Development of a Reliability, Maintenance, and Safety Model for Belt Conveyor Systems Using Structural Methodology

A Synopsis Submitted in Partial Fulfillment of the Requirements for the Award of the

Degree of

Doctor of Philosophy

In

MECHANICALENGINEERING

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March 2026

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1. Title of the thesis and abstract

Title of the thesis

Development of a Reliability, Maintenance, and Safety Model for Belt Conveyor System Using Structural Methodology

Abstract

Belt conveyor systems have become the primary means of transporting bulk materials across industries due to their reliability, flexibility, and capacity to handle large material inventories. Belt conveyor systems must be reliable, as any downtime results in wasted production time and costs. To keep a conveyor belt system safe and reliable throughout its lifespan, it must be maintained. Hence, the reliability, maintenance, and safety of belt conveyors are of ultimate importance. The trend toward outsourcing heavy equipment maintenance, including belt conveyor installations, is increasing. Owners and operators of such systems, on the other hand, face difficulties in finding a competent contractor to whom to outsource these maintenance services. This study proposes the development of frameworks for reliability assessment of belt conveyor systems, selection of a suitable contractor for maintenance outsourcing, and measurement of safety performance of belt conveyor installations.

The system reliability is also a function of several attributes. This study aims to develop a framework for deriving a reliability index based on the reliability attributes of the plant's design and operating conditions. Based on the literature review and interactions with plant professionals, five reliability attributes of belt conveyors have been identified. These interrelated attributes were modelled using a structural methodology based on graph theory and matrix approach (GTMA), enabling the computation of the belt conveyor system reliability index (BCSRI) and the corresponding belt conveyor system reliability index ratio (BCSRIR). The framework was applied to evaluate conveyor belt reliability at a sugar and a fertilizer plant. Sensitivity analysis revealed that the most significant factor contributing to the reliability index is the design of the conveyor belt system. The framework enables systematic diagnosis and targeted reliability enhancement strategies. The hydraulic direct drive system is one of the most critical components influencing the operational performance and reliability of belt conveyor systems. Failure of this component can result in complete system breakdown and substantial production losses. To address this issue, Failure Mode and Effects Analysis (FMEA) was conducted to identify potential failure modes and evaluate their impact on

system performance. The analysis helped identify critical components and propose preventive maintenance strategies to enhance system reliability and reduce downtime. Currently, maintenance activities for belt conveyor installations are often outsourced. There are numerous challenges in maintenance outsourcing. This research analyzed the challenges associated with outsourcing maintenance activities for belt conveyor systems. A hybrid decision-making methodology integrating Analytic Hierarchy Process (AHP) and PROMETHEE-II was employed to evaluate and select the most suitable maintenance contractor. Seven major evaluation criteria were identified, including financial health, organizational strength, service track record, maintenance service quality, personnel skills, tools and equipment support, and health, safety, and environmental practices. The proposed approach provides a systematic and transparent method for contractor selection.

In addition to reliability and maintenance, belt conveyor systems must be safe. Hence, developing a framework for measuring safety performance in belt conveyor systems is essential to ensuring plant safety. To this end, safety performance factors, including the design and operating contexts of belt conveyor systems, are identified. The factors, along with their interrelations, are modeled using a digraph. An equivalent matrix of the digraph yielded a safety performance function (SPF) for belt conveyor systems, thereby enabling the development of a safety performance index (SPI). The safety performance measurement framework was applied to evaluate the safety of belt conveyors at a sugar and a fertilizer plant. It will enable designers to evaluate and compare alternative conveyor system designs from a safety perspective. Plant operators can infer from the safety performance index (SPI) to identify weak contextual factors within the plant and develop action plans to mitigate them.

2. Brief description of the state of the art of the research topic

The reliability of conveyor belt systems depends not only on their design but also on appropriate system utilization [1]. The reliability characteristics of material handling equipment are affected by various attributes, including the operational environment, maintenance policies, and operator proficiency [2]. There will be interactions between system components and operational contextual attributes that are both structural and functional, and may significantly affect the evaluation of reliability [3]. This means reliability of belt conveyor systems encompasses structural relations that form the system design (SD) of the belt conveyor systems, along with the operating contextual attributes and their interconnections. For the analysis of structural and structural-type relationships, graph and directed graph (digraph) models are most suitable [4].

Outsourcing maintenance of belt conveyors is becoming increasingly common in today's mining industry. However, maintenance outsourcing for such safety-critical equipment, such as belt conveyors, is not straightforward. There are several challenges associated with the outsourcing of heavy equipment. Outsourcing maintenance services presents a range of challenges, including technical, managerial, economic, and legal issues [5]. According to the literature, there is no research on maintenance service outsourcing that addresses in depth the issues of service provider selection, appraisal, and performance measurement [6]. Additionally, many businesses faced operational challenges [7] as they sought to optimize their maintenance strategies and processes to transition to Industry 4.0. Moreover, no such studies are available in the field of belt conveyor maintenance. Consequently, identifying, evaluating, and selecting a suitable contractor for outsourcing maintenance activities among various alternatives is a challenging task for the owners and operators of belt conveyor installations.

Industries across the world have realized the social, economic, and environmental impact due to safety-related accidents and injuries [8], and industries are aimed at achieving zero incidents [9]. Hence, belt conveyors require a diligent approach across design, manufacture, installation, operation, and maintenance to ensure their safety [10]. Despite the safety risks associated with the operation and maintenance of belt conveyors, design standards do not address these risks, and tender specification documents do not quantify them [11]. However, no literature addresses how to ensure the safety of these machines during operation or how to measure their safety performance [12].

This necessitates the development of a multi-dimensional approach toward the analysis of belt conveyor safety performance. It was observed that operational contextual factors often compromise the system's inherent safety. Belt conveyor safety is determined by several factors, including design and operational context [13]. It can be envisaged that these factors are interrelated, i.e., the presence or absence of some factors affects the existence and intensity of others in varying degrees. The researcher argued that industrial safety is grounded in a socio-technical hierarchical system structure, governed by system elements such as design, management, the operational environment, controls, and regulations [7]. Moreover, the interactions among structural elements are also equally important [14]. Graph and directed graph (digraph) models are ideal for establishing the system structure, including structural relations [15]. Structural modelling of the safety performance factors of belt conveyor systems is achieved by the digraph model in this work. This, in conjunction with the matrix method, helped in the measurement of safety performance. This is achieved by evolving a safety performance index (SPI). The uniqueness of this work lies in considering design and operational contextual factors, including their structural interactions, in measuring safety performance.

2.1. Research Gap

The literature review provided insight into three broad areas: reliability, maintenance, and safety of belt conveyors, including the models and procedures applied. The following research gaps were identified in the context of belt conveyor systems.

- Work in reliability has not been performed for the belt conveyor system, considering both the design and contextual factors. There is a need for a better understanding of how to enhance and evaluate it for belt conveyor systems. For evaluation, considering both the design and contextual factors, including their mutual influences, should be investigated, which has not been explored. This can be modeled as a graph/digraph and, in conjunction with its corresponding matrix, can be used to develop a measure or index.
- Hydraulic direct drive is an important sub-system of belt conveyor systems. Hydraulic direct drives operate in harsh environments and are prone to failure. The failure of the hydraulic direct drive may contribute to the complete failure of the entire conveyor belt system. However, little work has been conducted on the FMEA analysis of hydraulic direct-drive belt conveyor systems. Hence, a suitable structural methodology can be employed for FMEA analysis of hydraulic direct-drive belt conveyor systems, accounting for the system structure.
- Heavy equipment maintenance is increasingly being outsourced nowadays, and belt conveyor installations are no exception. It is difficult for companies that own and operate these installations to find a qualified service provider to whom they can

outsource maintenance activities for belt conveyor installations. To the best of the researcher's knowledge, no significant work in this area has been conducted on the outsourcing of maintenance for belt conveyor systems. The integrated methodology can be used to establish a hierarchical structure of the challenges associated with outsourcing maintenance and their driver-dependent relationships.

- Industries across the world are striving for zero accidents because they have realized the social, economic, and environmental impact due to safety-related accidents and related injuries. Hence, belt conveyors require a diligent approach across design, manufacture, installation, operation, and maintenance to ensure their safety [10]. Despite the safety risks associated with the operation and maintenance of belt conveyors, design standards do not address these risks, and tender specification documents do not quantify them [11]. Conveyor design guidelines are available in the literature [16], along with safety guidelines [17]. However, no literature addresses how to ensure the safety of these machines during operation or how to measure their safety performance [12].This necessitates the development of a multi-dimensional approach toward the analysis of belt conveyor safety performance.

3. Definition of the Problem

Based on the above discussion, this research problem is formulated as follows: "Development of a reliability, maintenance, and safety model for belt conveyor systems using structural methodology".

4. Research objective and Scope of work

Sr.No	Research objectives	Research Activities
1	To develop reliability evaluation model for belt conveyor systems using structural methodology.	• Identification of reliability factors, including design and operational contextual factors. • Development of a framework for a reliability index by modeling reliability factors using a digraph and matrix.
2	To perform failure mode and effects analysis of hydraulic direct drives used in belt conveyor systems.	• Identification of failure modes of the hydraulic direct drive • Ranking of Failure Modes of the hydraulic direct drive using the hybrid approach of FAHP and FTOPSIS.

3	To identify and analyze challenges in the maintenance outsourcing of belt conveyor systems.	• Identification of challenges for maintenance outsourcing of the belt conveyor system. • Develop an integrated structural hierarchical framework of the identified challenges through Analytic Hierarchy Process (AHP) and Decision-Making Trial and Evaluation Laboratory (DEMATEL).
4	To develop a framework for contractor selection for outsourced maintenance services of belt conveyor systems.	• Identification of criteria and sub-criteria that affect the selection of maintenance contractors for belt conveyor systems. • Ranking of the selection criteria using AHP methodology and for selecting the best contractor among alternatives using PROMETHEE-II methodology.
5	To develop a quantitative framework for safety performance measurement of belt conveyor systems.	• Identification of safety factors, including design and operational contextual factors. • Development of a framework for safety performance measurement by modeling safety factors using a digraph and matrix.

5. Original Contribution by the Thesis

The key contributions of research work are outlined below.

- The proposed methodology of reliability evaluation is adaptable for broader industrial applications. It guides strategic maintenance planning, design improvements, and resource allocation to enhance reliability in belt conveyor systems.
- Failure mode and effects analysis of the hydraulic direct drive of the unit of the belt conveyor system installed at a 750MW thermal power station in western India has been performed. The findings of the analysis may help management and relevant personnel develop efficient and effective maintenance processes to prevent failure modes, particularly the most costly ones. As a result, the belt conveyor system would be more reliable and capable of operating continuously for longer periods.
- A comprehensive list of challenges and their prioritization in maintenance outsourcing of belt conveyor installations has been established. This will help organizations that own and operate these installations make judicious decisions regarding maintenance outsourcing.

- A framework for selecting the best contractor among alternatives is created. This will assist the organizations that own and operate these installations in making informed decisions about the hiring of suitable maintenance contractors.
- The developed framework for safety performance measurement will enable the designers to evaluate and compare alternative designs of conveyor systems from a safety viewpoint. Plant operators can infer from the SPI to identify weak contextual factors within the plant and develop action plans to mitigate them.

6. Methodology of Research, Results, and Discussion

6.1 Reliability and its index

Reliability modeling of belt conveyor systems requires a comprehensive analysis of the attributes that influence reliability and their interrelationships and dependencies. These influential traits were identified, and their structural interrelations can be efficiently modeled using graph-theoretic techniques. Digraph models are particularly effective for understanding the complex relationships within the system and for assessing the reliability of belt conveyor systems.

The reliability digraph is defined as R_d = (A, C), where A represents a set of nodes {A_1, A_2, A_3,…A_N}, and C is a set of edges {c_{ij}, ..., c_{NN}}, with *i* and *j* ranging from 1 to N. Nodes, such as A_1denote the first reliability attribute, while edges, for instance, c_{12}illustrate the influence of attribute one over two. The five reliability attributes identified include Fault Diagnosis (FD), Maintenance Practices (MP), Operating Environment (OE), Human Factors (HF), and System Design (SD). Each reliability attribute comprises multiple connected sub-attributes. These attributes serve as nodes in the reliability digraph. This is shown in Figure 1.

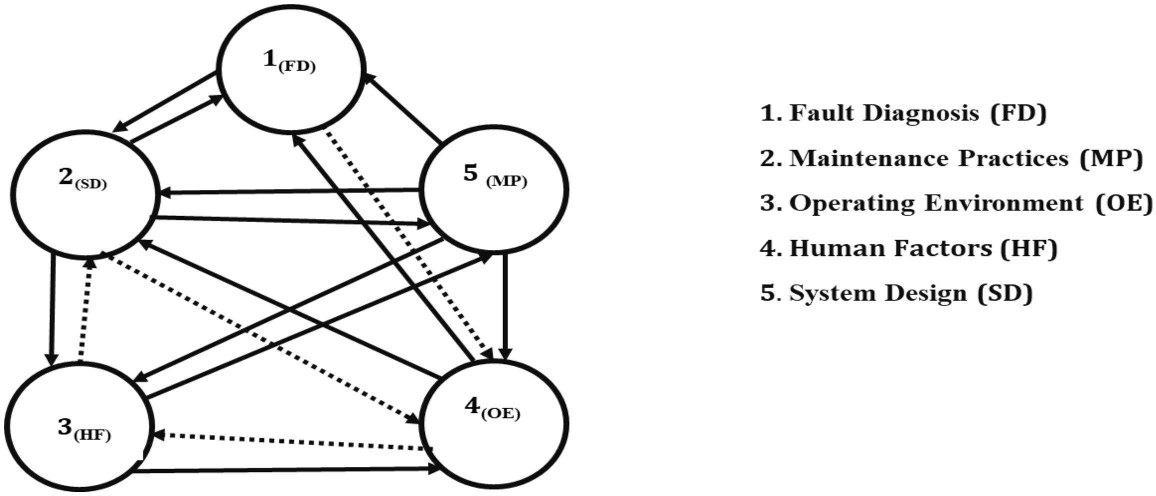

Figure: 1. Belt conveyor system reliability digraph

A one-to-one matrix derived from the digraph shown in Figure 1 is termed the belt conveyor system reliability matrix (B_R), which is shown in expression (1)

$$B_R=\begin{bmatrix} A_1 & c_{12} & 0 & c_{14} & 0 \\ c_{21} & A_2 & c_{23} & c_{24} & c_{25} \\ 0 & c_{32} & A_3 & c_{34} & c_{35} \\ c_{41} & c_{42} & c_{43} & A_4 & 0 \\ c_{51} & c_{52} & c_{53} & c_{54} & A_5 \end{bmatrix} \quad (1)$$

In the matrix expression (1), 'A_i' denotes the numerical value of the i^{th} reliability attribute, and 'c_{ij}' is the degree of interrelationships among attributes. The permanent of the above matrix is denoted as Per (B_R), which is called the belt conveyor system reliability function (BCSRF). BCSRF contains multiple invariant terms that encompass reliability aspects and interrelationships. Combinatorial mathematics characterizes the Permanent function as a standard matrix function [18], in which all terms are positive. The assessment of belt conveyor system reliability entails obtaining numerical values for both the diagonal elements, denoted as (A_i), and the non-diagonal elements, indicated as (c_{ij}), within the belt conveyor system reliability matrix. Ideal belt conveyor system reliability index (IBCSRI) signifies the utmost reliability attainable by any belt conveyor system. This is a scenario in which all sub-factors of the reliability attributes achieve their highest score.

The belt conveyor system reliability index ratio (BCSRIR) is

$$\text{BCSRIR} = \frac{\text{Belt Conveyor System Reliability Index(BCSRI)}}{\text{Ideal Belt Conveyor system Reliability index(IBCSRI)}}$$

An ideal scenario is denoted by BCSRIR, equaling "1". The BCSRIR value ranges from "0" to "1". Ideally, it should approach "1". A lower BCSRIR indicates areas for improvement in enhancing the reliability of the belt conveyor system.

A sensitivity analysis is required to assess the robustness of the proposed index. The sensitivity analysis is performed by varying the numerical values of the reliability factors, which correspond to the diagonal elements of the reliability matrix, and evaluating their impact on the reliability index.

6.1.1 Case study

To implement the above framework, an illustrative case study of a belt conveyor system in a sugar plant in western India has been considered. The belt conveyor handles a 50 kg sugar bag.The sugar bag transfer rate of 50 kg is 7,000 no. per 24 hours during the sugar cane crushing season. Walkways are provided inside the gallery on both sides of the conveyors for inspection and maintenance.The ambient temperature in the workplace ranges from 15° to 45°C. The conveyor is 110 metres long, and the belt width is 600 mm. The conveyor inclination is 30°, and the lift is 10 m. The conveyor is driven by three set shaft-mounted electric motors with couplings, and a helical gearbox is used for speed reduction. Each motor has a capacity of 5kW and a belt speed of 1.5 m/s. The idler spacing is 3 meters. A screw take-up at the tail end of the system is used to adjust belt tension.

The BCSRF is obtained from the permanent of the reliability matrix as Per B_R = 2485.11. Hence, the reliability index of the belt conveyor system of the sugar plant (BCSRI) is 2485.11

For determining the Ideal Belt Conveyor System Reliability Index (IBCSRI), an ideal belt conveyor system is to be assumed where all the reliability sub-attributes have their full score and obtained as Per $B_{R(ideal)}$ = 4180.81

Hence, the Ideal Belt Conveyor System Reliability Index (IBCSRI) =4180.81

The BCSRIR of the belt conveyor system SPC can now be evaluated as

BCSRIR= 2485.11/4180.81=0.594

6.1.2 Sensitivity Analysis

The sensitivity analysis of the BCSRI is performed to evaluate the influence of fluctuations in reliability attributes on the BCSRI. This will demonstrate the resilience of the proposed index across real-world applications. The percentage change in the BCSRI value is evaluated relative to the percentage change in the reliability attributes associated with each diagonal element of the equivalent matrix of the SPC reliability matrix. The scores for each reliability attribute are increased by 10%, and the resulting percentage change in the BCSRI for SPC is evaluated. The results of the sensitivity analysis are displayed in Table 1. Figure 2 depicts the percentage increase in the BCSRI corresponding to a 10% gain in attribute scores for each reliability attribute of SPC.

Table:1. Sensitivity analysis results

Sr. No	Reliability Attribute	% Increase in BCSRI for SPC
1	Fault Diagnosis (FD)	0.82
2	Maintenance Practices (MP)	0.317
3	Operating Environment (OE)	0.395
4	Human Factors (HF)	0.348
5	System Design (SD)	5.602

The graph illustrates that the BCSRI is sensitive to variations in reliability, indicating the model's resilience. Moreover, the model is clear, interpretable, and accessible to users.

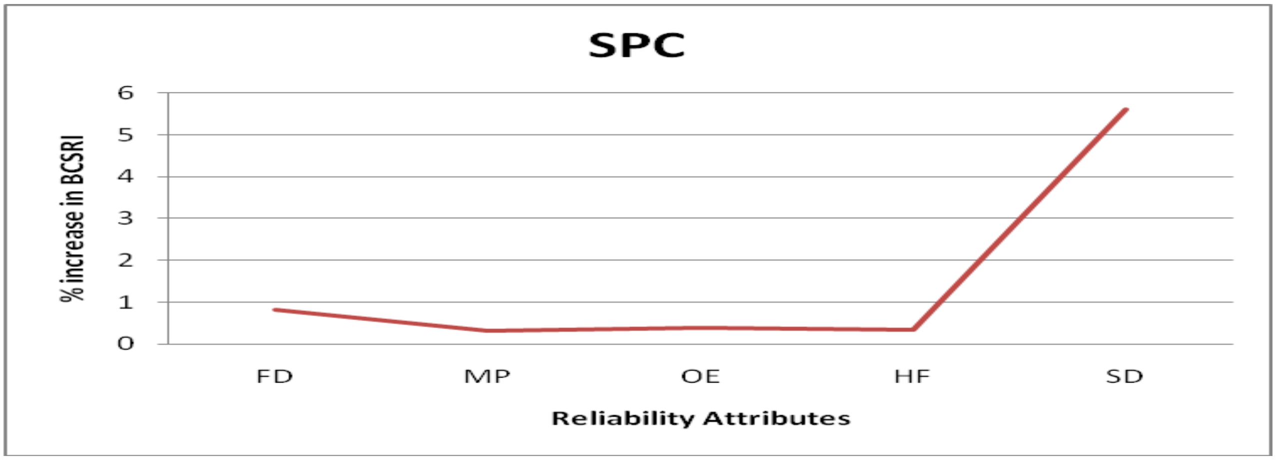

Figure: 2. Variation of BCSRI with variation of reliability attributes

6.1.3 Results and Discussions

The framework was applied to a sugar-plant belt-conveyor system handling sugar bags. The system's reliability attributes and sub-attributes were evaluated using expert scoring and AHP-based weightage assignment. The evaluated conveyor system reliability index for the Sugar plant conveyor was 2485.11, whereas the ideal index (IBCSRI) was 4180.81, yielding a BCSRIR of 0.59. These values reflect a moderate level of reliability, indicating room for improvement. Sensitivity analysis revealed that system design is the most significant factor in the reliability index, resulting in a 5.602 percentage increase in BCSRI and a 10% increase in SPC score. Other attributes showed comparatively lesser sensitivities. These insights suggest that investment in design enhancements such as modularity, control integration, and dynamic load management can significantly improve reliability outcomes.

6.2. FMEA of Hydraulic Direct Drive

FMEA of a hydraulic direct drive of a belt conveyor system, which is part of a thermal power plant, was performed by using the fuzzy-based MCDM techniques

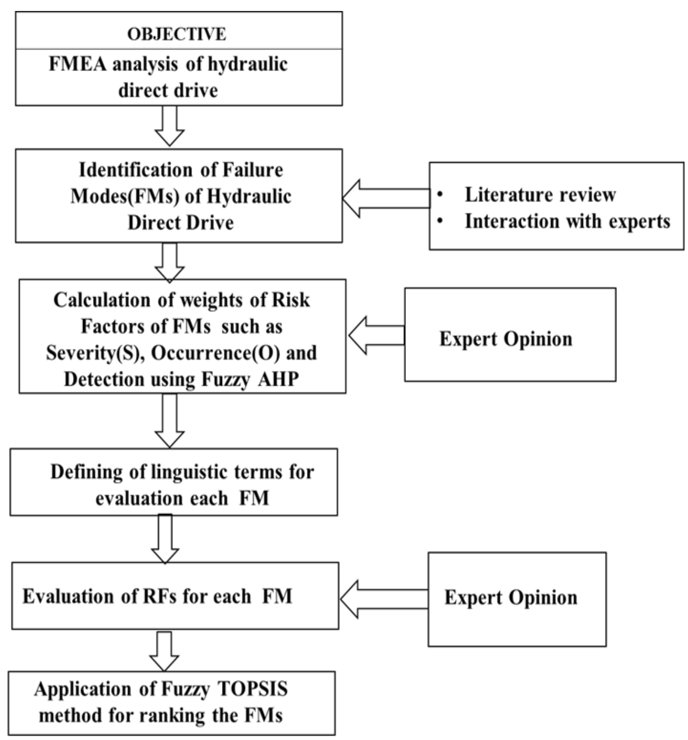

Figure:3. Methodology structure for FMEA of HDD

Based on expert consensus, eighteen potential failure modes (FMs) were identified for hydraulic direct drive.

Table: 2. Failure modes of hydraulic direct drive

Symbol	Failure Modes
FM1	Leakage in flex connections, pump and motor seals, and hydraulic system valves
FM2	Hydraulic filters choke up/clogged.
FM3	Hydraulic filter elements failure.
FM4	Low oil level in the system
FM5	A high temperature of oil above 65 degrees Celsius
FM6	A low temperature of the oil
FM7	High charge pressure
FM8	High case pressure of the hydraulic motor
FM9	The brake motor tripped
FM10	Radiator tripped
FM11	High case pressure of the pump
FM12	Unusual sound in the axial piston pump
FM13	Slow operation of the axial piston pump
FM14	Unusual sound in the hydraulic motor
FM15	Unusual sound in the gear pump
FM16	Slow operation of the gear pump
FM17	The direction control valve fails to operate properly.
FM18	The pressure relief valve fails to operate properly.

FAHP was first implemented to assign risk factor weights, followed by the use of fuzzy TOPSIS for prioritizing the various failure modes of hydraulic direct drive [19].

6.2.1. Sensitivity Analysis

The study's findings were checked for accuracy by sensitivity analysis (SA). The goal of sensitivity analysis (SA) is to identify which input variables are responsible for the observed uncertainty in the model's output [20]. One can assess the stability of the findings by examining how they change when inputs are modified. Sensitivity analysis can be conducted in several ways, some of which have been described in the literature. Here, we use the incremental percent change (IPC) to adjust the importance of the most heavily weighted risk factor (RF) and then analyze the effect on the rankings. This analysis employed a ±5% IPC, meaning that weights are varied by 5% in each sensitivity run. The relative importance of the other RFs was also adjusted so that their weights summed to 1, satisfying the additive constraint. In the sensitivity runs, FM5 ranks first, and FM4 ranks sixteenth. The alterations to the RF weights have also caused minor shifts in the rankings of the other FMs. Therefore, the

FM ranks are reliable.

6.2.2. Result and Discussion

In thermal power plants, uninterrupted coal feeding is required in the boiler to generate electric power. The belt conveyor system is used to feed coal, and the hydraulic direct drive is a crucial component of the system. To ensure uninterrupted hydraulic direct drive (HDD) operation, it is necessary to identify the failure modes (FMs) that lead to HDD failure and to evaluate the relevance of each mode to overall plant failure.

The following are the major findings of the current study.

- It can be observed that ‘High temperature of oil’ (FM5) and ‘Radiator tripped.’ (FM10) are the most and least critical FMs, with rankings of 1 and 18, respectively.
- The FMs are listed in descending order of severity. FM5 > FM10 > FM8 > FM11> FM7 >FM9 > FM15 > FM12 > FM17> FM14 > FM18> FM16 > FM1 > FM2 > FM3 > FM4 >FM13> FM6

The rankings of the FMs produced in this study may help assess the relative seriousness of the various FMs of the HDD. This study may help management and relevant personnel develop efficient and effective maintenance processes to avoid failures, particularly the most expensive ones. As a result, the belt conveyor system would be more reliable and capable of operating continuously for longer periods.

6.3. Analysis of outsourced maintenance services challenges

It is recommended that an integrated hybrid technique combining AHP and DEMATEL be used to analyze the relative weights of challenges and define their interrelationships. The AHP helps in determining which challenges are most important. The DEMATEL method helps identify interconnections among challenges by classifying them according to their causes and effects [21] [22]. This research employs a combination of the AHP and DEMATEL methods.

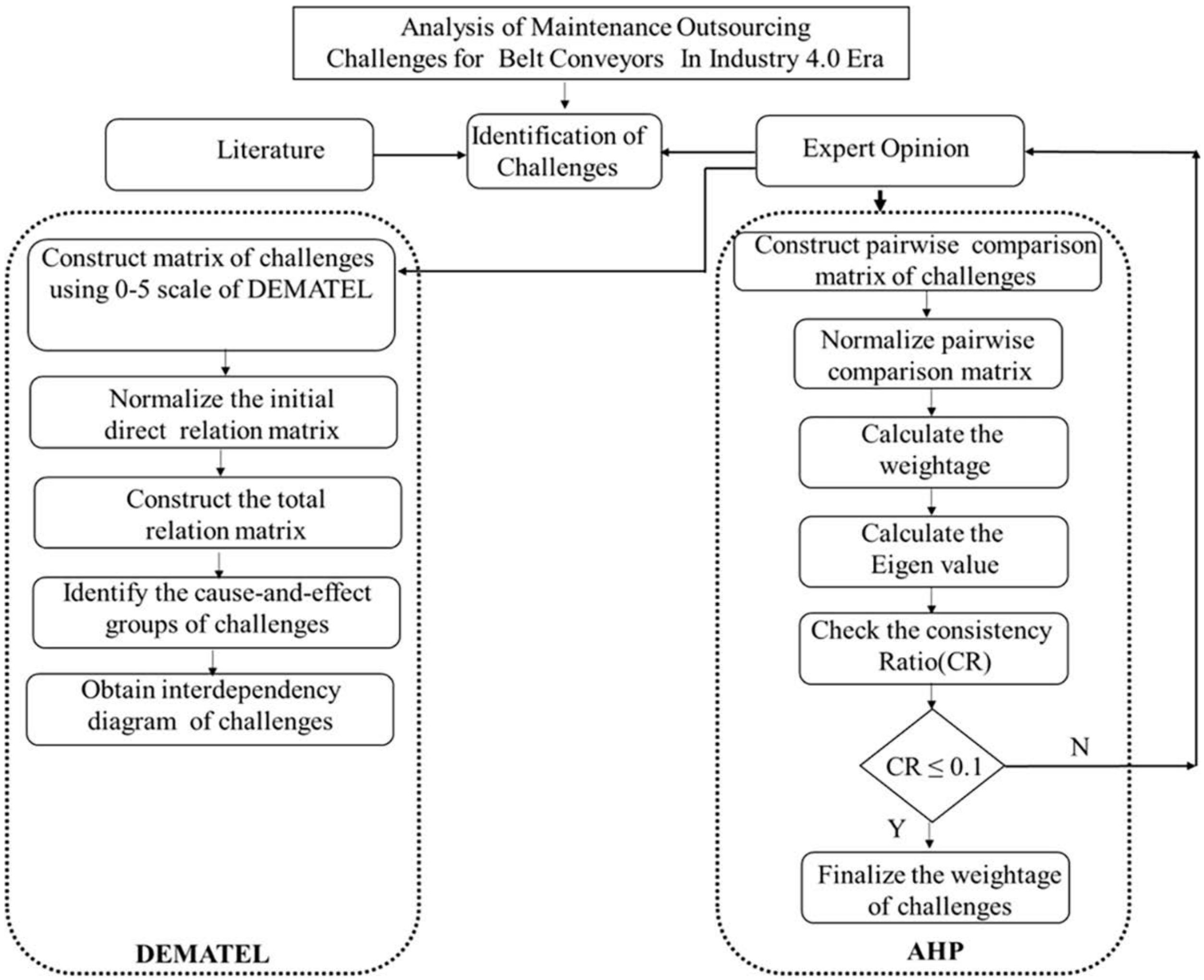

Figure: 4. Methodology Framework for Analysis of Outsourced Maintenance Service Challenges

The study has identified eight challenges, namely, attainment of organizational strength by contractors, legal and financial challenges for contractors, attainment of necessary technician skills by contractors, maintenance data acquisition and analysis challenges, facilitation with modern equipment, gadgets, and instrumentation, service quality challenges, health, safety, and environment-related challenges, and spares supply chain management challenges.

The segregation of driver and dependent challenges, including their hierarchical framework, has been established in this work.

Table: 3. Challenges in maintenance outsourcing of belt conveyors

Sr. no.	Challenges	Notation
1	Attainment of organizational strength by contractors	MOC1
2	Legal and financial challenges for contractors	MOC2
3	Attainment of necessary technician skills by contractors	MOC3
4	Maintenance data acquisition and analysis challenges	MOC4
5	Facilitation with modern equipment, gadgets, and instrumentation	MOC5
6	Service quality challenges	MOC6
7	HSE-related challenges	MOC7
8	Spares supply chain management challenges	MOC8

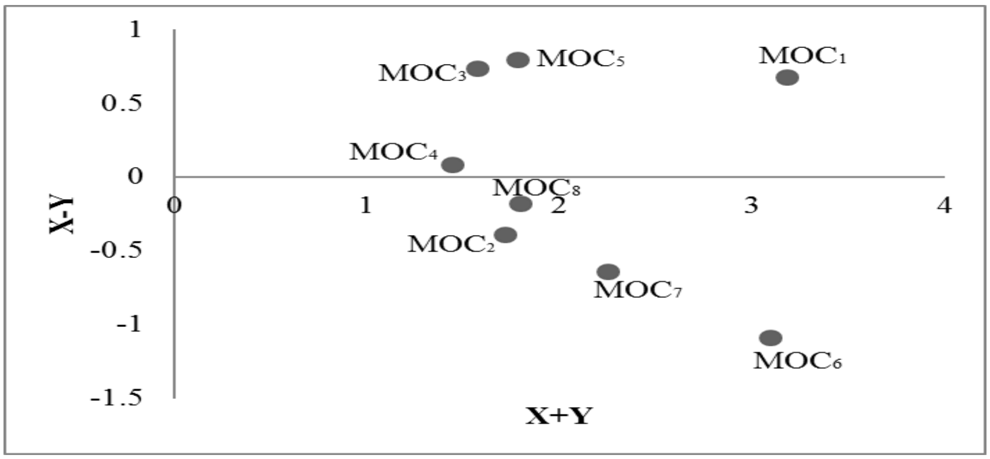

Figure: 5. Cause-and-Effect diagram of challenges

6.3.1. Result and Discussion

According to Figure 5, the strongest and most sought-after "Cause" to drive the challenges in maintenance outsourcing of belt conveyor installations in the era of I4.0 is "Facilitation with modern equipment, gadgets, and instrumentation (MOC5)". The AHP ranking for this challenge is three with a weightage of 15%. The challenge "Attainment of necessary technician skills by contractors" ranks second in the CE ranking for the "Cause" category. The AHP ranking of this challenge is also second. The challenge of achieving organizational strength by contractors (MOC1) ranked highest in the AHP analysis, with 32% of the weightage, and the DEMATEL study placed it in the "Cause" category with a CE ranking of 3**.** According to the results, the prominent challenge in the cause category is Facilitation with modern equipment, gadgets, and instrumentation (MOC5). This indicates that failure to address this challenge will have a cascading effect on the proliferation of other challenges. This is because the 4.0 regime requires greater sophistication across all operations, thereby making the need for modern equipment, devices, and instrumentation for condition monitoring highly justifiable. Hence, maintenance contractors need to procure and use modern equipment, devices, and tools. The second challenge in the cause category was "Attainment of necessary technician skills by contractors". This was a serious concern raised by every conveyor operator. There was a common observation made by the conveyor operators that their existing maintenance crew was reluctant to adapt to modern maintenance practices and was not enthusiastic about attending training on these. As maintenance in the I4.0 regime requires a more sophisticated approach from technicians, inefficiencies in the in-house maintenance crew would constitute a bottleneck that could pave the way for outsourcing. However, the maintenance contractor needs to recruit people with the latest technical knowledge and skills and train them adequately. Attainment of organizational strength by contractors was ranked third in the cause category. It is quite natural that demonstrated track record and reputation, demonstrated manpower, financial stability, an established level of commitment and professionalism, well-documented procedures, and the use of current project management tools. etc., which constitutes the organizational strengths of a contractor, must be strong for any maintenance service firm to secure the contract. Maintenance data acquisition and analysis challenges were the fourth ones in the cause category. Data acquisition and analysis is the cornerstone activities in PdM in the I4.0 environment. The data acquisition and its analysis are also crucial, as without them, the future course of actions from the maintenance point of view, especially in the case of a maintenance contract, could be difficult to execute.

6.4. Development of a framework for contractor selection for outsourced maintenance services

It is difficult to outsource the maintenance of safety-critical equipment like belt conveyors as outsourcing heavy machinery comes with a slew of difficulties. Technical, managerial, economic, and even legal concerns might arise when a company outsources maintenance services [5]. To maximize the potential benefits and limit the dangers of outsourcing policies, it is crucial to choose the correct contractor[23] and, hence, finding, evaluating, and selecting a suitable contractor for outsourcing the maintenance activities from various alternative options is a challenging task [5] for the owners and operators of belt conveyor installations. Selection of the best contractor among several competing contractors constitutes a multi-criteria decision-making problem that requires evaluating the available alternatives against appropriate criteria. This study proposed a decision-making framework that comprised the implementation of a hybrid MCDM approach (AHP-PROMETHEE-II) and demonstrated its application in selecting the best contractor to provide maintenance services for the belt conveyor installation of a thermal power plant. Consequently, this study considered the seven most suitable selection criteria including financial health, organizational strength, service track record, maintenance service quality, personal skills, tools and equipment support and health, safety, and environment and determined their weights, reflecting their importance, using the AHP method [23] and subsequently, ranked the competing contractors using the PROMETHEE-II method[24][25][26][27].

6.4.1. Result and Discussion

The proposed methodology is applied to select maintenance contractors for belt conveyors at a 2270 MW thermal power station in Western India. There are four potential contractors designated as C1, C2, C3, and C4, and the power plant management must select the best contractor from the alternatives. The results of the study are presented in Table 5.

Table: 4. Net outranking flows and Ranks of Alternatives

Net outranking flows and Ranks of Alternatives				
	$\Phi+$	$\Phi-$	$\Phi(x)$	Rank
C_1	0.547	0.106	0.653	1
C_2	0.232	0.230	0.463	3
C_3	0.067	0.553	0.620	2
C_4	0.224	0.179	0.404	4

The significance of this study is that it presents a framework to assist belt conveyor operators in selecting appropriate maintenance contractors to perform maintenance tasks efficiently, within stipulated timeframes, at minimum cost. The proposed framework encompasses selection of the criteria and sub-criteria for contractors' assessment that includes economic factors to guarantee cost-effectiveness and financial stability, organizational robustness for evaluating management systems and resource capabilities, service history for determining reliability based on previous performance maintenance service quality to measure compliance with service standards, technician competencies that reflect the technical and cognitive skills of contractor personnel, tools and equipment support to ensure access to contemporary tools and diagnostic systems and health, safety, and environment (HSE) practices emphasizing regulatory compliance and sustainability. This study emphasizes that addressing the challenges of adapting to technological advancements involves assessing readiness for predictive maintenance and contemporary tools, while managing risks associated with outsourced maintenance can be addressed through targeted initiatives focused on economic, environmental, and safety safeguards. The present study is particularly relevant to Industry 4.0 adaptation, which recognizes the need for contemporary contractors to be adept at innovative technologies such as IoT, predictive maintenance, and data analytics, in accordance with Industry 4.0 standards. The proposed framework illustrates adaptability in application through a case study tailored to thermal power plant operations. The framework mitigates risks associated with financial instability, safety violations, or service inefficiencies by assessing contractors against specific sub-criteria, such as punishment policies and environmental standards.

For managerial implications, decision-makers may find this study useful in addressing the problem of contractor selection by implementing clearly defined and prioritized evaluation criteria. Furthermore, they may address the issue of ensuring contractor reliability by integrating contractor track records and evaluations of organizational robustness. In addition, the findings of this study may inform decision-makers in formulating a strategic, systematic, and adaptable framework for belt conveyor operators, thereby enhancing their capacity to make informed, successful decisions regarding outsourced maintenance services.

6.5. Development of a framework for safety performance measurement

Safety performance modelling of belt conveyor systems requires identifying the factors that influence safety and their interrelationships. Modelling of these safety performance factors and their structural interrelations is feasible using a graph-theoretical approach via a digraph model. The digraph model is best suited for assimilating interrelationships among factors [15][28]. The nodes of the safety performance digraph are the safety performance factors, which are already identified. These include System Design (SD), Installation Accuracy (IA), Management Practices (MP), Operating Practices (OP), Human Factors (HF), Operating Environment (OE), and Maintenance System (MS). The mutual interrelationships/interactions among these seven factors are depicted by the edges in the safety performance digraph.

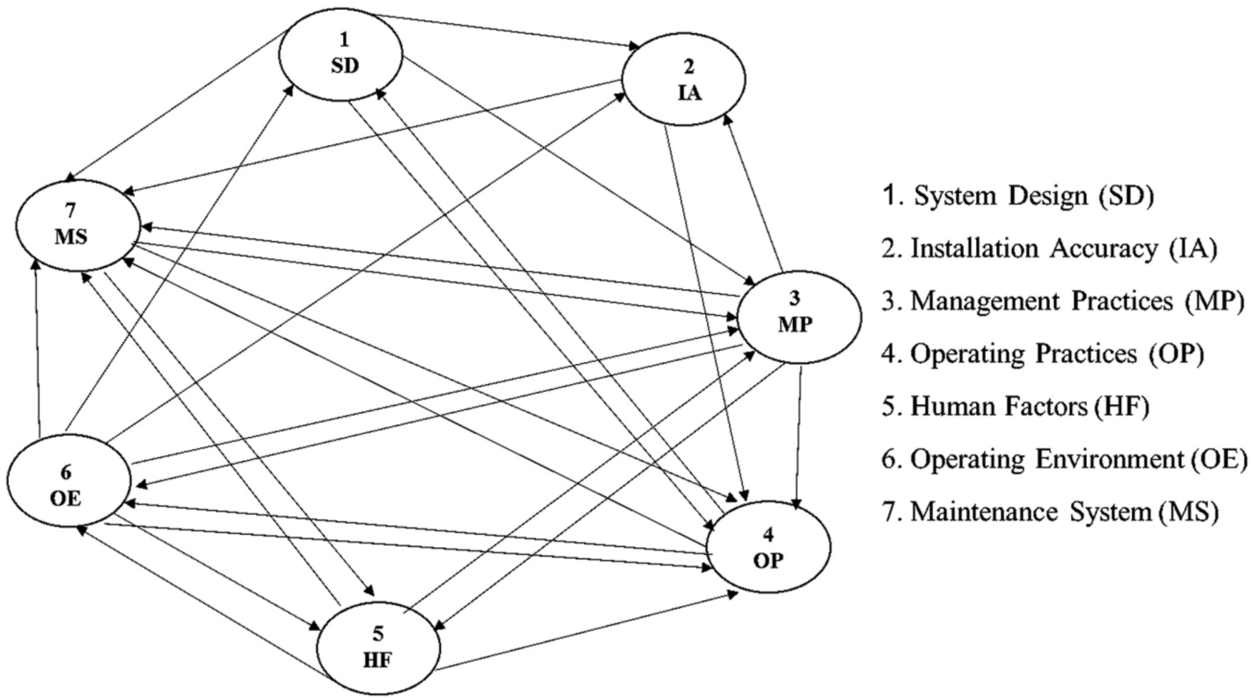

Figure:6. Safety performance digraph of the belt conveyor system

A matrix equivalent to the digraph is to be generated for analysis. The permanent of the equivalent matrix is titled as the safety performance function (SPF) of the belt conveyor system. The SPF consists of invariant terms of safety performance factors and their mutual influences. Combinatorial mathematics defines the permanent as a standard matrix function [18] that consists only of positive terms. The positive nullity of the digraph is best demonstrated through the permanent of a square matrix. Safety performance index (SPI) of a belt conveyor is a quantitative measurement of the safety performance of a belt conveyor system functioning in a plant or a site. This has evolved from the SPF. A higher value of this index indicates better safety performance for the belt conveyor system.

The numerical value of SPI can be large and, at some point, even unreasonable depending on the chosen scale; however, this can be addressed by introducing the ideal safety performance index (ISPI) and the safety performance index ratio (SPIR) for belt conveyor systems. The ideal is a belt conveyor system that is as safe as possible, with all safety performance factors in place. In such a situation, the score for all sub-factors attains its maximum value. The ratio of the safety index of a belt conveyor system (SPI) to the safety index of an ideal belt conveyor system (ISPI) is SPIR =SPI/ISPI.

If the SPIR value reaches “1”, it is slated to be an ideal condition. The SPIR ranges between “0” and “1”. A value closer to unity is expected from an engineering perspective to ensure maximum safety.

6.5.1. Case study

The developed model is used to measure the safety performance of a belt conveyor system in a fertilizer plant in western India. The conveyor system consists of two belt conveyors. Both the conveyors carry rock phosphate, which is unloaded from the ship onto the first conveyor on the wharf at certain elevations. The first conveyor, with a horizontal length of 70 m, transports material out of the wharf and transfers it to another large conveyor, which transports material into the storage silo. The horizontal length of the large conveyor is 127 m.

The SPF for the conveyor “B” is obtained from the permanent matrix “S_{DB}.”

$$S_{DB}=\begin{bmatrix} 2.623 & 0.75 & 0.75 & 1 & 0 & 0 & 1 \\ 0 & 0.075 & 0 & 0.75 & 0 & 0 & 0.75 \\ 0 & 0.75 & 0.142 & 1 & 1 & 0.5 & 0.75 \\ 0.75 & 0 & 0 & 0.145 & 0 & 0.25 & 1 \\ 0 & 0 & 0.75 & 0.75 & 0.295 & 0.25 & 1 \\ 1 & 0.5 & 0.5 & 1 & 0.75 & 0.215 & 1 \\ 0 & 0 & 0.5 & 1 & 0.5 & 0 & 0.509 \end{bmatrix}$$

- Per (S_{DB}) = 7.278
- i.e., safety performance index (SPI) of conveyor ‘B’ =7.278

Safety performance index (SPI) of conveyor “B” is 7.278.

Calculate the safety performance index of an ideal belt conveyor system, where all safety performance factors are expected to gain the highest score in their evaluation of all its sub-factors.

Per $S_{D\ ideal}$ = 11:835

i.e., Ideal safety performance index (ISPI) = 11.835.

The SPI ratio for conveyor “B”, i.e., SPIRB, is

SPIRB = SPI of conveyor B/ISPI of conveyor = 7:278/11:835 =0:614

6.5.2. Sensitivity analysis

Sensitivity analysis needs to be conducted to ensure the robustness of the proposed safety performance measurement index, SPI. Additionally, it can be used for comparing the effects of deviations in one or more input variables of a mathematical model on the output. The deviation in a variable can be either positive or negative. It is typically adopted in models implemented for decision-making. In this work, a generic method for examining factor sensitivity is utilized. A feasible range of deviations in the safety performance factors is specified as a bounded set of discrete 10% changes from the base-run value. A series of evaluations is performed by altering the scores of the safety performance factors, which are the diagonal elements of the safety performance matrix, one at a time, and observing their impact on the SPI. The percentage change in both the output and input is computed

Table 5. Result of sensitivity analysis of Fertilizer Plant Belt Conveyor

Sr.No	Safety Factors	% Change in SPI
1	System Design (SD)	4.61
2	Installation Accuracy (IA)	1.50
3	Management Practices (MP)	0.29
4	Operating Procedures (OP)	0.29
5	Human Factors(HF)	1.36
6	Operating Environment(OE)	1.09
7	Maintenance System(MS)	0.89

The graph illustrates that the SPI is sensitive to variations in Safety Performance, indicating the model's resilience. Moreover, the model is clear, interpretable, and accessible to users.

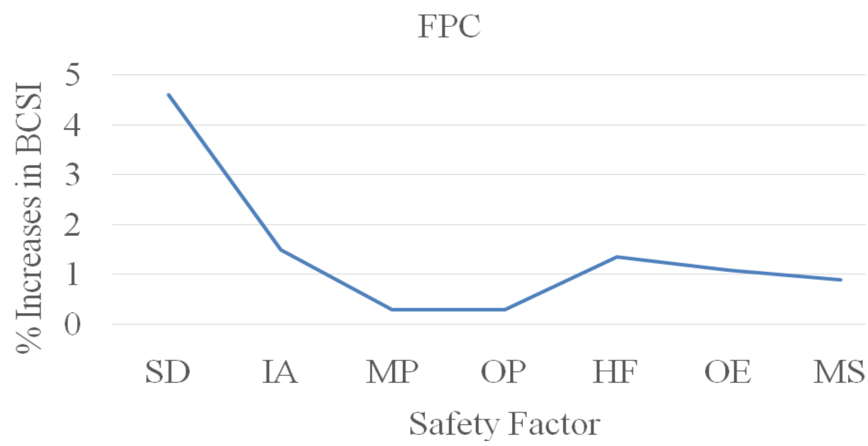

Figure: 7. Sensitivity Analysis of Fertilizer Plant Belt Conveyor

6.5.3. Result and Discussion

A threshold value, "SPIR," is proposed by the team of experts to guide conveyor operators in taking necessary corrective actions to enhance safety performance. A threshold of 60% or below is considered dangerous and requires serious interventions, such as system upgrade, repair, or overhaul. A threshold value between 60 and 70% is deemed to be satisfactory; 70–80% is considered good, and above 80% is excellent. In the case study, the SPIR of the belt conveyor system is found to be 0.614, which is nearly 62% of the expected value of "1". This indicates that the safety performance of conveyor system "B" is satisfactory but can be improved. This requires serious introspection from the conveyor operators. The sensitivity analysis revealed that an immediate safety improvement for belt conveyor "B" can be achieved by strengthening its system design. Since the conveyor belt is an old installation, suitable retrofitting may be required for installing contemporary electronic safety devices. Although the impact of installation accuracy is high, reinstalling the entire system is practically infeasible. Other practicable solutions for safety improvement include analysis of human factors and their enhancement, and improvements in the operating environment through proper guarding of the worksite and housekeeping of the area. Maintenance practices can also be reviewed for improvement.

7. Achievement with respect to Objectives

The following deliverables were identified in line with the research objectives.

- A framework for the evaluation of the reliability of the belt conveyor system is developed and applied to evaluate the belt conveyor reliability of a fertilizer plant and a sugar plant.
- Failure mode and effects analysis of the hydraulic direct drive of the unit of the belt conveyor system installed at a 750MW thermal power station in western India. Operators of belt conveyor installations can use the results for designing the preventive maintenance programs for critical components of the hydraulic direct drive
- An integrated structural hierarchical framework of the identified challenges is developed through the analytic hierarchy process and the decision-making trial and evaluation laboratory. The segregation of driver and dependent challenges, including their hierarchical framework, has been established in this work. This study will lead to the development of frameworks for maintenance contractor selection for such installations
- A structural methodology developed for the selection of the best contractor among alternatives for the maintenance of the conveyor belt system and applied to select a contractor for maintenance of the belt conveyor at Thermal Power Plant.
- A framework for the evaluation of the safety of belt conveyor systems is developed and applied to evaluate the belt conveyor safety of a fertilizer plant and a sugar plant.

8. Conclusion

Belt conveyor systems play a vital role in the transportation of bulk materials across various industries. The reliability, maintenance efficiency, and safety of these systems are essential for ensuring uninterrupted plant operations and minimizing production losses. This study focused on developing systematic frameworks to evaluate the reliability of belt conveyor systems, assist in the selection of suitable contractors for maintenance outsourcing, and measure the safety performance of belt conveyor installations.

A reliability assessment framework based on reliability attributes related to the design and operating conditions of belt conveyor systems was developed. Using the Graph Theory and Matrix Approach (GTMA), the Belt Conveyor System Reliability Index (BCSRI) and Belt

Conveyor System Reliability Index Ratio (BCSRIR) were computed. The application of the framework to conveyor systems in sugar and fertilizer plants demonstrated its effectiveness in identifying reliability-related issues. Sensitivity analysis highlighted that the design of the conveyor system is the most significant factor influencing overall system reliability. The framework provides a structured approach for diagnosing system weaknesses and implementing targeted reliability improvement measures.

The study also emphasized the importance of critical components such as the hydraulic direct drive system, whose failure can lead to complete system breakdown. Failure Mode and Effects Analysis (FMEA) was conducted to identify potential failure modes and their impact on system performance. The analysis enabled the identification of critical risk areas and supported the development of preventive maintenance strategies to enhance system reliability and reduce downtime.

In addition, the research addressed the challenges associated with outsourcing maintenance activities for belt conveyor systems. A hybrid decision-making methodology integrating Analytic Hierarchy Process (AHP) and PROMETHEE-II was employed to evaluate and select the most suitable maintenance contractor. Seven major evaluation criteria were identified, including financial health, organizational strength, service track record, maintenance service quality, personnel skills, tools and equipment support, and health, safety, and environmental practices. The proposed approach provides a systematic and transparent method for contractor selection.

Furthermore, a framework for measuring safety performance in belt conveyor systems was developed using a digraph-based modeling approach. The Safety Performance Function (SPF) and Safety Performance Index (SPI) were derived to evaluate the safety status of conveyor systems. The framework enables plant designers and operators to assess safety performance, identify weak contextual factors, and implement corrective actions to improve overall plant safety.

Overall, the frameworks developed in this study provide practical tools for improving the reliability, maintenance management, contractor selection process, and safety performance of belt conveyor systems. The results of this research contribute to enhanced operational efficiency, reduced downtime, improved maintenance decision-making, and safer industrial operations.

9. Publications

1. N.J.Parmar, Ajith Tom James (2021). Development of a framework for safety performance measurement of belt conveyor systems, International Journal of Productivity and Performance Management, Vol. 72 No. 4, pp. 1001-1024 (Web of Science)
2. N.J.Parmar, Ajith Tom James, Mohammad Asjad (2023). Analysis of maintenance outsourcing challenges for belt conveyors in the Industry 4.0 era, Journal of Global Operations and Strategic Sourcing, Vol. 16 No. 3, pp. 718-744 (Web of Science)
3. N.J.Parmar, Ajith Tom James, Mohammad Asjad, Zahid A Khan (2025). Development of a framework for contractor selection for outsourced maintenance services of belt conveyor installations, International Journal of Quality and Reliability Management, Vol.43 No.26, pp.761-783. (Web of Science).

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