In this study, the grey-DEMATEL technique is used, as it is capable of generating possible results with a limited data set. Grey-DEMATEL has been used in many studies, such as sustainable transportation [12], supply chain evaluation [13], and the drone system [14].

The remainder of the paper is organized as follows: Section 2 summarizes the literature review on thermal power plants in India and the challenges affecting the heat rate performance of thermal power plants. The research gaps and contributions of this study are provided in Section 3. The methodology used in this study is explained in Section 4. A real case study application is presented in Section 5. Discussions on the obtained results are provided in Section 6. Finally, Section 7 concludes the study by highlighting the contributions and future scope of the study.

2. Literature Review

2.1. Coal Thermal Power Plants in India

Following China, with 285 coal-fired thermal power plants, India is the second country to have a large number of coal-fired thermal power plants. Accordingly, India is the second largest coal polluter in the world [15]. The abundance and combustion properties of coal favor the preference for meeting energy demands. However, the poor functioning of the CBTPP has often been cited as the reason for the environmental pollution caused by the thermal power plant. The heat rate of CBTPPs is an important criterion to define the plant's efficiency. The studies that improve the performance of thermal power plants also help to save the environment by contributing to reduced GHG emissions and carbon footprints [16]. Despite the advances made in CBTPPs, the research is still insufficient concerning conventional fueled boilers with minimal thermal operating loads [17]. Many studies specific to the Indian region have shown interest in increasing the performance of Indian thermal power plants. Sahoo et al. [18] studied 71 Indian power plants to determine their efficiency and energy-saving potential, Singh and Bajpai [19] used data from 23 state-run power plants in India to arrive at an average efficiency level, and Malik et al. [20] assessed the data of 83 state- and central-run power plants in India to find evidence to improve the thermal efficiency of a power plant.

According to Guttikunda and Jawahar [21], India annually consumes 503 million tons of coal and generates 580 ktons of particulates with a diameter of 2.5 µm. This leads to 80,000 to 115,000 premature deaths and 20 million asthma cases. Another recent study [22] suggests that 32% of global chronic respiratory disease occurs in India. The disposal of coal ash into the environment exposes the communities to heavy metals and particulate matter waste. Fly ash produced during coal combustion contains toxic heavy metals, such lead (Pb), zinc (Zn), and nickel (Ni) [23]. As the fly ash is disposed directly into the water bodies, it causes water pollution. Studies on the environmental impact of the coal-fired thermal power plants indicate that the partial burning of the coal as the main cause of the increased emissions of carbon monoxide and other particulates. The thermal power plants are also facing many challenges in relation to coal combustion. The subsequent section explains the challenges affecting the heat rate performance of thermal power plants.

2.2. The Challenges Affecting the Heat Rate of Thermal Power Plants

To identify the challenges of improving the thermal power plant's heat rate, scholarly articles were searched from the databases, such as Science Direct, Google Scholar, and Web of Science. To collect the articles, the following keywords and Boolean operators were used: "challenges in thermal power plant OR problems faced by the thermal power plant", "thermal power plant in India", "difficulties faced by the thermal power plant AND challenges faced by thermal power plant", and "coal-fired power plant AND thermal power plant". From this, initially, 60 articles were collected. Then, the articles were checked for the nature of work. Here, 15 articles were found to be duplicate or replicate works.

After rejecting the duplicated works, the challenges of improving the boiler's heat rate were identified from the remaining articles.

Since, usually, the coal in the thermal power plants is not burned properly, this leads to the formation of fly ash. These fly ash wastes are not handled effectively and are often disposed of into the environment. The fly ash from the thermal power plants is a rich source of carbon content and it increases the global warming effect [24]. Likewise, the maintenance activities are not carried out properly in the thermal power plants, and this resulted in the damage to some of the critical components. Damage to the boilers and ducts may result in the trapping of incoming air, which leads to low pressure. At a low pressure condition, the fly ash generated during the combustion of coal may settle in the tube pathway [25]. This affects the heat rate performance of the thermal power plants. Talapatra et al. [26] state that moisture content present in the coal affects the combustion process and reduces the efficiency of coal. The identified challenges with descriptions and the relevant references are provided in Table 1.

Table 1. The challenges affecting the heat rate improvements of a boiler system.

Challenges	Brief Description	References
Fly ash unburned carbon content (B1).	The pulverized coal supplied to the boiler for burning is not completely burned inside the furnace and comes out with flue gas as unburnt.	[24,27]
Bottom ash unburned carbon content (B2).	The heavy pulverized coal comes out through the boiler bottom ash hopper with heavy ash particles.	[24]
Boiler and duct work air-in leakage (B3).	Any leakage in the ducts affects the draft pressure, leading to incomplete combustion and results in fuel loss and the increasing consumption of auxiliaries.	[25,28]
Optimizing pulverizer (B4).	Supplying the correct quantity of required air based on the quantity of coal fed into the boiler is called optimizing, which reduces heat loss due to excess air carryover and reduces the auxiliary consumption.	[29]
Pulverizer throat size and geometry optimization to reduce coal rejects (B5).	Pulverizer throat size and geometry optimization reduces the coal mill rejects.	[29]
Pulverizer fineness, mechanical tolerance, and tuning optimization (B6).	Optimize coal size based on the retention time in the furnace and required correct air flow.	[25]
Balanced fuel and air distribution into the burner belt (B7).	Measuring coal flow rating and supplying correct quantity of air leads to efficient firing.	[24]
NO_X reduction by burner adjustment (B8).	Coal distributor insertion depth in the coal burner plays a main role in the NO_X reduction in boiler.	[30]
Coal flow balancing (B9).	Balancing the coal flow among the burners in the boiler results in more efficient combustion.	[20]
Super heater de-super heating spray water flow (B10).	Heat in the superheated region of the main stream is wasted by utilizing this heat to heat the water sprayed into it.	[16]
Re-heater de-super heating spray water flow (B11).	Heat in a superheated region of hot reheat steam is wasted by utilizing this heat to heat the water sprayed into it.	[19]
Air pre-heater leakage (B12).	Air pre-heater leakage reduces the heat gain of primary and secondary air from flue gas.	[31]
Auxiliary consumption from non-optimized combustion (B13).	The boiler draft system and mill fans are excessively loaded due to non-optimized combustion, thus increasing the auxiliary consumption.	[17]

Table 1. *Cont.*

Challenges	Brief Description	References
Super heater outlet steam temperature (B14).	Air heater leakage, un-optimized combustion, and poor quality coal. Improper soot blowing is the main cause of low super heater outlet steam temperature.	[18]
Re-heater outlet steam temperature (B15).	Reduction in re-heater outlet steam temperature reduces the reheat cycle efficiency, reduces the boiler efficiency, and leads to low-pressure turbine final stage corrosion.	[20]
Air heater air outlet temperature (B16).	The high air outlet temperature increases the boiler efficiency, reduces the flue gas outlet temperature, and increases the boiler efficiency.	[30]
Air pre-heater exit gas temperature (B17).	Lowered exit flue gas temperature is the indicator of heat absorbed in the boiler if the air pre-heater is leak proof.	[17]
Boiler exit excess air (B18).	A high loss of heat energy is carried away by the excess air flow through the boiler.	[2]
Boiler vent and drain valve leakages (B19).	These are heat and high-cost demineralized water-loss points. They reduce plant efficiency.	[18]
Optimized soot blower operation (B20).	Soot blowers are used to remove the ash deposited in tube surfaces. Soot blower operations are programed with some periodicity, regardless of whether there is or is not an ash deposit.	[17,32]
Pulverizer coal spillage and rejects (B21).	Reducing coal spillage and rejects directly saves coal, thus reducing coal cost and auxiliary consumption.	[19,33]
Continuous monitoring (B22).	Operating the power plant with designed parameters helps to achieve the designed heat rate.	[24,34]

2.3. The Existing MCDM Methods

Since the performance of the thermal power plants is affected by multiple factors, MCDM techniques are widely used. Patel and Dwivedi [35] used AHP methodology to find the preventive maintenance ace of the critical components in thermal power plants. Li et al. [36] evaluated the competition criteria of thermal power plant generation by using a hybrid MCDM methodology. Yuan et al. [37] utilized ANP methodology to study the challenges of using CBTPPs in various countries. Mittal et al. [38] used the AHP methodology to evaluate the challenges of thermal power plants. Pradhan and Ghose [39] provided an analysis of the key factors of thermal power plants in the state of Tamil Nadu in India. Wu et al. [40] provided an analysis of the sustainable challengers for evaluating the thermal power plants. Most existing literature uses AHP methodologies, whereas this proposed research uses the DEMATEL methodology to rank the challengers of thermal power plants in India. Most of the existing literature on thermal power plants in India concentrate on improving the performance and generation capacity of boilers. Studies devoted to finding the challengers to improve the heat rate performance of CBTPPs are rare. This paper closes the literature gap by providing the challengers and prioritizing them based on rank. Most research papers used either AHP methodology or a few hybrid methodologies, AHP and ANP, for research purposes. Research conducted using the DEMATEL methodology for heat rate challengers of CBTPPs is rare in the existing literature. This paper applies the DEMATEL methodology to study the interaction between challengers and to rank them according to their obtained weights. Table 2 provides a list of research works in the field of thermal power plants using the MCDM methodology.

Table 2. The MCDM methodology in thermal power plant sectors.

MCDM Methodology Used	Area of Application	Reference
AHP	To evaluate the critical components of thermal power plants that require preventive maintenance.	[35]
ISM	To evaluate the hazards and challenges associated with thermal power plants.	[41]
DEMATEL	To assess the sustainability levels of the existing CBTPPs.	[40]

3. Research Gaps and Contributions

After reviewing the existing literature, we found that there is little research that considers and evaluates the challenges of improving the heat rate performance of CBTPPs. Lubega and Stillwell [42] suggested using cooling water to improve the performance of the thermal power plant. A study evaluating the challenges of improving the heat rate performance in thermal power plants in the Indian context has not been carried out to our knowledge. Some of the challenges evaluated in this study have not been found in published research articles. Moreover, the causal relationships among the challenges have not been explored in the past literature. Hence, to fill this gap, this study analyzes the challenges of improving a thermal power plant's heat rate performance. To this end, the grey-DEMATEL technique was employed. In short, the objectives of this research study are summarized as follow:

1. To identify the challenges affecting the heat rate performance of CBTPPs.
2. To reveal the causal interrelationships among the identified challenges.
3. To suggest some managerial implications that are needed to be applied by the industrial management to overcome the challenges.

4. Methodology

Grey-DEMATEL

The grey theory, proposed by Deng [43], has a major advantage of generating possible results using a small amount of data. Another advantage of grey theory is that it can handle incomplete and partial data. Grey numbers can be converted into crisp numbers by the modified CFCS (converting fuzzy data into crisp scores), by the following three steps:

Consider a grey number $\otimes A = \left[\underline{\otimes} A_{ij}, \bar{\otimes} A_{ij}\right]$, where $\underline{\otimes} A_{ij}$ and $\bar{\otimes} A_{ij}$ are the lower and upper limit values of $\otimes A$, respectively.

Step 1: normalization of the grey numbers

$$\begin{aligned} \bar{\otimes} A_{ij} &= (\bar{\otimes} A_{ij} - \min \bar{\otimes} A_{ij}) / \Delta_{\min}^{\max} \text{ and} \\ \underline{\otimes} A_{ij} &= (\underline{\otimes} A_{ij} - \min \underline{\otimes} A_{ij}) / \Delta_{\min}^{\max} \end{aligned} \tag{1}$$

where $\Delta_{\min}^{\max} = \max \bar{\otimes} A_{ij} - \min \underline{\otimes} A_{ij}$

Step 2: standardization of the total crisp values

$$Y_{ij} = \frac{(\underline{\otimes} A_{ij}(1 - \underline{\otimes} A_{ij}) + (\bar{\otimes} A_{ij} \times \bar{\otimes} A_{ij}))}{(1 - \underline{\otimes} A_{ij} + \bar{\otimes} A_{ij})} \tag{2}$$

Step 3: computation of the final crisp values

$$Z_{ij} = \min \bar{\otimes} A_{ij} + Y_{ij} \Delta_{\min}^{\max} \tag{3}$$

The DEMATEL (Decision Making Trial and Evaluation Laboratory) method, proposed by Fontela (1974), is a structural model method used to establish the causal relationship between complex factors. Using the DEMATEL method, the factors considered under study can be categorized in either a cause or effect group. The DEMATEL approach can also be used with a limited sample size [44]. Initially, the fuzzy concept is integrated with the DEMATEL technique for improving the accuracy of the results. The grey concept theory is integrated with the DEMATEL technique to overcome vagueness and the influence of human judgments [45]. In this study, the grey-DEMATEL approach is utilized to evaluate the challenges of improving heat rate performance. The steps involved in grey-DEMATEL are presented below:

Step 1: compute the direct influence matrix A presented by experts;
Step 2: obtain matrix Z using Equations (1)–(3);
Step 3: construct a normalized matrix X

$$X_{ij} = \frac{Z_{ij}}{S} \tag{4}$$

where $S = \max\left\{ \max_{1 \le i \le n} \sum_{j=1}^{n} Z_{ij}, \max_{1 \le i \le n} \sum_{j=1}^{n} Z_{ij} \right\}$
Step 4: compute the total influence matrix (T)

$$T = X(I - X)^{-1} \tag{5}$$

Step 5: determine the cause–effect group

$$R = [r_i]_{n \times 1} = \left[\sum_{j=1}^{n} t_{ij} \right]_{n \times 1} \tag{6}$$

$$C = [C_j]_{n \times 1} = \left[\sum_{i=1}^{n} t_{ij} \right]_{n \times 1} \tag{7}$$

$(R + C)$ represents the degree of relation between each factor with others and $(R - C)$ represents the severity of each factor's influence.
Step 6: draw the causal diagram. A cause–effect diagram is constructed using the data set consisting of the $(R + C)$ and $(R - C)$ values.

5. Real-Time Case Study

In this section, applying the grey-DEMATEL method and revealing the interrelationships among the challenges is demonstrated by considering a thermal power plant. The study identified 22 challenges and the identified challenges were discussed with experts (10) who have profound knowledge about the problem from the literature review. A questionnaire (Appendix A) consisting of 22 challenges was presented to the experts for making pair-wise comparisons using Table 3. The experts were asked to express their opinions regarding the identified challenges and to suggest challenges, if any were missed. The number of experts used in the study is acceptable as the DEMATEL approach can be used with a limited number of experts [46]. Then, the relationship between the challenges was analyzed using grey-DEMATEL and the results were validated using the existing literature and input of the experts. The steps of the grey-DEMATEL approach in our work are presented below [47]:

Step 1: first, the experts were asked to express their interrelationships among each challenge using a 5-point linguistic scale by using Table 3. The direct relationship matrices obtained from the experts are in grey numbers and are converted into crisp values using Equations (1)–(3). The response obtained from the experts using Appendix A are consolidated and presented in Appendix B. The conversion of the grey number into a crisp value is discussed below [48]:

Consider the first row of Table A4 in Appendix B. Take the first set [0, 0]. For this set, Equation (1) is applied. Here, $\overline{\otimes}A_{ij} = 0$, $\min\overline{\otimes}A_{ij} = 0$, and $\Delta_{\min}^{\max} = 4$. Similarly, $\underline{\otimes}A_{ij} = 0$, $\min\underline{\otimes}A_{ij} = 0$, and $\Delta_{\min}^{\max} = 4$. By applying these values in Equations (1)–(3), we obtain [0, 0].

Step 2: here, the final direct relation matrix (Z) is obtained by summarizing the response of the experts. The grey values are converted into crisp values using the CFCS technique, as discussed earlier.

Step 3: from the direct relation matrix (Z) obtained in step 2, the normalized matrix X is calculated using Equation (4) and is presented in Table A5 in Appendix B.

Step 4: the total relation matrix is calculated using Equation (5) and is presented in Table A6 in Appendix B.

Step 5: in this step, using Equations (6) and (7), the values of $m_i + n_i$ and $m_i - n_i$ for each challenge are calculated.

Step 6: using the data set of $(R - C)$, the causal diagram is drawn. Based on the $(R - C)$ value of the challenges, the challenges are categorized in the cause and effect group (Table 4) and a graph is drawn (Figure 1).

Table 3. The grey linguistic assessment and scales.

Scale	Linguistic Assessment	Grey Number
4	Very high influence (VHI)	[3, 4]
3	High influence (HI)	[2, 3]
2	Low influence (LI)	[1, 2]
1	Very low influence (VLI)	[0, 1]
0	No influence (NI)	[0, 0]

Table 4. The final matrix.

	$row_i(m_i)$	$col_i(n_i)$	$m_i + n_i$	$m_i - n_i$	Cause/Effect	Rank
B1	[1.17, 1.50]	[1.19, 1.45]	[2.36, 2.95]	[−0.01, −0.04]	Effect	13
B2	[1.17, 1.50]	[1.19, 1.45]	[2.36, 2.95]	[−0.01, −0.04]	Effect	14
B3	[0.49, 0.89]	[0.48, 0.66]	[0.97, 1.56]	[0.01, 0.23]	Cause	12
B4	[1.28, 1.74]	[1.80, 2.13]	[3.09, 3.87]	[−0.52, −0.39]	Effect	20
B5	[0.45, 0.89]	[0.29, 0.59]	[0.75, 1.49]	[0.16, 0.29]	Cause	7
B6	[0.90, 1.49]	[0.96, 1.39]	[1.87, 2.88]	[0.05, 0.09]	Cause	11
B7	[0.91, 1.53]	[1.01, 1.37]	[1.93, 2.91]	[−0.10, −0.15]	Effect	16
B8	[0.42, 0.81]	[0.47, 0.70]	[0.89, 1.51]	[−0.05, −0.10]	Effect	15
B9	[1.45, 1.91]	[0.73, 1.13]	[2.18, 3.05]	[0.72, 0.78]	Cause	2
B10	[0.33, 0.62]	[0.67, 1.24]	[1.00, 1.87]	[−0.34, −0.61]	Effect	18
B11	[0.26, 0.57]	[0.18, 0.94]	[0.45, 1.52]	[0.07, 0.37]	Cause	10
B12	[1.22, 1.72]	[0.41, 0.59]	[1.64, 2.31]	[0.81, 1.13]	Cause	1
B13	[0.05, 0.26]	[0.99, 1.46]	[1.05, 1.72]	[−0.94, −1.20]	Effect	22
B14	[0.56, 0.85]	[0.87, 1.31]	[1.44, 2.17]	[−0.30, −0.45]	Effect	17
B15	[0.43, 0.71]	[1.01, 1.52]	[1.44, 2.23]	[−0.57, −0.80]	Effect	21
B16	[1.20, 1.67]	[0.58, 0.98]	[1.78, 2.65]	[0.62, 0.69]	Cause	3
B17	[0.74, 1.13]	[1.23, 1.71]	[1.97, 2.85]	[−0.48, −0.57]	Effect	19
B18	[1.01, 1.28]	[0.80, 0.91]	[1.81, 2.20]	[0.20, 0.37]	Cause	6
B19	[0.22, 0.36]	[0.12, 0.20]	[0.34, 0.57]	[0.10, 0.16]	Cause	8
B20	[0.88, 1.23]	[0.64, 1.21]	[1.53, 2.44]	[0.23, 0.02]	Cause	5
B21	[0.37, 0.54]	[0.30, 0.51]	[0.68, 1.05]	[0.07, 0.03]	Cause	9
B22	[0.74, 1.32]	[0.35, 1.09]	[1.09, 2.41]	[0.38, 0.22]	Cause	4

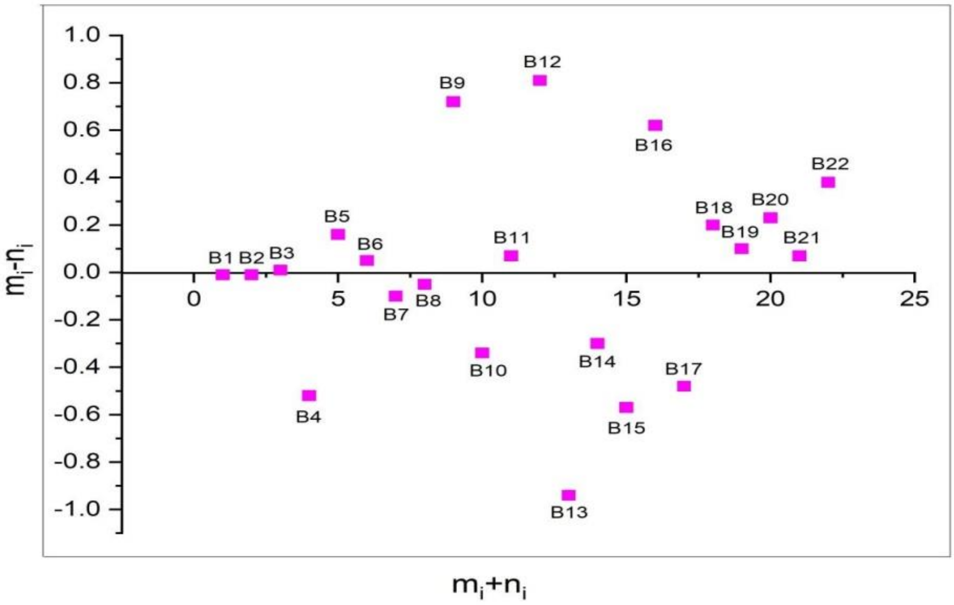

Figure 1. The causal relationship among the challenges.

To validate the results obtained using the grey-DEMATEL technique, a sensitivity analysis was performed. By using the sensitivity analysis, it is possible to measure the reliability and robustness of the obtained result. In the present study, a sensitivity analysis was carried out by assigning different importance weights to the experts, i.e., in one case, expert 1 was assigned a higher importance weight than the other experts. Similarly, in another case, expert 2 was assigned a higher importance weight than the other experts. The importance weights assigned to the experts are presented in Table 5 [48]. In the present study, the sensitivity analysis is carried out in ten different phases by assigning priority for each expert in one phase. In this way, the individual response of the expert is obtained and compared to the consolidated result obtained. Finally, the outcome of the sensitivity analysis is presented in Table 6.

Table 5. The weight importance assigned to ten experts in the sensitivity analysis.

Phase	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10
Phase 1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Phase 2	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Phase 3	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Phase 4	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1
Phase 5	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.1
Phase 6	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.1
Phase 7	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.1
Phase 8	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1
Phase 9	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1
Phase 10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3

Table 6. Sensitivity analysis of the challenges affecting the heat rate improvements of the boiler system.

	Phase 1			Phase 2			Phase 3			Phase 4			Phase 5		
	m_i+n_i	$m_i - n_i$	Rank	$m_i + n_i$	$m_i - n_i$	Rank	$m_i + n_i$	$m_i - n_i$	Rank	$m_i + n_i$	$m_i - n_i$	Rank	$m_i + n_i$	$m_i - n_i$	Rank
B1	[2.32, 2.97]	[0.00, 0.06]	12	[2.59, 4.35]	[0.24, −1.35]	21	[2.30, 3.43]	[0.04, −0.47]	11	[2.41, 3.60]	[−0.05, −0.54]	14	[3.50, 3.79]	[1.04, −0.75]	1
B2	[2.41, 2.92]	[−0.06, 0.07]	15	[2.37, 2.93]	[−0.02, 0.07]	14	[2.32, 2.95]	[0.02, 0.05]	12	[2.35, 2.95]	[0.00, 0.05]	12	[2.37, 3.01]	[−0.02, −0.11]	13
B3	[0.97, 1.58]	[0.01, 0.25]	11	[0.98, 1.59]	[0.02, 0.25]	7	[1.04, 1.53]	[−0.04, 0.23]	13	[0.98, 1.57]	[0.02, 0.23]	11	[0.98, 1.64]	[0.02, 0.30]	11
B4	[3.09, 3.92]	[−0.52, −0.44]	20	[3.91, 6.07]	[−1.12, 0.41]	5	[3.09, 3.90]	[−0.52, −0.36]	20	[3.09, 3.92]	[−0.52, −0.44]	20	[3.59, 4.68]	[−1.02, −0.40]	22
B5	[0.80, 1.53]	[0.21, 0.25]	5	[0.75, 1.50]	[0.17, 0.30]	6	[0.75, 1.48]	[0.17, 0.32]	7	[0.75, 1.54]	[0.17, 0.34]	7	[0.83, 1.53]	[0.09, 0.29]	9
B6	[1.87, 2.88]	[−0.05, 0.09]	14	[1.90, 2.91]	[−0.03, 0.08]	12	[1.87, 2.89]	[−0.06, 0.09]	14	[1.89, 2.89]	[−0.05, 0.10]	15	[1.87, 2.98]	[−0.06, −0.05]	15
B7	[1.98, 2.89]	[−0.15, 0.17]	16	[2.13, 2.91]	[−0.30, 0.16]	10	[1.92, 2.91]	[−0.11, 0.16]	16	[1.99, 2.91]	[−0.16, 0.16]	16	[1.93, 2.99]	[−0.10, −0.16]	16
B8	[0.89, 1.57]	[−0.05, 0.16]	13	[0.89, 1.47]	[−0.05, 0.15]	11	[0.92, 1.49]	[−0.08, 0.13]	15	[0.89, 1.51]	[−0.05, 0.11]	13	[0.89, 1.59]	[−0.05, −0.19]	14
B9	[2.18, 3.06]	[0.72, 0.77]	2	[2.89, 3.05]	[1.43, 0.78]	4	[2.19, 3.55]	[0.73, 1.28]	2	[2.21, 3.06]	[0.74, 0.77]	2	[2.20, 3.85]	[0.72, 1.58]	3
B10	[0.97, 1.87]	[−0.31, −0.61]	18	[1.15, 1.81]	[−0.34, −0.61]	19	[1.01, 1.87]	[−0.34, −0.61]	18	[1.01, 1.93]	[−0.34, −0.55]	18	[1.07, 1.87]	[−0.40, −0.61]	18
B11	[0.48, 1.52]	[0.10, −0.37]	8	[0.45, 1.52]	[0.08, −0.37]	16	[0.45, 1.53]	[0.08, −0.38]	9	[0.46, 1.57]	[0.07, −0.42]	10	[0.57, 1.58]	[0.00, −0.43]	12
B12	[1.64, 2.31]	[0.81, 1.13]	1	[1.68, 2.32]	[0.77, 1.13]	2	[1.63, 2.73]	[0.80, 1.55]	1	[1.60, 2.39]	[0.77, −1.07]	1	[1.82, 2.40]	[0.99, 1.06]	2
B13	[1.05, 1.74]	[−0.94, −1.22]	22	[1.06, 2.53]	[−0.93, −2.01]	22	[1.05, 1.73]	[−0.94, −1.21]	22	[1.05, 1.73]	[−0.94, −1.21]	22	[1.08, 1.73]	[−0.97, −1.21]	20
B14	[1.49, 2.17]	[−0.25, −0.45]	17	[1.44, 2.21]	[−0.31, −0.49]	17	[1.44, 2.17]	[−0.31, −0.45]	17	[1.49, 2.30]	[−0.26, −0.32]	17	[1.44, 3.02]	[−0.31, −1.20]	17
B15	[1.44, 2.23]	[−0.57, −0.80]	21	[1.51, 2.29]	[−0.65, −0.76]	20	[1.44, 2.24]	[−0.58, −0.81]	21	[1.45, 2.24	[−0.57, −0.81]	21	[1.44, 2.24]	[−0.58, −0.81]	19
B16	[1.78, 2.65]	[0.62, 0.69]	3	[1.78, 3.37]	[0.62, 1.31]	1	[1.78, 3.03]	[0.62, 0.27]	3	[1.77, 2.65]	[0.63, 0.69]	3	[1.83, 2.65]	[0.67, 0.69]	4
B17	[2.03, 2.89]	[−0.42, −0.53]	19	[2.08, 2.89]	[−0.44, −0.61]	18	[2.01, 2.90]	[−0.52, −0.52]	19	[1.98, 2.85]	[−0.49, −0.57]	19	[2.48, 2.85]	[−0.99, −0.57]	21
B18	[1.87, 2.25]	[0.14, 0.32]	7	[1.82, 2.92]	[0.20, 1.10]	3	[1.82, 2.70]	[0.20, 0.87]	6	[1.82, 2.20]	[0.20, 0.37]	6	[1.82, 2.20]	[0.20, 0.37]	6
B19	[0.34, 0.57]	[0.10, 0.16]	9	[0.35, 0.57]	[0.10, 0.16]	9	[0.35, 0.57]	[0.10, 0.16]	8	[0.35, 0.59]	[0.10, 0.14]	8	[0.35, 0.59]	[0.11, 0.16]	8
B20	[1.49, 2.45]	[0.20, 0.03]	6	[1.59, 2.49]	[0.18, 0.07]	13	[1.53, 2.45]	[0.24, 0.03]	5	[1.53, 2.45]	[0.24, 0.03]	5	[1.57, 2.50]	[0.20, −0.02]	7
B21	[0.68, 1.05]	[0.07, 0.03]	10	[0.68, 1.06]	[0.08, 0.04]	15	[0.68, 1.13]	[0.08, −0.05]	10	[0.68, 1.10]	[0.08, 0.08]	9	[0.68, 1.06]	[0.08, 0.03]	10
B22	[1.10, 2.44]	[0.33, 0.19]	4	[1.17, 2.43]	[0.31, 0.21]	8	[1.14, 2.98]	[0.43, −0.28]	4	[1.17, 3.03]	[0.41, 0.73]	4	[1.09, 2.42]	[0.39, 0.22]	5

Table 6. *Cont.*

	Phase 6			Phase 7			Phase 8			Phase 9			Phase 10		
	m_i+n_i	$m_i - n_i$	Rank	$m_i + n_i$	$m_i - n_i$	Rank	$m_i + n_i$	$m_i - n_i$	Rank	$m_i + n_i$	$m_i - n_i$	Rank	$m_i + n_i$	$m_i - n_i$	Rank
B1	[2.33, 3.06]	[−0.02, −0.07]	12	[2.39, 3.05]	[0.02, 0.05]	11	[2.74, 2.96]	[−0.38, 0.04]	18	[3.00, 2.97]	[−0.41, 0.07]	18	[2.46, 3.03]	[0.02, 0.09]	11
B2	[2.37, 2.95]	[−0.02, −0.05]	11	[2.37, 2.95]	[−0.02, 0.05]	13	[2.37, 2.94]	[−0.01, 0.02]	12	[2.37, 3.00]	[−0.02, 0.06]	12	[2.37, 3.02]	[−0.02, −0.05]	14
B3	[1.38, 1.55]	[0.41, 0.25]	4	[0.99, 1.57]	[0.01, 0.23]	12	[0.99, 2.01]	[0.02, 0.60]	11	[0.98, 1.70]	[0.02, 0.26]	11	[0.99, 1.69]	[0.02, 0.27]	12
B4	[3.09, 3.87]	[−0.52, −0.39]	20	[3.09, 3.87]	[−0.52, −0.39]	20	[3.10, 3.99]	[−0.53, −0.43]	20	[3.09, 3.92]	[−0.52, −0.34]	20	[3.14, 3.87]	[−0.47, −0.39]	19
B5	[0.76, 1.63]	[0.16, 0.43]	7	[0.75, 1.50]	[0.16, 0.30]	7	[0.82, 1.50]	[0.24, 0.30]	5	[0.75, 1.72]	[0.17, 0.07]	7	[0.82, 1.57]	[0.10, 0.22]	7
B6	[1.88, 2.89]	[−0.06, −0.10]	14	[1.87, 2.89]	[−0.06, 0.10]	14	[1.87, 2.97]	[−0.06, 0.02]	14	[1.88, 2.89]	[−0.06, 0.10]	13	[1.92, 2.93]	[−0.01, −0.14]	13
B7	[1.93, 2.91]	[−0.10, −0.16]	15	[1.93, 2.91]	[−0.10, 0.16]	16	[1.93, 2.91]	[−0.10, 0.16]	15	[1.93, 2.91]	[−0.10, 0.16]	14	[1.98, 2.91]	[−0.15, −0.15]	16
B8	[0.89, 1.60]	[−0.05, −0.02]	13	[0.92, 1.53]	[−0.08, 0.09]	15	[0.89, 1.51]	[−0.05, 0.11]	13	[0.96, 1.52]	[−0.12, 0.11]	15	[0.93, 1.51]	[−0.09, −0.10]	15
B9	[2.19, 3.05]	[0.73, 0.78]	2	[2.19, 3.05]	[0.73, 0.78]	2	[2.19, 3.05]	[0.73, 0.78]	3	[2.19, 3.11]	[0.73, 0.84]	3	[2.19, 3.05]	[0.73, 0.78]	2
B10	[1.01, 1.87]	[−0.34, −0.61]	18	[1.01, 1.99]	[−0.34, −0.57]	18	[1.01, 1.87]	[−0.34, −0.61]	17	[1.01, 1.87]	[−0.34, −0.61]	17	[1.01, 1.87]	[−0.34, −0.61]	18
B11	[0.46, 1.52]	[0.08, −0.37]	10	[0.45, 1.52]	[0.08, −0.37]	9	[0.47, 1.52]	[0.06, −0.37]	10	[0.45, 1.52]	[0.08, −0.37]	9	[0.46, 1.53]	[0.08, 0.37]	10
B12	[1.65, 2.32]	[0.80, 1.14]	1	[1.64, 2.32]	[0.81, 1.14]	1	[1.64, 2.32]	[0.81, 1.14]	2	[1.64, 2.39]	[0.81, 1.19]	2	[1.65, 2.32]	[0.82, 1.14]	1
B13	[1.05, 1.73]	[−0.94, −1.21]	22	[1.06, 1.73]	[−0.94, −1.21]	22	[1.06, 1.79]	[−0.94, −1.11]	22	[1.06, 1.73]	[−0.94, −1.20]	22	[1.05, 1.73]	[−0.94, −1.21]	22
B14	[1.44, 2.17]	[−0.31, −0.45]	17	[1.44, 2.17]	[−0.31, −0.45]	17	[1.44, 2.17]	[−0.31, −0.45]	16	[1.44, 2.23]	[−0.31, −0.45]	16	[1.44, 2.17]	[−0.31, −0.45]	17
B15	[1.44, 2.24]	[−0.58, −0.81]	21	[1.44, 2.27]	[−0.58, −0.78]	21	[1.44, 2.32]	[−0.58, −0.73]	21	[1.44, 2.24]	[−0.58, −0.81]	21	[1.45, 2.24]	[0.57, −0.81]	21
B16	[1.78, 2.64]	[0.62, 0.70]	3	[1.78, 2.65]	[0.62, 0.69]	3	[2.08, 2.65]	[0.92, 0.69]	1	[2.35, 2.72]	[1.19, 0.72]	1	[1.79, 2.65]	[0.63, 0.69]	3
B17	[1.98, 2.90]	[−0.49, −0.62]	19	[1.98, 2.84]	[−0.49, −0.58]	19	[1.98, 2.85]	[−0.49, −0.57]	19	[1.98, 2.85]	[−0.49, −0.57]	19	[1.99, 2.85]	[−0.48, −0.57]	20
B18	[2.22, 2.20]	[−0.20, −0.37]	16	[1.82, 2.17]	[0.20, 0.40]	6	[1.82, 2.60]	[0.20, −0.03]	7	[1.82, 2.20]	[0.20, 0.37]	6	[1.82, 2.21]	[0.21, 0.37]	6
B19	[0.36, 0.64]	[0.11, 0.22]	8	[0.35, 0.58]	[0.10, 0.17]	8	[0.35, 0.60]	[0.10, 0.16]	8	[0.35, 0.64]	[0.11, 0.11]	8	[0.37, 0.58]	[0.08, 0.16]	8
B20	[1.53, 2.45]	[0.24,0.03]	6	[1.53, 2.45]	[0.24, 0.03]	5	[1.53, 2.45]	[0.24, 0.03]	6	[1.53, 2.45]	[0.24, 0.03]	5	[1.53, 2.45]	[0.24, 0.03]	5
B21	[0.69, 1.11]	[0.08, −0.02]	9	[0.68, 1.05]	[0.08, 0.03]	10	[0.68, 1.05]	[0.08, 0.03]	9	[0.73, 1.06]	[0.03, 0.04]	10	[0.69, 1.09]	[0.08, −0.01]	9
B22	[1.11, 2.46]	[0.39, 0.18]	5	[1.10, 2.49]	[0.38, 0.15]	4	[1.09, 2.42]	[0.38, 0.22]	4	[1.18, 2.44]	[0.32, 0.24]	4	[1.10, 2.42]	[0.38,0.23]	4

6. Results and Discussions

6.1. Cause Group

According to Figure 1 and Table 4, the challenges considered in this study are categorized into a cause and effect group. The challenges are categorized based on $m_i - n_i$ values. Meanwhile, the rank provided in Table 4 is based on $m_i + n_i$ values. Among these causal challenges, B12 (air preheater leakage) is at the top of the cause group, which indicates that B12 is the critical challenge. Air preheater leakage reduces the regenerative heat gain of primary and secondary air from flue gas. Furthermore, due to high-pressure primary and secondary air passing into the flue gas duct radial and axial seals, this increases the induced draft fan load, thus leading to high auxiliary consumption. In this condition, the flue gas outlet quantity increases more than the induced draft fan capacity. Hence, the boiler cannot load to its full capacity and the negative draft pressure cannot be maintained in the furnace and flue gas path. Heidari-Kaydan et al. [49] also advocated that air preheater leakage has a major impact on the power plant's performance and tends to modify the performance behavior of the power plant. Next, challenge B9 (coal flow balancing) must be given significant attention. If the coal-supplying pulverizers are not properly balanced, this will result in an uneven burn in the boiler. These circumstances result in poor efficiency and reduce the optimal heat rate. Changing the setting of the classifier blades improves the fineness and balancing the primary air uses clean air and dirty air tests for reference. This improves combustion and increases the efficiency of the boiler system. This finding was supported by the study of Hübel et al. [50], which emphasizes that maintaining a proper balance of the input, i.e., coal, is crucial, as it helps to maintain the optimal heat rate. Only when the heat rate is optimal will the coal be uniformly burned and it will be possible to achieve an efficient output.

The third important cause challenge is B16 (air heater air outlet temperature). High-temperature air coming out of the air preheater is a good sign. The heat regenerative process that beneficially diverts the heat again into the boiler furnace is wasted into the atmosphere through flue gas. This high-temperature air preheater outlet air dries the coal, removes the moisture from the coal, preheats the pulverized coal, and makes it ready to fire when it enters the furnace. Similarly, challenge B22 (continuous monitoring) requires immediate attention, as it plays an important role in the operation of the thermal power plant. Each subsystem has its separate parameters and they are interlinked. The failure of one small subsystem may affect the power generation totally or partially. The deviation of the parameter's value from its designed value decreases the overall efficiency of the thermal power plant. Therefore, the vital parameters must be continuously monitored and a necessary correction be immediately performed if any deviation is found. Karuppiah et al. [51] also emphasizes that developing a predictive maintenance model based on the history of the equipment and parameters is critical to the prevention of a system failure. This is because failure at one point will impact the entire system. The fifth important challenge is B20 (soot blowing.) The "soot blowing" optimization, or smart soot blowing, is considered as excellent in power plant operation. The use of intelligent soot blowing system (ISB) systems for improving system efficiency also enhances the performance of the furnace and longevity of the tubing material, while minimizing the cycling effects of the steam turbine. The ISB system functions by monitoring both furnace exhaust gas temperatures and steam temperatures. A sophisticated ISB receives various inputs from the boiler system, which are then digitally processed to evaluate the real-time performance. Apart from the discussed challenges, other challenges, B18, B5, B19, B21, B11, B6, and B3, also need attention.

6.2. Effect Group

According to Figure 1, the challenges related to the effect group are sorted as follows: B1 > B2 > B8 > B7 > B14 > B10 > B17 > B4 > B15 > B13. Among these challenges, fly ash unburned carbon content (B1) requires special attention. This is due to the insufficient furnace retaining time, large fuel quantity (i.e., low fuel fineness), low furnace temperature, and insufficient air. Due to the above reasons, the pulverized fuel particles travel through the flue gas path without burning. The heat rate penalty for bituminous fly ash LOI (Loss on Ignition) is roughly accepted to be about 0.10% in efficiency for every 1.0% change in fly ash LOI. If combustion optimization is applied to the pulverizers, mechanical tolerances, and airflow, and the fly ash LOI is reduced to about 5%, then the heat rate improvement would roughly be about 100 BTUs. Next, the challenge bottom ash unburned carbon content (B2) must be considered a critical challenge. These unburned pulverized coal particles present in the bottom ash are due to a problem in the draft system. If the drafting system pressure and air flow quantity are insufficient inside, the furnace will fail to lift the pulverized coal particles and ignition. Hence, the unburned coal comes along with the bottom ash collected at the bottom of the furnace. Allowing for the deposition of the unburned carbon may block the entry of fresh air into the system, and thus affects the utilization of the coal content [52]. Such a problem results in an ineffective use of coal.

Third, the challenge of NO_X reduction by burner adjustment (B8) is very critical. Assume that the stratification of the flue gas exits from the burner tips to the boiler exits, then the burner adjustments were made to balance the excess air to control the CO and NO_X using low NO_X burners. The burner components that were adjusted include the secondary air shroud portion, secondary air inner and outer registers, and coal distributor insertion depth, which affect the total air flow of the burner. Similarly, balanced fuel and air distribution into the burner belt (B7) must be addressed early on. The coal flow control device for a three-way pipe split and three-way rifflers equally distributes the coal flows between the burners. The benefits are the reductions in the fly ash unburned carbon, baseline CO emissions, furnace excess O_2, heat rate, and ammonia injection rate [53].

Then, the challenge super heater outlet steam temperature (B14) is also very crucial. The super heater outlet temperature is also called the main steam temperature. It is the main design parameter of a thermal power plant. A high value in this temperature leads to more condenser loads, affects the condenser vacuum, and needs more condenser cooling water. To limit the temperature, more spray water is required, thus leading to a high heat rate. If the super heater outlet temperature is too low, the turbine output power is reduced, which leads to the sub-cooling of condensate in the condenser; that is a kind of energy loss that increases the unit heat rate. Hence, this parameter must be maintained to the designed value with slight tolerance, which is also beneficial, leading to a poor heat rate. Apart from these primary challenges, other challenges, B10, B17, 20, B15, and B13, also need attention.

Sensitivity analysis, based on the weight importance of experts (Table 6), represents the reliability of the obtained results. The result of the sensitivity analysis ensures the robustness of the result obtained using grey-DEMATEL. When viewed, it can be noticed that the B12 challenge occupies the top position, either the first or second positions in most cases. This indicates the severity of this challenge. Similarly, the position of most of the challenges remains the same, while a few challenges witnessed a positional change. This reveals the steadiness and robustness of the result.

7. Conclusions

Currently, most countries rely on coal energy for meeting their energy demands. Surging energy demands have necessitated the optimal use of the available energy resources for achieving SDGs; in particular, goal 7 and goal 13. Although renewable energy sources are being analyzed for meeting the requirements of energy demands, they are mostly in the developing stage. Hence, there is a need to use coal-based energy resources optimally. Considering the importance of improving the performance of the thermal power plant that is based on coal, this study analyzed the challenges affecting the heat rate of thermal power plants. Therefore, this research analyzed and evaluated the challenges of improving the heat rate performance of CBTPPs using the grey-DEMATEL technique. To identify the challenges of improving the heat rate of the thermal power plants, an extensive literature review was carried out. Furthermore, to capture the real-time challenges of improving the heat rate, the interactions with the management of the thermal power plants were made. As a result, twenty-two challenges affecting the heat rate of the thermal power plants were identified. The grey-DEMATEL technique was employed to evaluate the challenges. The outcomes indicate that fourteen challenges are the cause group challenges that deserve immediate attention and eight challenges are the effect group challenges. According to the prominence value, air preheater leakage is the most important challenge, followed by coal flow balancing and air heater air outlet temperature.

The research makes some valuable contributions to the literature on the sustainable performance of CBTPPs. First, this research explicitly analyzes and evaluates the challenges of improving the thermal power plant's heat rate performance. The challenges analyzed in this research have not been analyzed in other research work. Next, using the grey-DEMATEL technique, the present study captures the cause-and-effect relationship among the challenges and reveals the overall degree of influence of each challenge. Finally, the outcome of the research suggests policy implications for industrial managers involved in decision making.

This research has some limitations. Although the research analyzed and evaluated 22 challenges, the study did not consider the challenges from the organizational category. Future studies, in this context, must include the challenges from the organizational category. Furthermore, the challenges analyzed in the present paper are related to CBTPPs. The same challenges can be analyzed in other power plants, such as steam power plants or geothermal power plants. The same challenges can also be evaluated using the Interpretive Structural Modelling (ISM) technique or the Structural Equation Modelling (SEM) technique.

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Appendix A

Questionnaire presented to the experts.

The uncontrolled exploitation of the resources resulted in the scarcity of resources. Similarly, the failure in the optimal use of the resources has to lead to environmental pollution. Coal is one of the primary natural resources on which global countries rely for energy production. However, the failure in optimal use of coal resulted in environmental pollution. This study has drawn attention to this issue and identified several challenges that thermal power plants face in using coal optimally. The identified challenges are presented in below. The experts were requested to provide a pairwise comparison for the challenges using the provided greyscale.

Table A1. The challenges affecting the heat rate improvements of the boiler system.

Challenges	Notation
Fly ash unburned carbon content	B1
Bottom ash unburned carbon content	B2
Boiler and duct work air-in leakage	B3
Optimizing pulverizer	B4
Pulverizer throat size and geometry optimization to reduce coal rejects	B5
Pulverizer fineness, mechanical tolerance, and tuning optimization	B6
Balanced fuel and air distribution into the burner belt	B7
NO_X reduction by burner adjustment	B8
Coal flow balancing	B9
Super heater de-super heating spray water flow	B10
Re-heater de-super heating spray water flow	B11
Air pre-heater leakage	B12
Auxiliary consumption from non-optimized combustion	B13
Super heater outlet steam temperature	B14
Re-heater outlet steam temperature	B15
Air heater air outlet temperature	B16
Air pre-heater exit gas temperature	B17
Boiler exit excess air	B18
Boiler vent and drain valve leakages	B19
Optimized soot blower operation	B20
Pulverizer coal spillage and rejects	B21
Continuous monitoring	B22

Table A2. Grey linguistic assessment and scales.

Scale	Linguistic Assessment	Grey Number
4	Very high influence (VHI)	[3, 4]
3	High influence (HI)	[2, 3]
2	Low influence (LI)	[1, 2]
1	Very low influence (VLI)	[0, 1]
0	No influence (NI)	[0, 0]

Table A3. Pairwise comparison of the challenges. Please provide the rating using the scale presented in Table A2.

	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**	**B16**	**B17**	**B18**	**B19**	**B20**	**B21**	**B22**
B1	NI																					
B2		NI																				
B3			NI																			
B4				NI																		
B5					NI																	
B6						NI																
B7							NI															
B8								NI														
B9									NI													
B10										NI												
B11											NI											
B12												NI										
B13													NI									
B14														NI								
B15															NI							
B16																NI						
B17																	NI					
B18																		NI				
B19																			NI			
B20																				NI		
B21																					NI	
B22																						NI

Appendix B

Table A4. The consolidated input of the experts.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21	B22
B1	[0, 0]	[0, 0]	[2, 3]	[3, 4]	[0, 0]	[2, 3]	[3, 4]	[3, 4]	[2, 3]	[0, 0]	[0, 0]	[1, 2]	[0, 0]	[0, 0]	[0, 0]	[1, 2]	[2, 3]	[2, 3]	[0, 0]	[0, 1]	[0, 0]	[0, 1]
B2	[0, 0]	[0, 0]	[2, 3]	[3, 4]	[0, 0]	[2, 3]	[3, 4]	[0, 0]	[2, 3]	[0, 0]	[0, 0]	[1, 2]	[0, 0]	[0, 0]	[0, 0]	[1, 2]	[2, 3]	[2, 3]	[0, 0]	[0, 1]	[0, 0]	[0, 1]
B3	[0, 1]	[0, 1]	[0, 0]	[2, 3]	[0, 0]	[0, 0]	[1, 2]	[2, 3]	[0, 1]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 1]	[0, 1]	[0, 0]	[3, 4]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
B4	[3, 4]	[3, 4]	[0, 0]	[0, 0]	[0, 1]	[0, 1]	[2, 3]	[3, 4]	[2, 3]	[0, 1]	[0, 1]	[0, 0]	[3, 4]	[1, 2]	[1, 2]	[2, 3]	[1, 2]	[0, 0]	[0, 0]	[0, 1]	[1, 2]	[0, 1]
B5	[0, 1]	[0, 1]	[0, 0]	[1, 2]	[0, 0]	[2, 3]	[0, 1]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[1, 2]	[0, 0]	[0, 0]	[1, 2]	[2, 3]	[1, 2]
B6	[2, 3]	[2, 3]	[0, 0]	[2, 3]	[1, 2]	[0, 0]	[0, 1]	[0, 1]	[1, 2]	[0, 1]	[0, 1]	[0, 0]	[0, 1]	[0, 1]	[0, 1]	[1, 2]	[0, 1]	[2, 3]	[0, 0]	[1, 2]	[2, 3]	[0, 1]
B7	[3, 4]	[3, 4]	[1, 2]	[2, 3]	[0, 1]	[0, 1]	[0, 0]	[0, 1]	[1, 2]	[0, 1]	[0, 1]	[0, 0]	[0, 1]	[1, 2]	[1, 2]	[0, 1]	[0, 1]	[0, 1]	[0, 0]	[2, 3]	[0, 1]	[0, 1]
B8	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 1]	[0, 1]	[0, 0]	[1, 2]	[1, 2]	[1, 2]	[0, 1]	[2, 3]	[0, 0]	[0, 0]	[2, 3]	[0, 0]	[1, 2]
B9	[2, 3]	[2, 3]	[0, 0]	[2, 3]	[0, 1]	[3, 4]	[2, 3]	[0, 1]	[0, 0]	[2, 3]	[2, 3]	[0, 0]	[2, 3]	[2, 3]	[2, 3]	[0, 0]	[0, 1]	[2, 3]	[0, 0]	[2, 3]	[0, 0]	[2, 3]
B10	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[2, 3]	[2, 3]	[0, 1]	[0, 0]	[1, 2]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[1, 2]
B11	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[2, 3]	[0, 1]	[3, 4]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[1, 2]
B12	[1, 2]	[1, 2]	[0, 1]	[2, 3]	[0, 0]	[2, 3]	[2, 3]	[0, 0]	[1, 2]	[0, 1]	[0, 1]	[0, 0]	[1, 2]	[0, 1]	[0, 1]	[3, 4]	[3, 4]	[3, 4]	[0, 0]	[0, 0]	[0, 1]	[0, 1]
B13	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[1, 2]
B14	[0, 0]	[0, 0]	[0, 0]	[2, 3]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[3, 4]	[0, 1]	[0, 0]	[0, 1]	[0, 0]	[3, 4]	[0, 0]	[2, 3]	[0, 0]	[1, 2]	[0, 1]	[0, 0]	[0, 1]
B15	[0, 0]	[0, 0]	[0, 0]	[2, 3]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[3, 4]	[0, 1]	[0, 0]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[2, 3]	[0, 0]	[1, 2]	[0, 1]	[0, 0]	[0, 1]
B16	[2, 3]	[2, 3]	[0, 0]	[3, 4]	[2, 3]	[2, 3]	[2, 3]	[2, 3]	[1, 2]	[0, 1]	[0, 1]	[0, 0]	[1, 2]	[1, 2]	[1, 2]	[0, 0]	[1, 2]	[3, 4]	[0, 0]	[0, 1]	[0, 0]	[0, 1]
B17	[1, 2]	[1, 2]	[0, 0]	[1, 2]	[0, 0]	[0, 1]	[0, 1]	[0, 0]	[0, 0]	[0, 1]	[0, 1]	[3, 4]	[0, 0]	[2, 3]	[2, 3]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[2, 3]	[0, 0]	[0, 1]
B18	[3, 4]	[3, 4]	[0, 0]	[2, 3]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[1, 2]	[2, 3]	[0, 1]	[0, 1]	[1, 2]	[3, 4]	[0, 0]	[0, 0]	[1, 2]	[0, 0]	[0, 1]
B19	[0, 0]	[0, 0]	[0, 0]	[1, 2]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 0]	[1, 2]	[1, 2]	[0, 0]	[2, 3]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
B20	[0, 1]	[0, 1]	[0, 0]	[2, 3]	[0, 0]	[2, 3]	[1, 2]	[0, 0]	[0, 0]	[2, 3]	[2, 3]	[0, 0]	[1, 2]	[3, 4]	[3, 4]	[0, 1]	[1, 2]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
B21	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[3, 4]	[2, 3]	[0, 1]	[0, 0]	[1, 2]	[0, 0]	[0, 0]	[0, 0]	[1, 2]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]	[0, 0]
B22	[2, 3]	[2, 3]	[3, 4]	[1, 2]	[0, 0]	[1, 2]	[0, 1]	[0, 1]	[0, 1]	[1, 2]	[1, 2]	[0, 1]	[0, 0]	[1, 2]	[1, 2]	[0, 1]	[0, 1]	[0, 0]	[0, 0]	[0, 0]	[0, 1]	[0, 0]

Table A5. The normalized direct influence matrix $'X'$.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21	B22
B1	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.10, 0.08]	[0.00, 0.00]	[0.06, 0.06]	[0.10, 0.08]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.044]	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]
B2	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.10, 0.08]	[0.00, 0.00]	[0.06, 0.06]	[0.10, 0.08]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]
B3	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.06, 0.06]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.10, 0.08]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
B4	[0.10, 0.08]	[0.10, 0.08]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.06, 0.06]	[0.10, 0.08]	[0.06, 0.06]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.10, 0.08]	[0.03, 0.04]	[0.03, 0.04]	[0.06, 0.06]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.03, 0.04]	[0.00, 0.02]
B5	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.06, 0.06]	[0.03, 0.04]
B6	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.06, 0.06]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.02]	[0.03, 0.04]	[0.00, 0.02]	[0.06, 0.06]	[0.00, 0.00]	[0.03, 0.04]	[0.06, 0.06]	[0.00, 0.02]
B7	[0.10, 0.08]	[0.10, 0.08]	[0.03, 0.04]	[0.06, 0.06]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]	[0.03, 0.04]	[0.00, 0.04]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]	[0.03, 0.04]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.02]	[0.00, 0.02]
B8	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]	[0.03, 0.04]	[0.03, 0.04]	[0.00, 0.02]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.04]	[0.03, 0.04]
B9	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.02]	[0.10, 0.09]	[0.06, 0.06]	[0.00, 0.02]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.02]	[0.06, 0.06]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.06, 0.06]
B10	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.06, 0.06]	[0.10, 0.08]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]
B11	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.02]	[0.10, 0.08]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]
B12	[0.03, 0.04]	[0.03, 0.04]	[0.00, 0.02]	[0.06, 0.06]	[0.00, 0.00]	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.02]	[0.10, 0.08]	[0.10, 0.08]	[0.10, 0.08]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]
B13	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]
B14	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.10, 0.08]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.10, 0.08]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]
B15	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.10, 0.08]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]
B16	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.10, 0.08]	[0.06, 0.06]	[0.06, 0.06]	[0.06, 0.06]	[0.06, 0.06]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]	[0.03, 0.04]	[0.03, 0.04]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.02]
B17	[0.03, 0.04]	[0.03, 0.04]	[0.00, 0.0]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.02]	[0.10, 0.08]	[0.00, 0.00]	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.02]
B18	[0.10, 0.08]	[0.10, 0.08]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.06, 0.06]	[0.00, 0.02]	[0.00, 0.02]	[0.03, 0.04]	[0.10, 0.08]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.02]
B19	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]	[0.03, 0.04]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
B20	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.06, 0.06]	[0.00, 0.00]	[0.06, 0.06]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.06, 0.06]	[0.06, 0.06]	[0.00, 0.00]	[0.03, 0.04]	[0.10, 0.08]	[0.10, 0.08]	[0.00, 0.02]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
B21	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.10, 0.08]	[0.06, 0.06]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
B22	[0.06, 0.06]	[0.06, 0.06]	[0.10, 0.08]	[0.03, 0.04]	[0.00, 0.00]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.02]	[0.03, 0.04]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.00]	[0.03, 0.04]	[0.03, 0.04]	[0.00, 0.02]	[0.00, 0.02]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.02]	[0.00, 0.00]

Table A6. The total influence matrix $'O'$.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	[0.06, 0.07]	[0.06, 0.07]	[0.08, 0.08]	[0.16, 0.16]	[0.01, 0.02]	[0.09, 0.11]	[0.14, 0.13]	[0.02, 0.03]	[0.09, 0.10]	[0.01, 0.04]	[0.00, 0.03]
B2	[0.06, 0.07]	[0.06, 0.07]	[0.08, 0.08]	[0.16, 0.16]	[0.01, 0.02]	[0.09, 0.11]	[0.14, 0.13]	[0.02, 0.03]	[0.09, 0.10]	[0.01, 0.04]	[0.00, 0.03]
B3	[0.03, 0.06]	[0.03, 0.06]	[0.01, 0.01]	[0.09, 0.11]	[0.00, 0.01]	[0.01, 0.03]	[0.05, 0.07]	[0.07, 0.08]	[0.01, 0.05]	[0.00, 0.02]	[0.00, 0.02]
B4	[0.14, 0.13]	[0.14, 0.13]	[0.02, 0.03]	[0.07, 0.08]	[0.01, 0.04]	[0.04, 0.08]	[0.11, 0.12]	[0.11, 0.11]	[0.10, 0.11]	[0.02, 0.07]	[0.00, 0.06]
B5	[0.02, 0.05]	[0.02, 0.05]	[0.01, 0.02]	[0.05, 0.08]	[0.01, 0.02]	[0.08, 0.09]	[0.01, 0.09]	[0.01, 0.01]	[0.01, 0.05]	[0.01, 0.02]	[0.00, 0.02]
B6	[0.10, 0.11]	[0.10, 0.11]	[0.01, 0.02]	[0.11, 0.13]	[0.04, 0.06]	[0.03, 0.05]	[0.04, 0.07]	[0.02, 0.04]	[0.06, 0.08]	[0.01, 0.06]	[0.00, 0.05]
B7	[0.12, 0.13]	[0.12, 0.13]	[0.05, 0.07]	[0.12, 0.14]	[0.00, 0.04]	[0.03, 0.07]	[0.04, 0.05]	[0.02, 0.05]	[0.06, 0.08]	[0.02, 0.06]	[0.01, 0.05]
B8	[0.01, 0.02]	[0.01, 0.02]	[0.00, 0.01]	[0.02, 0.06]	[0.00, 0.01]	[0.01, 0.02]	[0.01, 0.04]	[0.00, 0.01]	[0.00, 0.02]	[0.02, 0.05]	[0.01, 0.04]
B9	[0.12, 0.12]	[0.12, 0.12]	[0.03, 0.03]	[0.14, 0.15]	[0.01, 0.04]	[0.13, 0.13]	[0.11, 0.12]	[0.02, 0.15]	[0.03, 0.05]	[0.09, 0.12]	[0.01, 0.10]
B10	[0.01, 0.02]	[0.01, 0.02]	[0.00, 0.01]	[0.01, 0.03]	[0.00, 0.03]	[0.00, 0.04]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.01, 0.02]	[0.00, 0.04]
B11	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.01, 0.02]	[0.00, 0.03]	[0.00, 0.03]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.01, 0.04]	[0.00, 0.01]
B12	[0.09, 0.11]	[0.09, 0.11]	[0.02, 0.05]	[0.13, 0.15]	[0.01, 0.03]	[0.10, 0.11]	[0.11, 0.12]	[0.02, 0.03]	[0.06, 0.09]	[0.01, 0.06]	[0.00, 0.05]
B13	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.03]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.03]	[0.00, 0.03]
B14	[0.01, 0.02]	[0.01, 0.02]	[0.00, 0.01]	[0.08, 0.09]	[0.00, 0.01]	[0.00, 0.02]	[0.01, 0.02]	[0.01, 0.01]	[0.01, 0.04]	[0.11, 0.11]	[0.00, 0.04]
B15	[0.01, 0.02]	[0.01, 0.02]	[0.00, 0.01]	[0.08, 0.09]	[0.00, 0.01]	[0.00, 0.02]	[0.01, 0.02]	[0.01, 0.01]	[0.01, 0.03]	[0.10, 0.10]	[0.00, 0.04]
B16	[0.11, 0.12]	[0.11, 0.12]	[0.02, 0.03]	[0.16, 0.16]	[0.07, 0.08]	[0.10, 0.11]	[0.10, 0.12]	[0.08, 0.09]	[0.06, 0.09]	[0.02, 0.07]	[0.00, 0.05]
B17	[0.05, 0.08]	[0.05, 0.08]	[0.01, 0.02]	[0.07, 0.10]	[0.00, 0.01]	[0.02, 0.06]	[0.03, 0.06]	[0.01, 0.02]	[0.02, 0.03]	[0.02, 0.06]	[0.00, 0.05]
B18	[0.13, 0.12]	[0.13, 0.12]	[0.02, 0.03]	[0.12, 0.13]	[0.01, 0.01]	[0.03, 0.04]	[0.04, 0.05]	[0.02, 0.02]	[0.03, 0.04]	[0.01, 0.03]	[0.00, 0.03]
B19	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.00]	[0.04, 0.05]	[0.00, 0.00]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.03]	[0.00, 0.01]	[0.03, 0.05]	[0.03, 0.05]
B20	[0.02, 0.06]	[0.02, 0.06]	[0.01, 0.01]	[0.10, 0.12]	[0.00, 0.02]	[0.07, 0.09]	[0.05, 0.07]	[0.01, 0.02]	[0.01, 0.03]	[0.09, 0.10]	[0.07, 0.09]
B21	[0.01, 0.02]	[0.01, 0.02]	[0.00, 0.01]	[0.02, 0.02]	[0.10, 0.09]	[0.08, 0.08]	[0.01, 0.04]	[0.00, 0.01]	[0.04, 0.06]	[0.00, 0.01]	[0.00, 0.01]
B22	[0.08, 0.10]	[0.08, 0.10]	[0.11, 0.10]	[0.07, 0.11]	[0.00, 0.02]	[0.05, 0.08]	[0.03, 0.07]	[0.02, 0.04]	[0.02, 0.06]	[0.04, 0.07]	[0.03, 0.06]

	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21	B22
B1	[0.05, 0.06]	[0.03, 0.05]	[0.03, 0.05]	[0.03, 0.05]	[0.06, 0.08]	[0.10, 0.12]	[0.10, 0.10]	[0.00, 00]	[0.03, 0.07]	[0.01, 0.02]	[0.01, 0.06]
B2	[0.05, 0.06]	[0.03, 0.05]	[0.03, 0.05]	[0.03, 0.05]	[0.06, 0.08]	[0.10, 0.12]	[0.10, 0.10]	[0.00, 00]	[0.03, 0.07]	[0.01, 0.02]	[0.01, 0.06]
B3	[0.01, 0.03]	[0.02, 0.03]	[0.01, 0.03]	[0.01, 0.05]	[0.01, 0.05]	[0.02, 0.04]	[0.10, 0.10]	[0.00, 0.00]	[0.01, 0.03]	[0.00, 0.01]	[0.00, 0.02]
B4	[0.02, 0.02]	[0.12, 0.13]	[0.06, 0.09]	[0.06, 0.10]	[0.08, 0.10]	[0.08, 0.11]	[0.03, 0.04]	[0.00, 0.01]	[0.03, 0.07]	[0.04, 0.06]	[0.01, 0.07]
B5	[0.01, 0.01]	[0.01, 0.05]	[0.01, 0.03]	[0.01, 0.03]	[0.01, 0.02]	[0.04, 0.07]	[0.01, 0.02]	[0.00, 0.05]	[0.04, 0.07]	[0.07, 0.08]	[0.03, 0.06]
B6	[0.01, 0.02]	[0.03, 0.07]	[0.02, 0.06]	[0.02, 0.07]	[0.05, 0.07]	[0.03, 0.08]	[0.09, 0.09]	[0.00, 0.01]	[0.05, 0.08]	[0.07, 0.08]	[0.01, 0.06]
B7	[0.01, 0.02]	[0.02, 0.07]	[0.05, 0.09]	[0.06, 0.09]	[0.02, 0.06]	[0.04, 0.08]	[0.03, 0.06]	[0.00, 0.01]	[0.08, 0.10]	[0.01, 0.04]	[0.01, 0.06]
B8	[0.01, 0.01]	[0.04, 0.06]	[0.05, 0.07]	[0.05, 0.08]	[0.00, 0.03]	[0.08, 0.09]	[0.00, 0.01]	[0.00, 0.01]	[0.07, 0.08]	[0.00, 0.01]	[0.03, 0.06]
B9	[0.02, 0.03]	[0.10, 0.12]	[0.10, 0.12]	[0.10, 0.13]	[0.03, 0.04]	[0.05, 0.10]	[0.09, 0.10]	[0.01, 0.01]	[0.09, 0.11]	[0.01, 0.02]	[0.07, 0.11]
B10	[0.00, 0.01]	[0.07, 0.08]	[0.10, 0.10]	[0.02, 0.05]	[0.00, 0.01]	[0.04, 0.06]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.04]	[0.00, 0.01]	[0.03, 0.06]
B11	[0.00, 0.01]	[0.07, 0.08]	[0.00, 0.04]	[0.10, 0.10]	[0.00, 0.01]	[0.01, 0.04]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.03]	[0.00, 0.01]	[0.03, 0.06]
B12	[0.02, 0.03]	[0.06, 0.10]	[0.03, 0.07]	[0.03, 0.08]	[0.12, 0.12]	[0.14, 0.15]	[0.12, 0.12]	[0.00, 0.01]	[0.03, 0.05]	[0.01, 0.04]	[0.01, 0.06]
B13	[0.00, 0.00]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.03]	[0.00, 0.01]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.03, 0.05]
B14	[0.01, 0.01]	[0.02, 0.05]	[0.02, 0.03]	[0.11, 0.11]	[0.01, 0.01]	[0.08, 0.09]	[0.00, 0.01]	[0.04, 0.05]	[0.01, 0.04]	[0.00, 0.01]	[0.01, 0.04]
B15	[0.01, 0.01]	[0.02, 0.05]	[0.02, 0.03]	[0.01, 0.03]	[0.01, 0.01]	[0.08, 0.08]	[0.00, 0.01]	[0.03, 0.01]	[0.01, 0.04]	[0.00, 0.01]	[0.00, 0.04]
B16	[0.01, 0.02]	[0.06, 0.09]	[0.06, 0.09]	[0.06, 0.10	[0.02, 0.04]	[0.07, 011]	[0.03, 0.03]	[0.00, 0.01]	[0.03, 0.07]	[0.02, 0.02]	[0.01, 0.06]
B17	[0.10, 0.10]	[0.02, 0.04]	[0.08, 0.10]	[0.09, 0.10]	[0.02, 0.03]	[0.04, 0.05]	[0.02, 0.03]	[0.01, 0.01]	[0.07, 0.09]	[0.00, 0.01]	[0.00, 0.05]
B18	[0.05, 0.07]	[0.09, 0.10]	[0.02, 0.06]	[0.03, 0.06]	[0.06, 0.08]	[0.13, 0.13]	[0.03, 0.03]	[0.00, 0.01]	[0.05, 0.07]	[0.01, 0.01]	[0.01, 0.05]
B19	[0.00, 0.00]	[0.07, 0.08]	[0.01, 0.01]	[0.01, 0.01]	[0.00, 0.01]	[0.00, 0.01]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.01]	[0.00, 0.00]	[0.00, 0.01]
B20	[0.01, 0.01]	[0.06, 0.08]	[0.12, 0.12]	[0.13, 0.13]	[0.01, 0.04]	[0.06, 0.09]	[0.01, 0.02]	[0.01, 0.01]	[0.01, 0.03]	[0.01, 0.01]	[0.01, 0.03]
B21	[0.00, 0.00]	[0.04, 0.06]	[0.01, 0.01]	[0.01, 0.01]	[0.00, 0.01]	[0.01, 0.02]	[0.01, 0.01]	[0.00, 0.02]	[0.01, 0.02]	[0.01, 0.01]	[0.01, 0.02]
B22	[0.01, 0.04]	[0.02, 0.04]	[0.04, 0.08]	[0.05, 0.08]	[0.01, 0.05]	[0.03, 0.07]	[0.03, 0.03]	[0.00, 0.01]	[0.01, 0.03]	[0.01, 0.03]	[0.00, 0.03]

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