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

A Thesis Submitted to Gujarat Technological University

for the Award of the Degree of

Doctor of Philosophy

in

MECHANICAL ENGINEERING

by

Narendrasinh Jesangbhai Parmar

Enrollment No.: 189999919030

under the supervision of

Dr. Ajith Tom James

GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

September 2026

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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 the reliability assessment of belt conveyor systems, the selection of a suitable contractor for maintenance outsourcing, and the measurement of the 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 plant. Sensitivity analysis revealed that the most significant factor contributing to the reliability index is the system 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 proposes 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 ata 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.

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Narendrasinh J. Parmar

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List of Abbreviations

Sr. No.	Abbreviation	Full Form
1	FMEA	Failure Mode and Effects Analysis
2	FM	Failure Mode
3	RPN	Risk Priority Number
4	S	Severity
5	O	Occurrence
6	D	Detection
7	CM	Corrective Maintenance
8	PM	Preventive Maintenance
9	PdM	Predictive Maintenance
10	TAM	Turnaround Maintenance
11	IoT	Internet of Things
12	IIoT	Industrial Internet of Things
13	RFID	Radio Frequency Identification
14	CPS	Cyber-Physical System
15	AR	Augmented Reality
16	RUL	Remaining Useful Life
17	MSC	Maintenance Service Contract
18	AHP	Analytic Hierarchy Process
19	DEMATEL	Decision-Making Trial and Evaluation Laboratory
20	PROMETHEE-II	Preference Ranking Organization Method for Enrichment Evaluation II
21	FAHP	Fuzzy Analytic Hierarchy Process
22	FTOPSIS	Fuzzy Technique for Order Preference by Similarity to Ideal Solution
23	TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
24	MARCOS	Measurement of Alternatives and Ranking by Compromise Solution
25	MULTIMOORA	Multi-Objective Optimization by Ratio Analysis plus Full Multiplicative Form
26	VIKOR	VlseKriterijumska Optimizacija I Kompromisno

		Resenje
27	FBWM	Fuzzy Best-Worst Method
28	FBN	Fuzzy Bayesian Network
29	PF	Pythagorean Fuzzy
30	Z-MOORA	Z-number Multi-Objective Optimization on the Basis of Ratio Analysis
31	CNC	Computer Numerical Control
32	MTTR	Mean Time to Repair
33	MTBF	Mean Time Between Failures
34	MTTF	Mean Time to Failure
35	ISO	International Organization for Standardization
36	IEC	International Electrotechnical Commission
37	HSE	Health, Safety and Environment
38	SPM	Safety Performance Measurement
39	SPI	Safety Performance Index
40	SPF	Safety Performance Function
41	SIL	Safety Integrity Level
42	OS&H	Occupational Safety and Health
43	GTMA	Graph Theory and Matrix Approach
44	BCSRI	Belt Conveyor System Reliability Index
45	BCSRIR	Belt Conveyor System Reliability Index Ratio
46	IBCSRI	Ideal Belt Conveyor System Reliability Index
47	BCSRF	Belt Conveyor System Reliability Function
48	MTAF	Matrix-based Theoretical Analysis Function *(contextual usage)*
49	BR	Belt Conveyor Reliability Matrix
50	FD	Fault Diagnosis
51	MP	Maintenance Practices
52	OE	Operating Environment
53	HF	Human Factors
54	SD	System Design
55	AI	Artificial Intelligence
56	ML	Machine Learning

57	OEM	Original Equipment Manufacturer
58	SPC	Sugar Plant Belt Conveyor
59	FPC	Fertilizer Plant Belt Conveyor

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CHAPTER 1

INTRODUCTION

Belt conveyor systems have become the primary means of transporting bulk materials across industries due to their reliability, flexibility, versatility, and capacity to handle large material assortments. Belt conveyors are versatile material handling systems capable of transporting materials of various shapes and sizes, with the flexibility to operate in both horizontal and vertical directions. Large-scale conveyor systems are often employed in continuous bulk material delivery, such as mines, fertilizer plants, sugar plants, and power plants. The belt conveyor system is widely recognized as an economically efficient option for material handling, offering advantages in terms of transportation efficiency, reduced maintenance requirements, lower power consumption, and minimized labor expenses.

The malfunction of a belt conveyor system causes all other machinery and equipment to cease operation [1]. Hence, failures of the belt conveyor system lead to substantial delay in production, reputation damage due to delay in delivery of product to customer, and financial losses. Hence, belt conveyor systems must be reliable since any downtime results in wasted production time and money. The bulk material handling industry has consistently prioritized the reliability of conveyor belts [2]. The reliability of a belt conveyor system, in terms of its hierarchical structure, is determined by the reliability of its many components, such as the belt, pulleys, drive unit, and idler rollers [3] from the system design perspectives. However, the reliability of conveyor belt systems in terms of their operations is dependent not only on the design of the systems themselves, but also on the right amount of usage of the systems [1]. Nouri et al. [4] stated that the reliability characteristics of material handling equipment are affected by various attributes, including the operational environment, maintenance policies, and operator proficiency. Traditionally, two fundamental methods can be utilized to analyze the reliability of mechanical systems, including statistical methods and system decomposition and modelling methods [5]. Although these procedures may be correct from a mathematical standpoint, they do not produce the actual reliability that is observed in practice [5]. Martin [6] pointed out that there will be interactions between system components and operational contextual attributes that are both structural and functional and may have a significant impact on the evaluation of reliability. This means that when considering reliability, not only components, but also their relationships with one another, including the contextual attributes based on the system's topology, must also be accounted for [7]. The literature has addressed the significance of system structure in relation to maintenance and reliability. The 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.

The belt conveyor system is made up of various components. The primary components consist of the belt, pulleys, idlers, take-up system, drive unit, and occasionally the brakes [8]. From a hierarchical perspective, the overall reliability of a belt conveyor system is determined by the combined reliabilities of its various constituent components, including the belt, pulleys, drive unit, and idler rollers. Belt conveyors are driven either mechanically or electrically. This is necessary to counteract energy dissipation, inertia, and gravity. A driving unit is utilized for this kind of propulsion. The belt receives its motive force from the pulley, which in turn receives it from the drive unit. Drive units are in general electrical systems, including an electric motor, coupling, and gearbox. However, there are some inherent inefficiencies in such systems. Though electric motors offer fewer operational problems, there are inefficiencies built into the gearbox coupling. Amin [9] pointed out that the gearbox is essentially too big and not as stable as it could be. Moreover, once the gear ratio is set, it can't be changed to work at the optimum speeds. The gearbox parts need frequent maintenance and repair while working in hot and dirty environments. Nowadays, modern power plants are using heavy-capacity belt conveyors that operate continuously in rugged operating environments. Under such circumstances, large hydraulic direct drives have become an effective and widely used solution. Since belt conveyor systems depend on hydraulic direct drive, if it fails, the entire plant could shut down. The extent to which each failure mode contributes to the overall failure of a belt conveyor system can be systematically evaluated through the application of Failure Mode and Effects Analysis (FMEA), which facilitates the assessment of risks associated with different failure modes of the hydraulic direct drive.

To keep a belt conveyor system safe and reliable throughout its lifespan, it must be maintained [10]. Industries worldwide adopt a range of strategies for maintaining their physical assets. Among these, corrective maintenance (CM), commonly referred to as run-to-failure, involves restoring a system or its components only after a failure has occurred. Preventive maintenance (PM) is based on pre-scheduled maintenance intervals but can also be based on a system's usage, as in the case of kilometers run by automobiles [11]. Since the onset of the Industrial Revolution, maintenance philosophies have evolved from reactive approaches to preventive strategies [12], and subsequently to the concept of condition-based maintenance [13]. As highlighted by Martinetti et al.[14], maintenance activities for belt conveyor systems typically encompass cleaning operations, lubrication of bearings, replacement of gearbox oil, systematic inspection and evaluation, as well as the repair or substitution of key components such as the belt, rollers, drums, bearings, electrical wiring, and structural mountings. According to Liu et al. [3], predictive maintenance is the best option for ensuring the reliability of belt conveyor systems. Apart from these, belt conveyors are an integral part of several process industries where turn-around maintenance (TAM) is a common practice [15]. As process facilities have gotten more automated, smart, and integrated, the knowledge required to diagnose and fix equipment faults, as well as manage maintenance activities in general, has become increasingly difficult [16]. Pinjala [17] added that TAM of process industries necessitates extra staff, and as a result, numerous maintenance activities may have to be outsourced.

Traditionally, all the maintenance activities for belt conveyor installations are performed by the maintenance crew of the organization that owns and operates them. However, in the upcoming era of Industry 4.0, maintenance activities, especially predictive maintenance, need more sophistication and expertise. In the context of Industry 4.0, maintenance technicians are expected to possess a diverse set of advanced technical competencies, including proficiency in IoT, RFID, cloud computing, data security, data analytics, automation, middleware, and collaborative software platforms [18, 19]. In addition to this, a broad spectrum of non-technical skills is essential, encompassing effective communication, accountability, adaptability, reliability, and a range of cognitive and managerial capabilities such as planning, leadership, organizational ability, teamwork, analytical and logical reasoning, continuous learning, creativity, documentation, emotional intelligence, and critical thinking [20, 21]. Developing these competencies through training programs can impose significant time and financial demands on organizations. Looking into the above complexities, contracting out both CM and PM is a common practice for companies [22]. For asset-intensive industries such as mining, aviation, and defense, outsourcing maintenance is critical since these industries require a large investment in maintaining complicated equipment and place a high value on system uptime [23]. Belt conveyors are an integral part of the mining industry whose maintenance activities are getting outsourced nowadays. However, maintenance outsourcing of such safety-critical equipment, like belt conveyors, is not straightforward. There are several challenges associated with the outsourcing of heavy equipment. Outsourcing maintenance services raises a variety of challenges, including technical, managerial, economic, and even legal issues [24].

Chinniah [25] emphasized that machinery is associated with numerous safety hazards throughout its entire lifecycle, including stages such as installation, commissioning, operation, cleaning, fault diagnosis, disassembly, repair, and maintenance. Similarly, belt conveyor systems present significant safety risks across all facilities in which they are deployed [26, 27, 28]. Industries across the world have realized the social, economic, and environmental impact due to safety-related accidents and related injuries [29] and are striving for the accomplishment of zero incidents [30]. Hence, belt conveyors need a diligent approach during the design, manufacture, installation, operations, and maintenance to ensure their safety [31]. Despite the inherent safety risks associated with the operation and maintenance of belt conveyor systems, existing design standards fail to adequately incorporate these safety considerations, and tender specification documents seldom quantify such risks [32]. Conveyor design guidelines are available in the literature [33] along with safety guidelines [34]. However, no literature explains how to ensure the safety of these machines during operation and measure their safety performance [35]. This necessitates the development of a multi-dimensional approach towards the analysis of belt conveyor safety performance.

From the above discussion, it is quite evident that there is ample scope for conducting research in the area of reliability, maintenance, and safety analysis of belt conveyor systems using a structural approach in the following aspects/issues that have been examined above. This required an extensive literature review for identifying the research gaps and formulating the research problem, which is described in the next chapter.

- Development of a model for the reliability of the belt conveyor system
- Failure mode and effects analysis of the hydraulic direct drive of the belt conveyor system
- Identify and analyze maintenance outsourcing challenges for the belt conveyor system
- Development of a framework for contractor selection for outsourced maintenance services of belt conveyor systems
- Development of a model for safety performance measurement for the belt conveyor system

Motivation to research the problem is described in the next section.

1.1 MOTIVATION

This research has targeted the reliability, maintenance, and safety aspects of belt conveyor systems. Its motivation, based on the above discussion, is as follows.

- There are a lot of opportunities and challenges in the belt conveyor systems sector.
- Belt conveyor system usage is increasing across industries around the world. Maintenance and reliability are two of its main key factors that influence not only its installation but also its efficient operation
- Finding, evaluating, and selecting a suitable contractor for outsourcing the maintenance activities from various alternative options 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 related injuries and are striving for the accomplishment of zero incidents.

1.2 THESIS ORGANIZATION

This thesis is structured into eight chapters. Chapter 2 provides a comprehensive review of the literature, encompassing reliability modeling of belt conveyor systems, failure modes and effects analysis (FMEA) of hydraulic direct drive, identification and evaluation of challenges in outsourced maintenance, modeling approaches for maintenance outsourcing, and safety assessment of belt conveyor systems, culminating in the formulation of the research problem. Chapter 3 focuses on the reliability modeling of the belt conveyor system using a digraph and matrix-based methodology. Chapter 4 presents the FMEA of the hydraulic direct drive. In Chapter 5, key challenges associated with outsourced maintenance of belt conveyor systems are identified and analyzed, while Chapter 6 addresses the selection of contractors for outsourcing maintenance activities of belt conveyor systems. Chapter 7 evaluates the safety performance of belt conveyor systems by identifying relevant design and contextual factors and determining their relative significance. It further develops a safety index based on these factors and their interrelationships using a digraph model, with evaluation supported by a matrix approach. Finally, Chapter 8 summarizes the conclusions, outlines the contributions and limitations of the study, and suggests directions for future research.

The next chapter describes the literature review and problem formulation.

CHAPTER 2

LITERATURE REVIEW AND PROBLEM FORMULATION

This chapter presents the literature review and formulation of the research problem. It examines five key aspects identified in Chapter 1, namely the reliability of belt conveyor systems, failure modes and effects analysis (FMEA) of hydraulic direct drive, challenges associated with maintenance outsourcing, development of a contractor selection framework for outsourced maintenance services of belt conveyor systems, and safety considerations of belt conveyor systems. Pertinent studies related to each of these aspects are systematically reviewed and discussed in the subsequent sections.

2.1 RELIABILITY AND ITS INDEX

Belt conveyor systems have emerged as the predominant method for transporting substantial quantities of materials due to their reliability, versatility, and capacity to accommodate a diverse array of materials [26]. Given the substantial expense associated with production downtime, reliable belt conveyor systems are imperative [10]. The bulk material handling industry has consistently prioritized the reliability of conveyor belts [2]. The malfunction of a belt conveyor, a fundamental component of this transport system, causes all other machinery and equipment to cease operation [1]. Liu [3] noted that failures of belt conveyors, essential equipment in coal mining production and conveyance systems, lead to substantial economic losses. Also, the reliability of belt conveyor systems is dependent on the system design and other operational aspects.

Traditionally, two fundamental methods can be utilized to analyze the reliability of mechanical systems, including statistical methods and system decomposition and modelling methods [5]. Although these procedures may be correct from a mathematical standpoint, they do not produce the actual reliability that is observed in practice [6]. Sehgal et al. [5] pointed out that there will be interactions between system components and operational contextual attributes that are both structural and functional and may have a significant impact on the evaluation of reliability. The literature has addressed the significance of system structure in relation to maintenance and reliability. It has been demonstrated in numerous fields that there is a robust correlation between the structure of a system and its performance [36]. For the examination of system structure and the relationships among its components, graph-based and directed graph (digraph) modeling approaches are particularly well-suited. This, combined with a matrix technique, facilitates the analysis and development of an index or measure. The 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. Moreover, the structural assessment of the reliability of belt conveyor systems can be represented by a digraph model. This, in conjunction with a matrix methodology, facilitates the quantification of reliability.

2.2 FAILURE MODE AND EFFECT ANALYSIS OF HYDRAULIC DIRECT DRIVE

Belt conveyor systems have become the most common way to move large amounts of materials because they are reliable, flexible, and able to handle a wide range of materials [26]. Many different types and sizes of belt conveyors are available that can move both up and down [35]. Continuous bulk material delivery is frequently done using large-scale belt conveyor systems in places like mines, ports, and power plants [37]. According to Swinderman et al. [38], the belt conveyor system offers the best value in terms of transportation, maintenance, power usage, and labor expenses per tonne. Due to the high cost of production downtime, reliable belt conveyor systems are essential [10]. Liu et al. [3] noted that, within the mining sector, belt conveyors, being essential equipment for coal production and material handling, can lead to substantial economic losses when failures occur. A belt conveyor system comprises multiple components, with the principal elements including the belt, pulleys, idlers, take-up system, drive unit, and, in certain cases, braking mechanisms [8]. From a hierarchical perspective, the overall reliability of the system is determined by the combined reliabilities of its individual components, such as the belt, pulleys, drive unit, and idler rollers. Belt conveyors are driven either mechanically or electrically. This is necessary to counteract energy dissipation, inertia, and gravity. A driving unit is employed to provide the necessary propulsion in belt conveyor systems. The motion is transmitted from the drive unit to the pulley, which subsequently imparts movement to the conveyor belt. Typically, these drive units comprise components such as an electric motor, coupling, and gearbox. Despite their widespread use, such systems exhibit certain inherent inefficiencies. While electric motors generally function with minimal operational issues, inefficiencies are primarily associated with the gearbox and coupling mechanisms. As highlighted by Amin [9], gearboxes are often oversized and lack the desired level of stability. Furthermore, once a gear ratio is fixed, it restricts the system from operating at optimal speeds. In addition, gearbox components require frequent maintenance and repairs, particularly when operating under high-temperature and contaminated environmental conditions.

In modern power plants, heavy capacity belt conveyors are increasingly deployed, operating continuously under harsh and demanding environments. In such conditions, hydraulic direct drives have emerged as an efficient and widely adopted alternative. These systems are particularly suitable for applications involving the movement of heavy loads at variable speeds while accommodating shock loads, all while ensuring reliable and energy-efficient performance. According to Amin [9], hydraulic direct drives offer superior performance compared to conventional electrical drives in terms of power density, energy efficiency, smooth starting and stopping characteristics, and overall reliability.

Given the dependence of belt conveyor systems on hydraulic direct drive, any failure in this subsystem can potentially lead to a complete shutdown of the plant. The contribution of individual failure modes (FMs) to overall system failure can be systematically evaluated using Failure Mode and Effects Analysis (FMEA), which assesses the associated risks of different failure modes. FMEA serves as an effective tool for anticipating and mitigating potential issues in systems, designs, processes, or services [39]. The initial step in a conventional FMEA involves identifying all possible failure modes, followed by risk prioritization using the Risk Priority Number (RPN) as proposed by [40].

The RPN is determined based on three risk factors: severity (S), occurrence (O), and detection (D). Severity reflects the impact of a failure mode on system performance, with higher values indicating more critical consequences. Occurrence denotes the frequency or likelihood of the failure mode, while detection represents the probability of identifying the failure before it occurs; higher detection values indicate greater difficulty in detection. A failure mode characterized by high severity, frequent occurrence, and low detectability is considered highly critical. Typically, each of these factors is rated on a scale of 1–10 or 1–5 [41, 42], and the

RPN is calculated as the product of S, O, and D [43]. The failure modes are then ranked in descending order of their RPN values, with the highest-ranked mode identified as the most critical contributor to system failure.

Despite its widespread application, several limitations of the traditional FMEA approach have been highlighted in the literature [44,45,46,47]. These include the assumption of equal importance for all risk factors, the possibility of identical RPN values arising from different combinations of S, O, and D despite varying risk implications, difficulties in accurately estimating these factors in real-world scenarios, and the sensitivity of the multiplicative RPN formulation to variations in input parameters. FMEAs built on fuzzy MCDM approaches have been widely adopted by the scientific community over the past decade as a means of overcoming these drawbacks [48]. The following Table 2.1 shows a brief of contemporary literature on the above aspects.

Table 2.1 Literature on fuzzy MCDM-based FMEA

Sr.No	Reference	Methodology	Application
1	[48]	Integrated FAHP and fuzzy TOPSIS	FMEA of typical wastewater treatment plants in wet subtropical areas
2	[49]	The integrated methodology combines Fuzzy Analytic Hierarchy Process (Fuzzy AHP) with the MARCOS (Measurement of Alternatives and Ranking by Compromise Solution) approach.	Identifying the causes and effects of the main human errors that occur during CNC machining operations
3	[50]	Combined fuzzy AHP and fuzzy weighted MULTIMOORA techniques	FMEA analysis of a steel factory
4	[51]	Fuzzy AHP and fuzzy technique for preference ordering based on resemblance to ideal solution (fuzzy TOPSIS)	Risk ranking of flaws in electropneumatic brake modules of railway coaches
5	[52]	An integrated approach of the fuzzy Pythagorean (PF) k-means algorithm and PF-VIKOR	FMEA analysis of dehydration gas refinery
6	[53]	Combined Fuzzy Best-Worst Method (FBWM) and Z-MOORA	Failure prioritization in the automotive spare industry
7	[54]	Integrated FBWM and fuzzy Bayesian network (FBN)	FMEA analysis of an industrial kitchen equipment manufacturing facility
8	[55]	Integration of Intuitionistic Fuzzy Sets and Group Determination	FMEA of a personal fall arrest system in an ambiguous environment based on intuition

9	[56]	Cumulative prospect theory and fuzzy type-2 approach	FMEA of the railway train bogie system
10	[57]	Integrated FAHP and fuzzy TOPSIS	Failure mode prioritization in the foundry industry
11	[58]	Hybrid fuzzy analytic hierarchy process and grey relational approach	FMEA of a gas turbine system
12	[59]	FMEA in combination with fuzzy analytical hierarchy process (AHP).	Process failure identification in a cement industry warehouse

2.3 CHALLENGES IN MAINTENANCE OUTSOURCING

Industries worldwide employ a variety of strategies for the maintenance of physical assets. Corrective maintenance (CM), often referred to as run-to-failure, involves restoring a system or its components only after a breakdown has occurred. However, the approach of preventive maintenance aims to avert failures in advance, typically without considering the current condition of the system [60]. Apart from these, predictive maintenance utilizes information on system health and historical maintenance data to determine the optimal timing for interventions, thereby minimizing unnecessary repairs and ensuring timely corrective actions [60].

The emergence of Industry 4.0 has introduced transformative opportunities for maintenance practices. The integration of real-time monitoring and advanced digital technologies enhances the efficiency and effectiveness of maintenance operations [61]. These advancements enable early and accurate fault detection, reducing downtime and operational costs [62]. Intelligent predictive maintenance systems, supported by such technologies, contribute to substantial reductions in equipment downtime and service durations [63]. The use of Internet of Things (IoT) platforms facilitates communication among devices, enabling machine health monitoring and maintenance scheduling [64]. The Industrial Internet of Things (IIoT) further supports the development of Cyber-Physical Systems (CPSs), allowing seamless data exchange across systems [65]. Advanced data analytics, particularly big data techniques, play a critical role in real-time decision-making for predictive maintenance [66], while also improving the management of spare parts logistics [67]. Simulation-based approaches enable the prediction of system risks and comparison of system health under varying maintenance conditions [68]. Emerging technologies such as augmented reality (AR) are increasingly being incorporated into maintenance processes, with applications such as head-mounted display systems for training and operational support [69]. Furthermore, the prediction of remaining useful life (RUL) using sensor-based data analytics represents a significant advancement in maintenance planning [70, 71]. Future developments in robotics, drones, and wearable technologies are also expected to further enhance smart maintenance capabilities [72].

Traditionally, maintenance activities for belt conveyor installations have been carried out by in-house maintenance teams of the owning and operating organizations. However, with the advent of Industry 4.0, maintenance, particularly predictive maintenance, demands higher levels of technical sophistication and specialized expertise. In asset-intensive sectors such as mining, aviation, and defense, maintenance outsourcing is particularly critical due to the high investment required for sustaining complex equipment and the emphasis on system availability [23]. Belt conveyors, which play a vital role in mining operations, are increasingly subject to outsourced maintenance. Existing literature indicates a lack of comprehensive studies addressing service provider selection, evaluation, and performance measurement in maintenance outsourcing [73]. Furthermore, organizations often encounter operational difficulties when adapting maintenance strategies to align with Industry 4.0 requirements [74]. In the specific context of belt conveyors, research remains limited, prompting the present study to identify and prioritize key challenges associated with maintenance outsourcing in the Indian Industry 4.0 landscape using methodologies such as AHP and DEMATEL.

Outsourcing, a long-established practice, can be categorized into horizontal and vertical contracting, with maintenance representing a typical vertical outsourcing function [75]. Over recent decades, maintenance service contracts (MSCs) with third-party providers have gained prominence [76]. Organizations are motivated to outsource maintenance to reduce departmental costs, avoid continuous training requirements, and comply with evolving technological, safety, and environmental standards [75]. Additional benefits include improved workforce morale and the ability for management to focus on core strategic functions. Nevertheless, outsourcing is not without drawbacks, such as reduced operational control, dependency on external providers, variability in service quality, and potential workforce displacement [77]. Therefore, selecting an appropriate contractor is a critical determinant of successful outsourcing outcomes [78].

From an organizational perspective, effective maintenance contractors are expected to demonstrate strong operational capabilities, including proven expertise, financial stability, skilled manpower, professionalism, and well-documented procedures [78]. Additional competencies include innovation, efficient communication systems, proactive management, reliability, and the ability to maintain dynamic relationships with asset owners [79]. The use of advanced software tools such as computerized maintenance management systems, enterprise asset management systems, and enterprise resource planning platforms is also essential for effective maintenance operations [80]. Achieving these capabilities is particularly challenging in the Industry 4.0 environment, where technological and organizational requirements are increasingly complex.

Maintenance outsourcing also involves intricate contractual, legal, and financial considerations. Maintenance service contracts (MSCs) govern technical, economic, and legal aspects, with common types including work package, performance-based, and facilitator contracts [75,76]. These contracts must address factors such as maintenance scope (CM and/or PM), task specifications, turnaround time, documentation, payment structures, penalties, risk allocation, and warranty conditions. Selecting appropriate contractual arrangements and terms is therefore a complex and critical task for asset owners.

The transition to Industry 4.0 has further intensified skill requirements in maintenance. While advanced technologies such as cyber-physical systems support maintenance personnel, complete automation remains unattainable, necessitating highly skilled human intervention [81]. A shortage of technicians proficient in digital technologies and knowledge management presents a significant barrier [82]. Moreover, challenges related to real-time data processing, interpretation, and decision-making demand enhanced analytical capabilities from maintenance personnel. Consequently, maintenance contractors must invest in developing advanced competencies to meet these evolving demands.

Data acquisition and management constitute critical components of modern maintenance systems. Effective predictive maintenance relies on accurate, comprehensive, and well-structured data. However, existing maintenance data are often incomplete, inconsistent, or poorly managed [83]. Surveys indicate that many organizations fail to maintain systematic maintenance records or utilize available data effectively [84]. Additionally, the adoption of advanced data acquisition systems, sensor technologies, and analytical tools entails high costs and technical challenges. Maintenance data analysis further requires expertise in statistics, reliability theory, and stochastic processes, necessitating specialized knowledge within maintenance organizations [76].

The implementation of Industry 4.0-based maintenance also requires advanced instrumentation and monitoring technologies. Techniques such as embedded conductive layers, image processing, and motor performance monitoring are employed to detect potential faults in conveyor systems [84, 85,86]. However, challenges arise in sensor design, placement, data integration, and software usability. The incorporation of augmented reality (AR) further enhances maintenance processes but adds to the technological complexity [87]. Ensuring service quality remains a major concern in maintenance outsourcing. Service quality encompasses both technical aspects, such as equipment reliability and repair effectiveness, and nontechnical aspects, including responsiveness and service orientation [79]. Performance indicators such as maintenance response time, turnaround time, and mean time between failures are critical for evaluating contractor performance [78],[88]. Maintaining high service quality in the demanding Industry 4.0 environment is therefore a significant challenge for contractors.

Health, safety, and environmental (HSE) considerations are also paramount in maintenance outsourcing. Maintenance activities, particularly turnaround maintenance, involve substantial safety risks, necessitating robust safety management systems [89]. Contractor selection must therefore incorporate safety criteria, including past safety performance, technical competence, workforce capability, and HSE planning.

Finally, spare parts management and supply chain coordination present additional challenges. Maintenance activities often increase demand for spare parts, requiring efficient inventory management strategies [90]. Decisions regarding spare parts control, whether managed by asset owners or contractors, significantly influence operational efficiency and contract profitability [23]. Various inventory models have been proposed to address different demand and repair conditions [91, 92, 93]. Consequently, developing an effective spare parts supply chain policy remains a complex and critical aspect of maintenance outsourcing for belt conveyor systems.

2.4 CONTRACTOR SELECTION FOR OUTSOURCED MAINTENANCE SERVICES

Various procedures and approaches are employed by various industries throughout the world to maintain their physical assets. The term "run-to-failure" refers to the practice of restoring a system or one of its components after it has malfunctioned via corrective maintenance (CM). Preventive maintenance is another practice that involves maintaining a working system before it breaks down [60]. Since the onset of the Industrial Revolution, maintenance philosophies have progressively evolved from reactive approaches to preventive strategies, and ultimately to condition-based maintenance [94].

The reliability of belt conveyor systems can be ensured by employing predictive maintenance methods [3]. In addition, belt conveyors are used in many industrial sectors where turn-around maintenance (TAM) is typical practice [15]. Traditional practice dictates that all belt conveyor maintenance be handled by the company that owns and operates the machines themselves, with no outside help. In the contemporary industrial environment, increasing levels of automation, intelligence, and system integration have significantly complicated the tasks of fault diagnosis, troubleshooting, and overall maintenance management [16]. In particular, predictive maintenance in the emerging Industry 4.0 paradigm demands enhanced technical sophistication and specialized expertise. Maintenance personnel are required to develop advanced technological competencies, including proficiency in IoT, RFID, cloud computing, data security, data analytics, automation, middleware, and collaborative software platforms [18, 19]. In addition to these technical capabilities, Industry 4.0 necessitates a broad set of non-technical skills, such as effective communication, responsibility, adaptability, reliability, cognitive and planning abilities, organizational and teamwork skills, analytical and logical reasoning, continuous learning, documentation, emotional intelligence, and critical thinking. Organizations will have to spend a lot of time and money training their employees to have the aforementioned abilities. Contracting out CM and PM is a frequent approach in the above scenario [22], and consequently, several maintenance tasks may have to be outsourced to process industries [17]. Ahmed [95] also pointed out that organizations are increasingly outsourcing their maintenance functions to outside suppliers due to a rising dearth of trained maintenance engineers and limited maintenance facilities and resources. Godoy et al. [23] even cautioned that asset-intensive industries like mining, aviation, and defense demand a substantial investment in maintaining complex equipment and a high emphasis on system uptime, which would necessitate outsourcing of maintenance. Outsourcing candidates for maintenance tasks include the maintenance and repair of generic or common equipment, electronics, environmental equipment, transport fleets, buildings, and grounds, as well as plant overhaul or turnaround [96]. Many of the belt conveyor installations are an integral part of power plants or process industries where TAM is frequently of high value, and their operations are often demanding, complex, and costly, necessitating diligent planning, scheduling, coordination, and execution with the involvement of customers, partners, external maintenance contractors, and technology providers [97]. Hence, outsourcing maintenance of belt conveyors is becoming increasingly common in today's mining industry. However, 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 [24].To maximize the potential benefits and limit the dangers of outsourcing policies, it is crucial to choose the correct contractor [77] and, hence, finding, evaluating, and selecting a suitable contractor for outsourcing the maintenance activities from various alternative options is a challenging task [24] for the owners and operators of belt conveyor installations. This study aims to propose a structured framework for selecting contractors for outsourced maintenance services of belt conveyor installations by employing a hybrid methodological approach. The selection criteria for maintenance contractors are identified through an extensive review of the literature and consultations with industry experts. The relative importance of these criteria is determined using the Analytic Hierarchy Process (AHP), while the PROMETHEE-II method is applied to rank and select the most suitable contractor from a set of alternatives [98]. The effectiveness of the proposed framework is subsequently validated through a case study.

2.5 EVALUATION OF SAFETY PERFORMANCE OF BELT CONVEYOR SYSTEMS

Industries across the world have realized the social, economic, and environmental impact due to safety-related accidents and related injuries [29] and are striving for the accomplishment of zero incidents [30]. Hence, belt conveyors need a diligent approach during the design, manufacture, installation, operations, and maintenance to ensure their safety [31]. Despite the safety risks linked with the operation and maintenance of conveyors, the design standards do not address these safety issues, and tender specification documents never address the safety concerns quantitatively [32]. Conveyor design guidelines are available in the literature [33] along with safety guidelines [34]. However, no literature explains how to ensure the safety of these machines during operation and measure their safety performance [35]. This necessitates the development of a multi-dimensional approach toward the analysis of belt conveyor safety performance.

A review of the literature indicates that several researchers have investigated safety considerations associated with belt conveyor installations. Notably, Kecojevic [27] proposed a risk assessment methodology grounded in injury and fatality data from U.S. mining operations spanning 1995 to 2006. Similarly, Jocelyn [99] attempted to evaluate the safety probability of belt conveyor systems using accident data. However, [32] highlighted the limited extent of research on the safety performance of such systems and introduced a safety integrity level (SIL) model for their assessment, utilizing reliability and maintenance data. However, the model has not considered the design attributes, human factors, and the operational environment. Abbaspour [28] also pointed out that the existing safety studies on belt conveyor systems are predominantly statistical analyses of previous data and lack a multivariable-based safety analysis.

According to HSE reports [100], safety performance measurement (SPM) is essential for organizations, as it provides vital information on safety levels that helps them introspect and make decisions. Arezes and Sergio [101] noted that, although different methodologies exist for measuring safety performance, contemporary practices mostly consider safety culture and safety climate within organizations. They added that the traditional safety performance indicators based on accident statistics may no longer convey the safety performance of organizations. The literature highlights several significant contributions to safety performance assessment employing diverse factors and methodological approaches. For instance, Hsu et al. [102] evaluated organizational safety performance using structural equation modeling, incorporating elements such as organizational structure, management practices, control mechanisms, and behavioral factors. Similarly, Beriha et al. [103] analyzed safety performance in Indian industries using a fuzzy-based approach, considering variables such as safety training, tools, equipment, machinery, materials, environmental conditions, and protective systems.

Building upon these studies, the present work proposes a novel framework for evaluating safety performance by integrating both design-related and operational contextual factors specific to belt conveyor installations. Inherent safety, as a design attribute, reflects the integration of occupational safety and health (OS&H) considerations during the system design phase [104]. However, it is observed that such inherent safety features may be compromised by prevailing operational conditions. The overall safety of belt conveyor systems is therefore influenced by a combination of design and contextual operational factors, which are often interdependent. The presence or absence of certain factors can significantly influence the behavior and impact of others.

Levenson et al. [105] emphasized that industrial safety is rooted in a socio-technical hierarchical system structure governed by elements such as design, management, operational environment, control mechanisms, and regulatory frameworks. Furthermore, the interactions among these elements play a crucial role in determining system safety. To effectively capture such structural relationships, graph and directed graph (digraph) models are particularly suitable. Accordingly, this study employs a digraph-based approach to model the structural interdependencies among safety performance factors of belt conveyor systems. When combined with matrix-based techniques, this approach facilitates the quantification of safety performance through the development of a Safety Performance Index (SPI). The distinct contribution of this work lies in the simultaneous consideration of both design and operational contextual factors, along with their interrelationships, for a comprehensive assessment of safety performance.

2.6 RESEARCH GAPS

The above literature review provided an insight into four broad areas of reliability, maintenance, and safety, including models and procedures applied. Based on this and discussions in Chapter 1, the following research gaps were identified in the context of belt conveyor systems.

- Work in reliability has been performed for a variety of systems, but surprisingly not so much 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 the evaluation of reliability, the design and contextual factors, including their mutual influences, should be investigated, which have not been explored. This can be modeled in terms of a graph/digraph, and this, in conjunction with its equivalent matrix, can help in developing a measure or index.
- Hydraulic direct drive is an important subsystem of the belt conveyor systems. Due to the extensive use of belt conveyor systems in the handling of bulk materials, the hydraulic direct drives operate in very harsh environments and are subject to failures. The failure of the hydraulic direct drive may contribute to the complete failure of the entire belt conveyor system. However, not much work has been carried out for FMEA analysis of hydraulic direct drive of belt conveyor systems. Hence, a suitable structural methodology can be employed for FMEA analysis of hydraulic direct drive of belt conveyor systems with consideration of the system structure. The results can be used by operators of belt conveyor installations for designing the preventive maintenance programs for critical components of the hydraulic direct drive.
- Heavy equipment maintenance is increasingly being outsourced nowadays, and belt conveyor installations are no exception. It is difficult for the companies who own and operate these installations to find a qualified service provider to whom they may outsource maintenance connected with outsourcing maintenance activities for belt conveyor installations. Based on the existing literature, it has been revealed that no significant work in this direction has been carried out in the domain of outsourcing maintenance of the conveyor belt system. The integrated methodology can be used to establish a hierarchical structure of the challenges for outsourcing maintenance and their driver and dependent relationships. The integrated methodology can establish a

hierarchical structure of the challenges and their driver and dependent relationships. This approach will assist organizations operating belt conveyor installations in identifying key challenges and thereby facilitate informed decision-making in selecting a suitable agency for maintenance outsourcing. Accordingly, a systematic model can be developed to support the rational selection of an appropriate maintenance service provider.

- Industries across the world are striving for zero accidents because they have realized the social, economic, and environmental impact of safety-related accidents and related injuries. Hence, belt conveyors need a diligent approach during the design, manufacture, installation, operations, and maintenance to ensure their safety [31]. Despite the significant safety risks associated with the operation and maintenance of belt conveyor systems, existing design standards fail to adequately address these issues, and tender specification documents rarely incorporate quantitative measures to evaluate and manage safety performance [32]. Conveyor design guidelines are available in the literature [33] along with safety guidelines [34]. However, no literature explains how to ensure the safety of these machines during operation and measure their safety performance [35]. This necessitates the development of a multi-dimensional approach toward the analysis of belt conveyor safety performance.

2.7 PROBLEM FORMULATION AND RESEARCH OBJECTIVES

Based on the above discussion, this research problem is formulated and entitled: "Development of a reliability, maintenance, and safety Model for belt conveyor systems using structural methodology". The main objectives of the research are:

- Development of a reliability model of belt conveyor systems using structural methodology.
- Failure mode and effects analysis of the hydraulic direct drive of the belt conveyor system.
- Identification and analysis of challenges in maintenance outsourcing of the belt conveyor system.
- Development of a model for contractor selection for outsourced maintenance services of the belt conveyor system.
- Development of a framework for safety performance measurement of belt conveyor systems.

2.8 RESEARCH ACTIVITIES

The following research activities were undertaken to meet the objectives in the context of belt conveyor systems:

2.8.1 Reliability and its index

Under this, the understanding of the reliability of the belt conveyor system is taken up, including how to enhance and evaluate it. A methodology to evaluate the reliability index has been developed. For this, the design and contextual factors affecting the reliability of the belt conveyor system, like Fault Diagnosis, maintenance practices, operating environment, system design, and Human factors, etc., are examined and analyzed using a digraph model. This in conjunction with the matrix method, led to the development of the reliability index. This is helpful in evaluating reliability and guides strategic maintenance planning, design improvements, and resource allocation to bolster system reliability in belt conveyor operations.

2.8.2 Failure mode and effect analysis of Hydraulic direct drive

Under this, the identification of potential Failure Modes of the hydraulic direct drive, which constitutes the drive unit of the belt conveyor system. To establish the ranking of FMs, two fuzzy-based MCDM techniques are integrated, namely the fuzzy analytic hierarchy process (FAHP) and the fuzzy technique for order of preference by similarity to ideal solution (FTOPSIS). Using the hybrid approach of FAHP and FTOPSIS, the FMs were ranked. The results can be used by operators of belt conveyor installations for designing the preventive maintenance programs for critical components of the hydraulic direct drive.

2.8.3 Identification and Analysis of challenges in maintenance outsourcing of belt conveyor system

Eight key challenges associated with the outsourcing of maintenance for belt conveyor installations have been identified. An integrated structural hierarchical framework is developed using the Analytic Hierarchy Process (AHP) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) to analyze these challenges. This study enables organizations operating such systems to recognize the most critical issues and supports informed decision-making in selecting an appropriate agency for maintenance outsourcing.

2.8.4 Contractor selection for outsourced maintenance services of the belt conveyor system.

Seven criteria influencing the selection of maintenance contractors for belt conveyor systems have been identified, namely financial stability, organizational capability, service track record, quality of maintenance services, personnel competencies, availability of tools and equipment, and health, safety, and environmental considerations. Each of these criteria is further defined through multiple sub-criteria. The Analytic Hierarchy Process (AHP) is employed to determine the relative importance of these criteria, while the PROMETHEE-II method is utilized to rank and select the most suitable contractor from the available alternatives.

2.8.5 Safety performance measurement of the belt conveyor system

In this context, the development of a framework for evaluating the safety performance of belt conveyor systems is essential to ensure overall plant safety. To achieve this, relevant safety performance factors, encompassing both design attributes and operational contextual conditions, are identified. These factors and their interdependencies are represented using a digraph model. Subsequently, an equivalent matrix representation of the digraph is employed to derive a safety performance function (SPF), which forms the basis for establishing a Safety Performance Index (SPI) for the system.

Table 2.2 shows various research activities and steps planned for the accomplishment of research objectives in detail.

Table 2.2 Research activities and steps for achieving research objectives

Sr.No	Research Activities	Steps
1	Reliability and its index	• 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	Failure mode and effect analysis of the hydraulic direct drive	• 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	Identification and Analysis of Challenges in Maintenance Outsourcing of the Belt Conveyor System	• Identification of challenges for maintenance outsourcing of the belt conveyor system. • To develop an integrated structural hierarchical framework for the identified challenges by employing the Analytic Hierarchy Process

		(AHP) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodologies.
4	Contractor selection for outsourced maintenance services of the belt conveyor system	• 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	Safety performance measurement of the belt conveyor system	• Identification of safety factors, including design and operational contextual factors. • Development of a model for safety performance measurement by modeling safety factors using a digraph and matrix.

Inputs for the structural modeling of this research work were obtained through extensive interactions with professionals in the belt conveyor industry, including designers, manufacturers, safety regulatory bodies, conveyor users, and maintenance professionals in India.

2.9 RESEARCH DELIVERABLES

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 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. The results can be used by operators of belt conveyor installations for designing the preventive maintenance programs for critical components of the hydraulic direct drive.
- A prioritized ranking of the eight key outsourcing challenges using Analytic Hierarchy Process (AHP), along with quantified cause–effect relationships derived through DEMATEL.
- A structural methodology for the selection of the best contractor among alternatives for the maintenance of the belt conveyor system.
- A framework for the evaluation of the safety of belt conveyor system is developed and

applied to evaluate the belt conveyor safety of a fertilizer plant.

The research objectives were achieved through the development in the following chapters. The next chapter describes the evaluation of the reliability of the belt conveyor system.

CHAPTER 3

BELT CONVEYOR SYSTEM RELIABILITY AND ITS INDEX

This chapter deals with reliability and its index. Under reliability, its understanding in the context of belt conveyor systems, how it can be improved, and the need for its evaluation are described. This is followed by the development of its index.

3.1 RELIABILITY AND ITS EVALUATION

Belt conveyor systems are widely used for bulk material handling in several industries. Its failure will adversely affect the production operations. Hence, the reliability of belt conveyors is of ultimate importance. The system reliability can be built during this stage; however, the reliability of conveyor belt systems in terms of their operations is dependent not only on the design of the systems themselves, but also on the right amount of usage of the systems [1]. Nouri et al. [4] stated that the reliability characteristics of material handling equipment are affected by various attributes, including the operational environment, maintenance policies, and operator proficiency. The reliability of belt conveyor systems is dependent on the system design and other operational aspects. For the evaluation of the reliability of the belt conveyor system, develop a framework that will result in a reliability index based on the reliability attributes that consist of design as well as operating contextual attributes in a plant. Based on the literature review and interactions with plant professionals, five reliability attributes of belt conveyors have been identified. The interdependent attributes were modeled using a structural approach based on graph theory and the matrix method (GTMA), facilitating the calculation of the Belt Conveyor System Reliability Index (BCSRI) and the corresponding reliability index ratio (BCSRIR). The proposed framework is implemented to assess the reliability of belt conveyor systems in a sugar plant. Sensitivity analysis indicated that system design is the most influential factor affecting the reliability index. Furthermore, the framework supports systematic fault diagnosis and the formulation of targeted strategies for reliability improvement.

3.2 DEVELOPMENT OF RELIABILITY INDEX

This is developed in the rest of the chapter. The purpose of this reliability index is to help in the evaluation of reliability quantitatively, which has been emphasized above. The belt conveyor system reliability index (BCSRI) provides meaningful insights into system performance and guides strategic maintenance planning, design improvements, and resource allocation to bolster system reliability in material handling operations. The index is also likely to be useful in comparing and analyzing various alternatives of the belt conveyor system. It is also already mentioned that reliability is a function of both design and operating contextual factors, and hence, the reliability index should be a reflection of both. The system design is unique to each belt conveyor system, while operating contextual factors vary for different belt conveyor systems. In this context, the system can be characterized through structural relationships involving system design and the contextual factors associated with belt conveyor operations, along with their interdependencies. The literature supports the application of digraph models in conjunction with matrix-based approaches for the development of such an index. As an initial step in this process, the relevant reliability factors are identified and subsequently discussed in the following section.

3.3 RELIABILITY ATTRIBUTES

It is essential to establish the reliability attributes and sub-attributes of belt conveyor systems. An unstructured exploratory study has been undertaken across 5 different belt conveyor installations, as well as two belt conveyor manufacturers in western India. The interviewees comprised design engineers of belt conveyor systems, plant operating managers, maintenance engineers, supervisors, and both operating and maintenance technicians. Additionally, a comprehensive literature analysis was done to validate the survey results. The identified reliability attributes 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. This sub-section elucidates those details.

3.3.1 Fault Diagnosis

Effective fault diagnosis is the cornerstone for enhancing the reliability of belt conveyor systems as it facilitates early detection of faults, rectification of them, and thereby minimizing the downtime and maintenance costs [106]. In this regard, the availability of diagnostic tools, such as ABB Ability™ Condition Monitoring for belts, which offer real-time information on the condition of conveyor belts, allows for predictive maintenance and a 30% reduction in unscheduled downtime. Apart from these, diagnostic accuracy is significant in the case of belt conveyors. Signature analysis is an effective way of belt conveyor fault diagnosis [107]. Another contemporary method for early fault detection is the use of infrared thermography [108]. Effective fault detection and maintenance decision-making in conveyor systems depend on the accurate interpretation of diagnostic data, such as vibration signals and thermal imaging [3]. This can be achieved through human skills and expert systems. Using AI in conveyor belt systems can improve reliability, where technologies like IoT, computer vision, and machine learning can predict and prevent faults, and alter settings to enhance system efficiency [109].

3.3.2 Maintenance Practices

According to Vatn and Aven [110], system and component maintenance will typically increase reliability. Liu et al. [3] proposed predictive maintenance procedures to enhance the reliability of belt conveyors. Hence, the existence of a diligent preventive maintenance schedule is necessary [111]. Since belt conveyors consist of several sliding and rolling components, regular lubrication of such systems is indispensable for enhancing reliability. A study revealed that an efficiency improvement of 40-55% is feasible with diligent lubrication of belt conveyor systems [112]. Belt conveyor systems need frequent replenishment of parts that include rollers, idler rollers, bearings, etc. A proper stock of these parts enhances the maintenance activities. A study by Nouri et al. [4] in the context of material handling equipment reliability revealed that the availability of spare parts is a crucial component that can enhance the system's performance and efficiency. The time taken for maintenance plays a profound role in belt conveyor maintenance. Research in this area by Kumar [113] found that extended maintenance intervals increase downtime and reduce the availability and productivity of belt conveyor systems. A review of historical data regarding failures, repairs, and replacements of components, parts, and sub-assemblies would assist managers in maintenance planning, thereby reducing equipment downtime and mean time to repair (MTTR). Comprehensive upkeep of fault data is necessary for reliability trend analysis and efficient maintenance planning [114]. Since maintenance is a human-centric activity, the skill of the technicians plays a major role. Skilled and experienced technicians are essential for fault detection, maintenance, and thereby enhancing system reliability [115]. It was postulated that mastering the required technician skills is essential to overcoming maintenance challenges of belt conveyors, especially in the context of Industry 4.0, where cutting-edge technologies are being incorporated into maintenance procedures.

3.3.3 Operating Environment

Hancovic et al. [116] reported that environmental operating conditions, particularly elevated humidity and temperature, can accelerate the degradation of conveyor belts. Prolonged exposure to thermal shocks further diminishes the mechanical properties of the belt material [117]. A significant proportion of idler roller bearing failures, approximately 43%, is attributed to the presence of moisture and dust particles, which impair lubricating grease and increase rolling resistance [118]. Field investigations by Vasic et al. [119] in surface mining applications identified corrosive wear (30.7%) and fretting corrosion (11.6%) as major contributors to bearing damage.

During operation, roller bearings are subjected to various degrading factors, including dynamic loading, moisture, temperature variations, vibration, and dust [120]. These conditions may induce excessive structural vibrations, potentially leading to resonance and associated risks [121]. Key indicators for evaluating the operational condition of rollers include noise levels, vibration characteristics, temperature rise, and changes in lubricant properties [122]. Furthermore, transverse vibration signals in conveyor belts have been identified as a contributing factor to roller damage [123]. Sadeghi et al.[124] emphasized that maintaining cleanliness in the conveyor environment is essential for ensuring operational reliability and mitigating fire hazards. Additionally, variability in load during conveyor operation significantly influences the lifespan of both the belt and the drive unit [116].

3.3.4 Human factors

Human factors, which include aspects like education, training, experience, physical fitness, and mental health, have a big influence on how reliable belt conveyor systems are [125]. Workers associated with conveyors must get specialized training for established preventive measures, SOPs, and all safety-related procedures and instruction in addition to formal task-related training [26]. The experience of technicians in operations and maintenance is a determining factor. According to Chinniah (2015), 46% of accidents involved workers with less than five years of experience, and 30% involved workers with less than a year of experience. Apart from these, knowledge and adherence to safety protocols by the workers [125] also positively influence reliability. Apart from these, interactions revealed that workload and fatigue management of the technicians working in both operations and maintenance is a crucial aspect. Effective communication and teamwork are vital in belt conveyor operations to ensure safety and efficiency. Clear communication helps workers coordinate tasks and alert each other to potential health hazards, reducing the risk of accidents. Team collaboration ensures that operations and maintenance are conducted smoothly, minimizing downtime and enhancing productivity.

3.3.5 System Design

The reliability of belt conveyor systems largely depends on the conveyor design features. [126] postulated that a reliable system will exhibit minimal failure occurrences, and MTTF (Mean Time to Failure) serves as a crucial metric for assessing system reliability. Apart from this, MTBF (Mean Time Between Failures) is also another important parameter. Hence, incorporating the above two reliability metrics in the design of belt conveyor system components would enhance reliability. A key concern in the design of belt conveyor systems is maintainability [127]. Maintainability is a design characteristic of systems that enables examination, diagnosis, repair, and replacement of various subsystems and components [128]. Under the broad umbrella of maintainability features, such as simplicity and modularity, component accessibility, and system disassemblability are most important and relevant to belt conveyor systems. In critical applications like belt conveyors, where interruptions are expensive, incorporating redundancy is crucial for enhancing reliability, including integrating redundant drive systems, auxiliary conveyors, etc. The design of belt conveyors should protect them from all types of safety hazards. Martinetti et al.[14] delineated categories of safety protection for conveyor belts. [129] discussed various deterrent devices, such as roller side plates and guardrails with mid-rails, for the enhancement of safety. Integrating the above devices into the design can enhance both the reliability and safety of belt conveyors. Apart from these, integrating control systems with the design of belt conveyors is crucial for reliability. Internationally recognized standards such as ISO 13849-2 [130] and IEC 62061

[131] are advocated for the utilization of electronic control of belt conveyor systems. Belt conveyors are designed for both static and dynamic loads. However, the dynamic loads significantly affect reliability. Dynamic loads in conveyor belts are caused by factors like fluctuating material flow, belt slippage, uneven loading, improper tension, and environmental conditions. This can increase the belt tension and vibration, and lead to damage to the system. Hence, dynamic load-carrying capacity is a crucial reliability factor in belt conveyors [132]. Apart from these, the quality of materials used for the belt [133] and other components, such as structural elements, rollers, idlers, drives, gearbox [134], etc. The system also critically affects the reliability of systems

Table 3.1 Qualitative Reliability Attributes and Sub-Attributes

Sr. No	Attributes	Sub-Attributes
1	Fault Diagnosis (FD)	• Availability of a condition monitoring system
		• Diagnostic Accuracy
		• Practice of signature analysis
		• Practice of thermography
		• Skill for fault symptom interpretation
		• AI-based fault prediction
2	Maintenance Practices (MP)	• Preventive maintenance scheduling
		• Llubrication practices
		• Spare part management
		• Maintenance time
		• Upkeep of maintenance records
		• Skill of maintenance technicians
3	Operating Environment (OE)	• Ambient temperature and humidity
		• Dust and particulate levels
		• Exposure to corrosive substances
		• Noise, vibration, and shock
		• Installation area cleanliness
		• Load variability during operation
4	Human Factors (HF)	• Skill level of operators and technicians
		• Training and skill upgradation of workers
		• Communication and teamwork
		• Workload and fatigue management
		• Years of experience
		• Adherence to safety protocols
5	System Design (SD)	• Simplicity and modularity of design
		• Component accessibility

		• System disassemblability
		• Redundancy in design
		• Built-in safety features
		• Belt material quality
		• Material selection for components
		• Control system integration
		• Dynamic load handling capacity
		• Incorporation of reliability metrics (e.g., MTBF, MTTF)

3.4. Methodology

Reliability modeling of belt conveyor systems necessitates a thorough examination of the factors affecting system reliability, along with their interrelationships and interdependencies. In Section 3.3, the key influencing attributes are identified, and their structural relationships are effectively represented using a graph-theoretical approach. Directed graph (digraph) models are particularly well-suited for capturing the complex interactions within such systems, thereby providing a robust framework for reliability assessment. In this study, a digraph is constructed wherein nodes represent distinct reliability attributes, and the directed edges illustrate the influence among these attributes.

A directed graph (digraph) is a mathematical structure comprising a finite set of nodes or vertices interconnected by directed edges or arcs. In this representation, each node corresponds to a distinct system variable, state, or attribute associated with the reliability of belt conveyor systems, while the directed edges capture the directional relationships and influences among these elements. Such a representation effectively characterizes the complex structural interactions within the system's reliability framework, emphasizing the interdependence of multiple attributes that collectively influence overall performance. Consequently, the digraph model provides a rigorous and systematic tool for modeling and evaluating the reliability of belt conveyor systems.

The reliability digraph is represented as R_d = (A, C), where A denotes the set of nodes {A_1, A_2, A_3,…A_N}, and C denotes 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 in the preceding section are modeled as nodes within the reliability digraph. This is shown in Figure 3.1.

The design of belt conveyor systems has a crucial impact on other reliability aspects. The diagnosis of faults is consistently enhanced by the design elements of the system; the incorporation of a condition monitoring system, as well as access for thermography and signature analysis, is determined by the system's architecture. This relationship is represented by a directed edge from node 5 to node 1. The maintenance techniques are also influenced by the system's structure. Accessibility and disassemblability can considerably influence maintenance duration. This relationship is depicted through an edge from node 5 to 2. The system design also impacts the operational environment. Appropriate precautions can protect belt conveyor systems from the adverse impacts of the surrounding environment. The selection of premium materials for belt conveyor production also improves environmental performance. In addition to this safety feature and other precautionary measures, the belt conveyor systems can be protected from overloading situations. This relationship is depicted by a directed edge extending from node 5 to node 3. System design significantly impacts human factors as well. Intricate designs and controls require advanced skills and training for operators and technicians. Furthermore, when the design grows intricate, technicians may experience increased factory fatigue, which may negatively impact their performance. This is represented in the digraph by a directed edge from node 5 to node 4.

Similar interrelationships among nodes in the reliability digraph are systematically defined and illustrated in Figure 3.1. The digraph illustrates relationships, but further study necessitates the creation of a corresponding matrix, which will be examined in the following section.

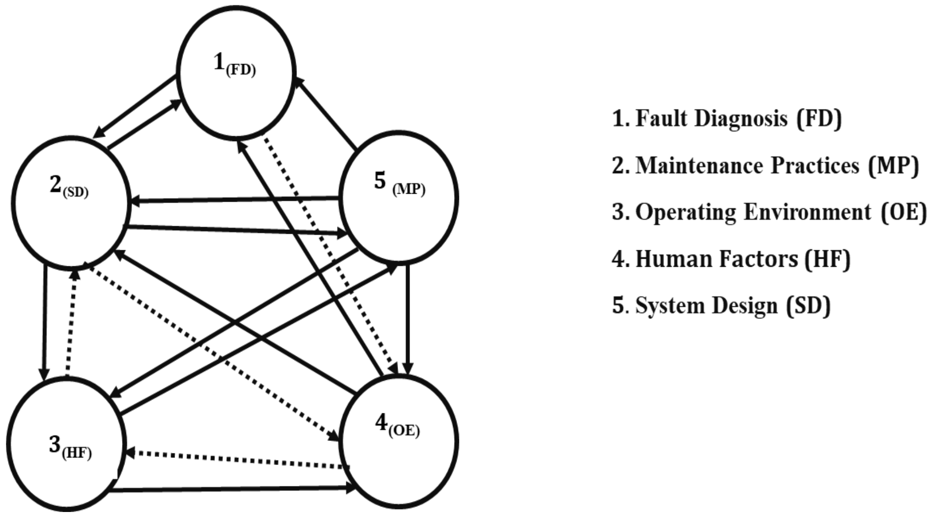

Figure 3.1 Belt conveyor system reliability diagraph

3.4.1 Matrix representation of the reliability digraph

This section presents the formulation of an equivalent matrix corresponding to the reliability digraph, facilitating a systematic representation of the mutual interdependence among the identified attributes affecting the reliability of belt conveyor systems. The matrix derived from the digraph illustrated in Figure 3.1 is referred to as the belt conveyor system reliability matrix (B_R), as expressed in Equation (3.1).

$$B_R = \begin{bmatrix} A_1 & c_{12} & 0 & c_{14} & 0 \\ c_{21} & A_2 & c_{23} & c_{24} & c_{25} \\ 0 & c_{32} & A_3 & c_{34} & c_{35} \\ c_{41} & c_{42} & c_{43} & A_4 & 0 \\ c_{51} & c_{52} & c_{53} & c_{54} & A_5 \end{bmatrix} \quad (3.1)$$

In Equation (3.1), 'A_i' represents the numerical value of the i^{th} reliability attribute, while 'c_{ij}' denotes the degree of interrelationship between attributes. The permanent of this matrix, expressed as Per (B_R), is referred to as the Belt Conveyor System Reliability Function (BCSRF). The BCSRF comprises multiple invariant terms that collectively capture both the reliability attributes and their interdependencies. In combinatorial mathematics, the permanent is a well-established matrix function characterized by exclusively positive terms [135,136]. It is analogous to the determinant, with the key distinction that it does not involve alternating signs, thereby providing a consistent positive formulation.

To obtain a generalized expression for the BCSRF, a reliability matrix consisting of 'N' attributes is considered, as represented in Equation (3.2). The permanent of the matrix '$B_{R(NxN)}$ is the MTAF, which is represented as equation (3.3).

$$\boldsymbol{B_{R\,(NxN)}} = \begin{bmatrix} A_1 & c_{12} & \cdots & \cdots & c_{1N} \\ c_{21} & A_2 & \cdots & \cdots & c_{2N} \\ c_{ij} & c_{ik} & \cdots & \cdots & .\,c_{iN} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{N1} & c_{N2} & \cdots & \cdots & A_N \end{bmatrix} \quad (3.2)$$

$$Per\left(B_{R(NxN)}\right) = \prod_{i=1}^{N} A_i + \sum_i \sum_j \sum_k \sum_l \sum_m \ldots\ldots \sum_N \left(c_{ij}c_{ji}\right) A_k A_l A_m \ldots\ldots A_N$$
$$+ \textstyle\sum_i \sum_j \sum_k \sum_l \sum_m \ldots\ldots \sum_N \left(c_{ij}c_{jk}c_{ki} + c_{ik}c_{kj}c_{ji}\right) A_l A_m \ldots\ldots A_N \quad (3.3)$$

Researchers have extensively utilized the concept of directed graphs (digraphs) and their corresponding matrices for decision variables, as well as the assessment of permanent matrices, across multiple fields. Noteworthy examples include mechatronic system reliability modelling and analysis [137], evaluation of a performability index of a biogas plant [138], development of a supply chain resilience index [139], etc.

3.4.2 Evaluation of Belt Conveyor System Reliability

In the previous section, it was highlighted that the belt conveyor system reliability function (BCSRF) expression serves as a representation of belt conveyor system reliability. Building on this perspective, the conveyor system reliability is derived from the BCSRF, incorporating terms associated with both individual attributes (A_i) and their interrelationships (c_{ij}). Accordingly, the evaluation of system reliability requires the determination of numerical values for the diagonal elements, represented as (A_i), and the off-diagonal elements, represented as (c_{ij}), representing the individual attribute measures, as well as the off-diagonal elements, which capture the interactions among these attributes within the reliability matrix.

3.4.2.1 Quantification of Diagonal Elements

In the quantification of reliability attributes during the evaluation of belt conveyor system reliability, it is essential to assign appropriate weights (W_i) to each attribute. This approach recognizes that all attributes do not contribute equally, as their relative significance in determining overall system reliability may differ. Accordingly, the assessment of "A_i" is formulated as follows:

$$A_i = W_i \left(\sum_{j=1}^{m} E_{ij} \right) \tag{3.4}$$

Where (i = 1, 2, ..., 7) represents the belt conveyor system reliability attributes, and (j = 1, 2, ..., m) signifies the sub-attributes. E_{ij} is the assigned score by the evaluators for each reliability attribute.

Saaty [140] created the Analytic Hierarchy Process (AHP) approach, which is used to determine the weights *(Wi)*. The Analytic Hierarchy Process (AHP) is particularly effective for addressing complex decision-making problems that involve human judgment and subjective evaluation within a hierarchical framework [141]. This methodology has been widely applied in diverse domains, including the assessment of site suitability for solar power plants [142], the selection of optimal landfill locations [143], and the evaluation of distribution system alternatives [144]. Hence, the AHP methodology is employed in assigning weights to the reliability attributes of belt conveyor systems.

The first stage in the quantification procedure entails the evaluation of the diagonal elements of the reliability matrix, denoted as (A_i). Each reliability attribute (A_i) comprises various sub-attributes (A_{ij}), where i varies from 1 to 5 and j ranges from 1 to m. Table 2 provides a comprehensive list of these attributes and sub-attributes

The assigned score, denoted asE_{ij}, corresponds to the j^{th} sub-attribute of the i^{th} reliability attribute. Consistent with prior studies [141], a discrete scoring ranging from 0–2 is employed for evaluation. This scale represents discrete values corresponding to different levels, such as 0 indicates none, 1 indicates average, and 2 indicates high for sub-attributes. Because of the subjective nature of this task, it is done as a team to reduce bias. The job is done by a team, which is made up of professionals who work with belt conveyor systems in different capacities. The team of experts to come up with an evaluation plan that will help them rate the sub-attributes on a qualitative level. This is shown in Tables 3.2 through 3.6.

Table 3.2 Evaluation Scheme for Attribute 'Fault Diagnosis'

Sub-Attributes (A_{ij})	None (0)	Average(1)	High(2)
Availability of a condition monitoring system	No diagnostic tools available	Basic tools available	Comprehensive and advanced tools are available and regularly used
Diagnostic Accuracy	Diagnostic results are ambiguous	Moderate accuracy	High accuracy with minimal false readings
Practice of signature analysis	No practice of vibration analysis	Basic parameters analyzed	Regular use of signature analysis with proper instruments
Practice of thermography	No thermography analysis	Thermography analysis for critical systems	Regular and advanced thermography studies for the complete system
Skill for fault symptom interpretation	No capability to interpret early failure symptoms	Partial competency	Skilled technicians available for interpreting early symptoms
AI-based fault prediction	No use of AI tools	Basic rule-based or semi-automated prediction tools are used	Advanced AI/ML models used with high predictive reliability

Table 3.3 Evaluation Scheme for Attribute 'Maintenance Practices'

Sub-Attributes (A_{ij})	None (0)	Average(1)	High(2)
Preventive maintenance scheduling	No preventive maintenance schedule	Irregular scheduling without strict adherence	Optimized and enforced a preventive maintenance schedule
Lubrication practices	No regular practice of lubrication	Lubrication done, but not adhering to OEM rules	Regular lubrication as per OEM specifications
Spare part management	No systematic practice of spare	Partial and reactive	Computer-based inventory management

	inventory management	inventory management	system
Maintenance Time	Maintenance time is highly unpredictable, with frequent delays, and no time standards are followed.	Some adherence to estimated maintenance time; occasional delays happen	Maintenance tasks are consistently completed within the standard time
Upkeep of maintenance records	highly inconsistent manual logging	Partial maintenance is kept, either manually or digitally, but not updated regularly.	Comprehensive and regularly updated maintenance records are maintained in a digital system
Skill of maintenance technicians	Technicians lack proper training and skills	Basic skills are there, but they lack advanced training	Well-trained and certified technicians

Table 3.4 Evaluation Scheme for Attribute 'Operating Environment'

Sub-Attributes (A_{ij})	**None (0)**	**Average(1)**	**High(2)**
Skill level of operators and technicians	Untrained or under-skilled personnel	Basic skills present, but lacks troubleshooting ability	Highly skilled with in-depth system knowledge and fault diagnosis
Training and skill upgradation of workers	No formal training or upskilling programs	Occasional and informal training sessions are organized	Regular and structured training and upskilling program in practice
Communication and teamwork	Lack of communication and coordination among team members	Basic communication and teamwork exist	Effective communication and strong team coordination are enforced
Workload and fatigue management	Excessive workload with no fatigue management practices	Moderate workload with limited relaxation practices	Balanced workload with proper fatigue and shift management strategies
Years of experience	Less than 3 years of	Average	Average experience of

	average experience	experience of 3-5 years	more than 5 years
Adherence to safety protocols	Operators do not adhere completely to safety protocols	Inconsistent adherence to safety protocols	Strict adherence to protocols every time

Table 3.5 Evaluation Scheme for Attribute 'Human Factors'

Sub-Attributes (A_{ij})	**None (0)**	**Average(1)**	**High(2)**
Skill level of operators and technicians	Untrained or under-skilled personnel	Basic skills present, but lacks troubleshooting ability	Highly skilled with in-depth system knowledge and fault diagnosis
Training and skill upgradation of workers	No formal training or upskilling programs	Occasional and informal training sessions are organized	Regular and structured training and upskilling program in practice
Communication and teamwork	Lack of communication and coordination among team members	Basic communication and teamwork exist	Effective communication and strong team coordination are enforced
Workload and fatigue management	Excessive workload with no fatigue management practices	Moderate workload with limited relaxation practices	Balanced workload with proper fatigue and shift management strategies
Years of experience	Less than 3 years of average experience	Average experience of 3-5 years	Average experience of more than 5 years
Adherence to safety protocols	Operators do not adhere completely to safety protocols	Inconsistent adherence to safety protocols	Strict adherence to protocols every time

Table 3.6 Evaluation Scheme for Attribute 'System Design'

Sub-Attributes (A_{ij})	**None (0)**	**Average(1)**	**High(2)**
Simplicity and modularity of design	Complex and non-modular system with high	Partially modular design with moderate	Highly modular design allowing maintenance and upgrades

	dependency among components	complexity	
Component accessibility	Components are hard to access for maintenance or replacement	Moderately accessible with some tools and effort	Easily accessible design for all critical components
System disassemblability	Difficult or time-consuming disassembly process	Partial disassemblability with moderate effort	Easy and tool disassembly facilitates quick maintenance
Redundancy in design	No redundancy; failure of one component leads to a full system halt	Partial redundancy for selected components	Full redundancy incorporated to ensure system continuity
Built-in safety features	No or very limited safety features integrated into the design	Basic safety features are provided	Comprehensive safety features are well integrated into the system design
Belt material quality	Poor belt quality with high wear and tear	Moderate quality of belts used with average performance	Use of high-quality belts ensures longevity and optimal performance
Material selection for components	Low-grade or inappropriate materials are used without standards	Moderate grade materials used with basic standards followed	High-grade, standardized, and suitable materials are used for durability
Control system integration	No integrated control system; manual operation only	Basic control integration with some automation	Fully automated and integrated control systems with a feedback mechanism
Dynamic load handling capacity	The conveyor system stalls or fails when there is a sudden increase in load; no buffer or control mechanism exists.	System handles moderate load fluctuations, but shows reduced performance or wear under sustained dynamic loads.	The conveyor is equipped with advanced load control features (variable speed drives, tension control) and can effectively handle dynamic load fluctuations without operational impact.
Incorporation of reliability metrics (e.g., MTBF, MTTF)	Reliability metrics are not considered in design	Basic reliability parameters are considered without detailed analysis	Comprehensive inclusion of reliability metrics with analysis

3.4.2.2 Evaluation of Non-diagonal Elements

In the context of quantifying the non-diagonal elements "c_{ij}", they represent the degree of influence among various reliability factors. Values are assigned on a scale from "0" to "4", where "0" denotes no influence, "4" denotes high influence, and "above average," "average," and "minor" are intermediate levels.

For example, the influence of system design on other reliability attributes is explained. The system design has above-average influences on fault diagnosis, maintenance practices, and human factors; it has an average influence on the operating environment. Similarly, the degree of mutual influence among other factors is encapsulated in Table 3.7.

Table 3.7 Degree of influence among the reliability attributes

From \ To	FD	MP	OE	HF	SD
FD	-	4	0	1	0
MP	3	-	3	1	3
OE	0	1	-	3	2
HF	3	3	1	-	0
SD	3	3	2	3	-

3.5 Evaluation of Belt Conveyor System Reliability Index

The Belt Conveyor System Reliability Index (BCSRI) is a quantitative measure of the reliability of belt conveyors. It is generated from the reliability function of the belt conveyor system (BCSRF), substituting numerical values for "A_i" and "c_{ij}". A higher numerical value indicates greater reliability of the belt conveyor system.

The absolute value of the BCSRI may become unwieldy if excessively high scale values for "A_i" and "c_{ij}" are employed. To tackle this issue, two supplementary metrics have been introduced: the Ideal Belt Conveyor System Reliability Index (IBCSRI) and the Belt Conveyor System Reliability Index Ratio (BCSRIR). The 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 shown in expression (3.5)

$$BCSRIR = \frac{BCSRI\ of\ a\ belt\ conveyor}{BCSRI\ of\ an\ ideal\ belt\ conveyor} \tag{3.5}$$

The Belt Conveyor System Reliability Index Ratio (BCSRIR) attains a value of 1 under ideal operating conditions. Its value lies within the range of 0 to 1, with values closer to unity indicating superior system reliability. Conversely, lower BCSRIR values highlight deficiencies and signify the need for improvements to enhance the reliability of the belt conveyor system.

3.6 Sensitivity Analysis

Sensitivity analysis is conducted to assess the robustness and reliability of the proposed index. It also serves as a systematic approach to examine how variations in one or more input parameters of a mathematical model influence the resulting output. Such variations may have either positive or negative effects on the model's outcome. This analytical technique is widely applied in decision-making models to identify key variables that significantly impact the final results.

In the present study, sensitivity analysis is carried out by altering the numerical values associated with reliability attributes, specifically those represented by the diagonal elements of the reliability matrix and observing the corresponding changes in the reliability index. During this process, the interrelationships among the reliability attributes are maintained unchanged. The findings derived from the sensitivity analysis are useful in identifying the most influential attributes that critically affect the reliability performance of the belt conveyor system.

3.7 Illustrative Case Example

For the implementation of the above framework, an illustrative case example of a belt conveyor system in a sugar plant located in western India has been considered.

3.7.1 Sugar plant belt conveyor system.

The belt conveyor handles sugar bags of 50 Kg. The ambient temperature of the workplace is 10 - 45°C. There is always dusty conditions. The conveyor is 110 meters long, and belt width is 600 mm. The belt material is nylon-PVC reinforced, which has anti-abrasion resistance properties. The conveyor inclination is 30 degrees, and after that, the lift is 10 meters. The conveyor is driven by three set shaft-mounted electric motors with a fluid coupling, and a helical gearbox is used for speed reduction. The three motors have a capacity of 5 kW, with a belt speed of 1.5m/s. The idler spacing is 1.2 meters. A screw take-up at the tail end of the system is used for belt tensioning. The sugar bag of 50 Kg transfer rate is 7000 No's per 24 hours in the sugar cane crushing season. The system transfers bags from the bagging section to the storage section. Maintenance walkways and monitoring ports are provided every 5 meters. For enhancing safety, emergency stop buttons are provided every 10 meters. For maintaining anonymity, the belt conveyor is designated as 'Sugar Plant Conveyor (SPC)'

First, the AHP process is used to determine the reliability attribute weightage (W_i). Matrix expression (3.6) shows a pairwise comparative matrix of the reliability attribute utilizing Saaty's 1–9 scale. It is displayed as a matrix "Z."

Reliability Attributes	FD	MP	OE	HF	SD
FD	1	1	6	3	0.12
MP	1	1	8	4	0.25
OE	0.17	0.12	1	0.5	0.11
HF	0.33	0.25	2	1	0.11
SD	8	4	9	9	1

$$Z = \begin{bmatrix} 1 & 1 & 6 & 3 & 0.12 \\ 1 & 1 & 8 & 4 & 0.25 \\ 0.17 & 0.12 & 1 & 0.5 & 0.11 \\ 0.33 & 0.25 & 2 & 1 & 0.11 \\ 8 & 4 & 9 & 9 & 1 \end{bmatrix} \quad (3.6)$$

The weight (W_i) of each attribute assessed using AHP is presented in Table 3.8

Table 3.8 Weight (W_i) of each attribute

Reliability Attributes	**Normalized relative weight (W_i)**
FD	0.14
MP	0.18
OE	0.03
HF	0.05
SD	0.60

Each attribute has been assessed on a scale of 0-2 by the team of specialists, with visits to the site of belt conveyor installation according to the parameters outlined in Tables 3.2 to 3.6. Table 3.9 is formed based on sugar plant belt conveyor evaluations.

Table 3.9 Sub-attributes Evaluation of Sugar Plant

Attribute (A_i)	Sub-Attributes (A_{ij})	SPC	
		Evaluation	Sub-factor Score (E_{ij})
FD (A_1)	A_{11}	None	0
	A_{12}	Average	1
	A_{13}	None	0
	A_{14}	None	0
	A_{15}	High	2
	A_{16}	None	0
MP (A_2)	A_{21}	High	2
	A_{22}	High	2
	A_{23}	High	2
	A_{24}	High	2
	A_{25}	High	2
	A_{26}	High	2
OE (A_3)	A_{31}	Average	1
	A_{32}	Average	1
	A_{33}	High	2
	A_{34}	Average	1
	A_{35}	Average	1
	A_{36}	Average	1
HF (A_4)	A_{41}	High	2
	A_{42}	Average	1
	A_{43}	High	2
	A_{44}	High	2
	A_{45}	High	2
	A_{46}	Average	1
SD (A_5)	A_{51}	Average	1
	A_{52}	Average	1
	A_{53}	High	2
	A_{54}	Average	1
	A_{55}	High	2
	A_{56}	High	2
	A_{57}	Average	1
	A_{58}	None	0
	A_{59}	Average	1
	A_{60}	Average	1

An illustration of the evaluation of attributes for the sugar plant conveyor is shown with the attribute 'Fault Diagnosis'. The sub-attribute scores are given in Table 3.9. Using equation 3.4, FD attributes score for SPC = 0.14 × 3 = 0.42 where Wi = 0.14 and $\sum E_{ij}$ = 3. Similarly, other factors are also evaluated for SPC

$$B_{R(SPC)} = \begin{bmatrix} 0.98 & 4 & 0 & 1 & 0 \\ 3 & 0.64 & 3 & 1 & 3 \\ 0 & 1 & 0.21 & 3 & 2 \\ 3 & 3 & 1 & 0.40 & 0 \\ 3 & 3 & 2 & 3 & 7.8 \end{bmatrix} \quad (3.8)$$

The BCSRF is obtained from the permanent of the reliability matrix shown in expression (3.8) on the lines of equation (3.3) and obtained as Per BR(SPC) = 2485.11. Hence, the reliability index of the belt conveyor system SPC 2485.11

To compute the Ideal Belt Conveyor System Reliability Index (IBCSRI), an idealized system configuration is assumed in which all reliability sub-attributes attain their maximum possible scores. Specifically, each sub-attribute associated with the main reliability attributes is assigned the highest value of 2, as defined by the adopted scoring scheme.

Under these optimal conditions, an equivalent matrix representing the ideal belt conveyor system is constructed, wherein all A_i values are set to their maximum levels. This idealized matrix is expressed in Equation (3.9).

$$B_{R(ideal)} = \begin{bmatrix} 1.68 & 4 & 0 & 1 & 0 \\ 3 & 2.16 & 3 & 1 & 3 \\ 0 & 1 & 0.36 & 3 & 2 \\ 3 & 3 & 1 & 0.60 & 0 \\ 3 & 3 & 2 & 3 & 12 \end{bmatrix} \quad (3.9)$$

Per ($B_{R(ideal)}$)= 4180.81

Hence, the IBCSRI=4180.81

The BCSRIR of the belt conveyor system of SPC can now be evaluated using the expression (3.5)

For SPC

BCSRIR= 2485.11/4180.81=0.594

3.7.2 BCSRI Sensitivity Analysis

A sensitivity analysis of the Belt Conveyor System Reliability Index (BCSRI) is conducted to assess the impact of variations in reliability attributes on the overall index value. This analysis demonstrates the robustness and applicability of the proposed index under practical operating conditions. The percentage variation in the BCSRI is determined with respect to proportional changes in the reliability attributes corresponding to the diagonal elements of the equivalent reliability matrix for the system under consideration (SPC).

For this purpose, the scores of each reliability attribute are increased by 10%, and the corresponding percentage change in the BCSRI is evaluated. The outcomes of this analysis are presented in Table 3.10. Furthermore, Figure 3.2 illustrates the percentage increase in the BCSRI resulting from a 10% increment in the attribute scores for each reliability attributes of the SPC system. The observed trends indicate that the BCSRI responds to changes in reliability parameters, thereby confirming the sensitivity and robustness of the proposed model. Additionally, the model is characterized by clarity, ease of interpretation, and practical usability

Table3.10. Sensitivity analysis results of SPC

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

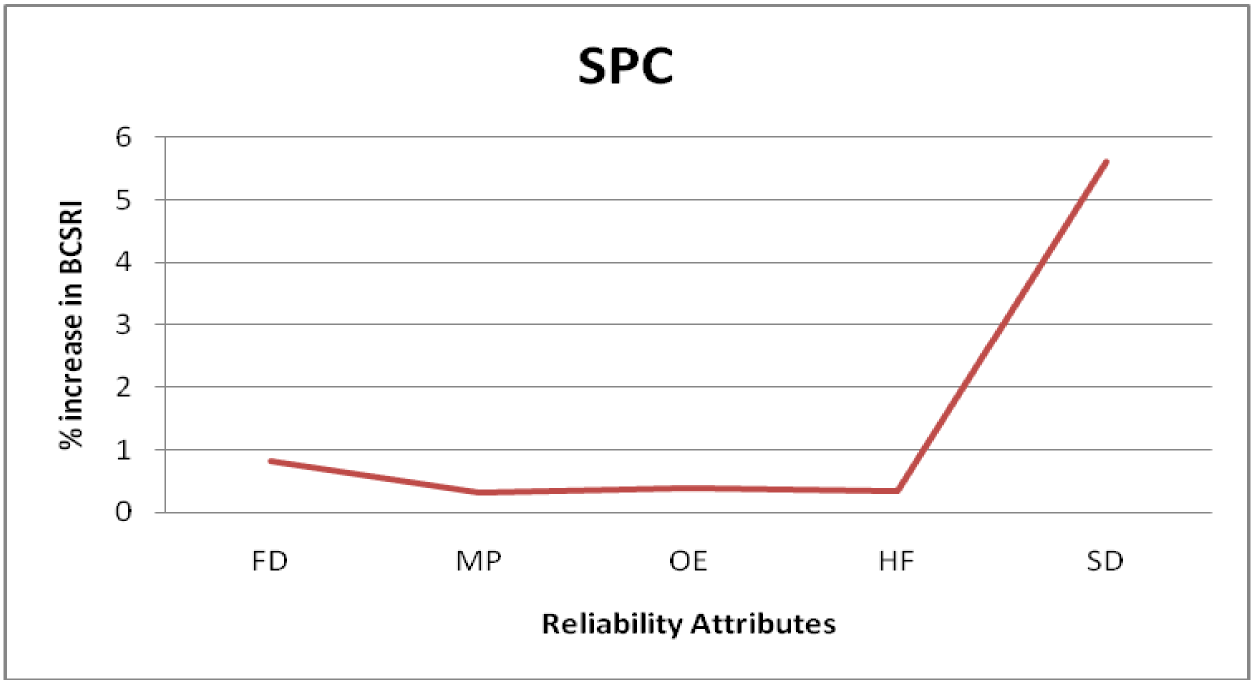

Figure 3.2 Sensitivity analysis of SPC

3.8 Results and Discussions

The framework was applied to a sugar plant. The system's reliability attributes and sub-attributes were evaluated using expert scoring and AHP-based weightage assignment. The evaluated belt conveyor system reliability index for the sugar plant conveyor is 2485.11, while the ideal index (IBCSRI) was 4180.81, resulting in a BCSRIR of SPC equaling 0.594. These values reflect a moderate level of reliability, indicating room for improvement. Sensitivity analysis revealed that system design is the most significant attribute of the reliability index, showing a 5.97 percentage increase in BCSRI with a 10% improvement in its score for SPC. Other attributes showed comparatively less sensitivity. These insights suggest that investment in design enhancements such as modularity, control integration, and dynamic load management can significantly improve reliability outcomes.

CHAPTER 4

FAILURE MODE AND EFFECTS ANALYSIS OF HYDRAULIC DIRECT DRIVE

This chapter deals with failure mode and effect analysis of hydraulic direct drive, which is an important subsystem of the belt conveyor systems. This study identifies 18 potential FMs for the hydraulic direct drive, which constitutes the drive unit of the belt conveyor system installed at a 750MW thermal power station in western India, using the consensus of five experts and the literature. Using the hybrid approach of FAHP and FTOPSIS, the FMs were ranked. The results can be used by operators of belt conveyor installations to design preventive maintenance programs for critical components of the hydraulic direct drive.

4.1 Introduction.

Maintaining high reliability in belt conveyor systems is of critical importance, given the substantial financial implications associated with production interruptions [14]. Structurally, a belt conveyor system comprises multiple components, including the belt, pulleys, idlers, take-up mechanism, and drive unit, with braking systems incorporated where necessary [8]. The overall reliability of the system is dependent on the performance and reliability of these individual components.

Belt conveyors are powered through either mechanical or electrical drive systems designed to overcome resistance arising from inertia, frictional losses, and gravitational forces. The drive unit supplies power to the pulley, which subsequently transmits motion to the belt. Typically, conventional drive systems consist of electric motors coupled with gearboxes and couplings. Despite their widespread use, such configurations exhibit inherent inefficiencies, particularly within gearbox and coupling mechanisms. Although electric motors generally operate with fewer issues, gearbox-related limitations remain significant. Amin [9] noted that gearboxes are often oversized, less stable, and lack flexibility once a fixed gear ratio is established, thereby preventing operation at optimal speeds. Additionally, gearbox components demand frequent maintenance, especially under harsh environmental conditions characterized by high temperatures and contamination.

In recent years, the adoption of high-capacity belt conveyor systems operating under demanding conditions has increased, particularly in modern power plants. Under such challenging circumstances, hydraulic direct drive systems have emerged as a viable and efficient alternative. These systems are particularly advantageous for applications requiring the movement of heavy loads at variable speeds while accommodating shock loads and ensuring reliable and energy-efficient performance [9]. Compared to conventional electrical drives, hydraulic direct drives offer enhanced power density, improved energy efficiency, smoother operational control during start and stop phases, and greater overall reliability. Furthermore, they contribute to reduced total cost of ownership, including savings in maintenance, space requirements, and energy consumption.

Industry experts have identified several benefits associated with the use of hydraulic direct drives as the primary driving mechanism for belt conveyors. These advantages include the ability to start and stop the system frequently without operational constraints, seamless speed variation from zero to maximum, and precise control over acceleration and deceleration. Additional benefits include ease of maintenance through inching operations in both forward and reverse directions, consistent torque availability across the entire speed range, elimination of the need for oversized electrical components, and extended belt life due to integrated overload protection. Moreover, the simplified system design eliminates the need for gearboxes, V-belts, fluid couplings, and other complex mechanical components. The structural configuration of the hydraulic direct drive system, illustrated in Figure 4.1, represents a subsystem within the overall belt conveyor system.

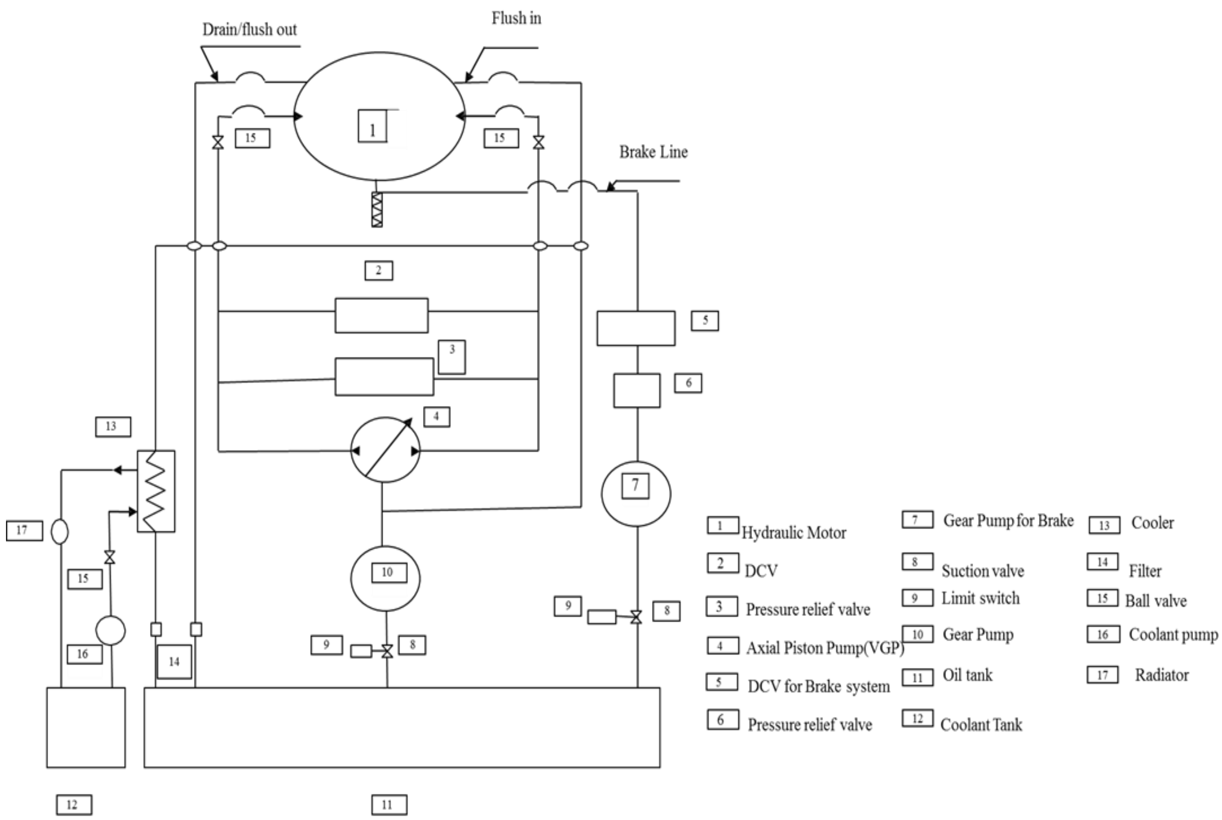

Figure 4.1 Schematic diagram of hydraulic direct drive in a belt conveyor installation

Oil stored in the reservoir is initially drawn by a gear pump and subsequently delivered to an axial piston pump, where it is pressurized to the required operating level. The flow direction of this pressurized fluid is regulated using a directional control valve. Thereafter, the high-pressure oil is supplied to a radial piston hydraulic motor through a ball valve, which functions as a flow-regulating component. The radial piston hydraulic motor serves as a mechanical actuator that transforms hydraulic energy into rotational motion, offering superior torque output at low speeds compared to axial piston motors. The rotational output generated at the motor shaft is utilized to drive the belt conveyor system.

In addition to power transmission, the hydraulic fluid performs a damping function by absorbing load fluctuations within the conveyor system. After completing its cycle, the fluid is returned to the reservoir via a drain or flush-out line. A filtration unit is installed along the return path to remove contaminants such as dust, debris, and other particulate matter, thereby maintaining fluid cleanliness and system reliability. Before the system starts up, an adequate volume of oil is ensured within the casing of the radial piston motor, and the braking mechanism is engaged. The braking system facilitates controlled stopping and holding of the conveyor whenever required. To safeguard the system against excessive pressure buildup, a pressure relief valve is incorporated. Furthermore, maintaining the hydraulic fluid within an acceptable temperature range is essential; hence, a cooling arrangement comprising a radiator and a motor-driven coolant pump is integrated into the system.

Based on the configuration and working principle of the hydraulic direct drive, it is evident that the system consists of multiple interconnected components, each performing a distinct function. Since the belt conveyor operation is critically dependent on the hydraulic direct drive, any failure within this subsystem can potentially lead to a complete shutdown of the plant. Therefore, evaluating the severity and impact of individual failure modes (FMs) on the overall system necessitates a systematic Failure Mode and Effects Analysis (FMEA).

Failure Mode and Effects Analysis (FMEA) is a systematic and proactive approach used to identify, assess, and mitigate potential failures within systems, designs, processes, or services [39]. The traditional FMEA process begins with the comprehensive identification of all possible failure modes. These failure modes are subsequently evaluated and prioritized based on their associated risk levels using the Risk Priority Number (RPN), as introduced by Cai et al.[40].

The RPN is determined by considering three critical risk parameters: severity (S), occurrence (O), and detection (D). The severity factor quantifies the extent of the impact that a particular failure mode has on overall system performance, with higher values indicating more significant consequences. The occurrence parameter reflects the likelihood or frequency with which a failure may arise, whereas the detection factor represents the probability of identifying the failure prior to its occurrence. A higher detection rating signifies greater difficulty in detecting failure in advance.

Failure modes characterized by high severity, frequent occurrence, and low detectability (i.e., high D value) are considered highly critical, as they pose significant risks to system operation. In traditional FMEA, each of these risk factors is assigned a numerical rating, typically within the range of 1–10 or 1–5 [41, 42]. The RPN is then calculated as the product of these three parameters [43], and the resulting values are ranked in descending order. The failure mode with the highest RPN is identified as the most critical contributor to system failure.

Despite its widespread application, conventional FMEA has several limitations. Researchers such as [44, 45, 46], and Wang et al. [47] have highlighted concerns regarding the RPN calculation methodology. These limitations include the equal weighting assigned to all risk factors, which may not accurately reflect real-world conditions, and the possibility of different combinations of severity, occurrence, and detection ratings yielding identical RPN values despite representing varying levels of risk. Additionally, accurately assigning numerical ratings to risk factors in practical scenarios can be challenging, and the multiplicative nature of the RPN calculation makes it highly sensitive to variations in input parameters.

To overcome the limitations of conventional approaches, fuzzy multi-criteria decision-making (MCDM) techniques have attracted considerable attention in recent years. Fuzzy-based FMEA frameworks offer enhanced flexibility and a more realistic representation of uncertainty and subjectivity inherent in risk evaluation, thereby improving the robustness of decision-making outcomes [48].

A comprehensive review of existing literature indicates that the application of Failure Mode and Effects Analysis (FMEA) to the hydraulic direct drive subsystem of belt conveyor systems has not been adequately explored. In response to this research gap, the present study conducts a detailed FMEA focused specifically on the hydraulic direct drive system. The key objectives are to systematically identify potential failure modes (FMs) that could compromise the functioning of the entire belt conveyor system and to rank these failure modes according to the severity of their consequences.

To achieve these objectives, a hybrid analytical framework combining the Fuzzy Analytic Hierarchy Process (FAHP) and the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS) is employed, enabling a more comprehensive and reliable prioritization of failure modes under uncertain conditions.

4.2. Methodology

As previously stated, the criticality of FMs is traditionally established by RPN in conventional FMEAs. However, several academics have voiced their concerns about this approach. Hence, in this chapter, FMEA of a hydraulic direct drive of a belt conveyor system, which is part of a thermal power plant, was completed by using the fuzzy-based MCDM techniques FAHP and FTOPSIS. The formation of the FMEA team, which was made up of five specialists, was the first step in the FMEA process. Table 4.1 includes the list of experts and their expertise.

Table 4.1 List of experts

Sr.No	Designation	Domain of expertise	Experience
1	Senior Engineer, Maintenance Department	Moving and material handling equipment (MMHE) division of the thermal Power Plant	8 years
2	Manager, Maintenance Dept	MMHE division of thermal Power Plant	15 years
3	Senior Engineer, Maintenance Department	MMHE division of a fertilizer company	8 years
4	Managing Director	MMHE division of the sugar plant	15 years
5	Senior Engineer, Maintenance Department	MMHE division of milk dairy	10 years

Based on the consensus of the experts, eighteen potential FMs for the hydraulic direct drive were identified and are enumerated in Table 4.2.

Table 4.2.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

4.2.1 Procedure of Fuzzy AHP

In 1965, Zadeh invented and refined the fuzzy theory that translates the language factors involved in managerial decision-making onto a numerical scale. Following on from previous fuzzy research, Bellman and Zadeh [145] used fuzzy theory with a multi-criteria decision to estimate the relative importance of several factors. However, AHP isn't without its flaws, such as its failure to straighten out the chaos and/or uncertainty linked to the mapping of expert assessment into a specific number [146]. This is because the AHP method relies on comparison evaluations made by experts, and experts may not always make reliable value judgments [147]. This procedure may consequently be dominated by the uncertainty of the vagueness type. The confidence of decision-makers is often boosted when they are given a choice between interval ranges rather than a single numerical value. Most computational and mathematical tools also necessitate extremely exact numbers. The qualitative and unpredictable facets of the choice-making process are not captured by these models. To efficiently handle these differences and uncertainties, one can employ Fuzzy Set Theory [145], which can evaluate qualitative and incomplete information [148]. The Analytical Hierarchy Process (AHP) is a well-established method, whereas the Fuzzy Logic Theory (FLT) is a relatively new approach. Effective and efficient decisions that may be ambiguous can be made with the help of fuzzy AHP [149]. Here are the steps needed to apply Fuzzy AHP [150] for determining relative importance.

Step 1: Development of a pairwise comparison matrix.

This step performs a pairwise comparison of the RFs using linguistic terms like "extremely high importance" (EHI), "very high importance" (VHI), "high importance," (HI), "moderately high importance" (MHI), "equally important" (EI), "moderately low importance" (MLI), "low importance," (LI), and "extremely low importance" (ELI) are gathered from the experts. The fuzzy pairwise judgment matrix 'R' is then created using their equivalent triangular fuzzy numbers, as shown in equation (4.1). When there are multiple experts present, R is calculated using the combined values of all the experts.

$$R = \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{n1} & \tilde{r}_{n2} & \cdots & \tilde{r}_{nn} \end{bmatrix} \quad (4.1)$$

where, $\tilde{r}_{ij} = \left(r_{ij}^{l}, r_{ij}^{m}, r_{ij}^{u}\right)$ denotes the importance of risk factor 'i ' in comparison with risk factor 'j' in terms of fuzzy numbers. The range of variation of the variables i and j is from 1 to n.

Step 2: Computation of geometric mean $\widetilde{gm}_i = (gm_i^l, gm_i^m, gm_i^u)$of each RF

This stage uses equation (4.2) for the computation of the geometric mean.

$$\tilde{g}_i = \begin{Bmatrix} gm_i^l = (r_{i1}^l \times r_{i2}^l \times r_{i3}^l \dots\dots\dots \times r_{in}^l)^{1/n} \\ gm_i^m = (r_{i1}^m \times r_{i2}^m \times r_{i3}^m \dots\dots\dots \times r_{in}^m)^{1/n} \\ gm_i^u = (r_{i1}^u \times r_{i2}^u \times r_{i3}^u \dots\dots\dots \times r_{in}^u)^{1/n} \end{Bmatrix} \quad (4.2)$$

Step 3: Determination of weight $\widetilde{w}_i = (w_i^l, w_i^m, w_i^u)$of the RF using equation (4.3).

$$\widetilde{w}_i = \begin{Bmatrix} w_i^l = \frac{g_i^l}{gm_1^u + gm_2^u + gm_3^u \dots\dots\dots + gm_n^u} \\ w_i^m = \frac{g_i^m}{gm_1^m + gm_2^m + gm_3^m \dots\dots\dots + gm_n^m} \\ w_i^u = \frac{g_i^l}{gm_1^l + gm_2^l + gm_3^l \dots\dots\dots + gm_n^l} \end{Bmatrix} \quad (4.3)$$

Step 4: Performing the consistency check

To make sure that the expert judgments and views are consistent, each fuzzy pairwise comparison matrix must be validated for consistency. It is done by putting a clear number in place of each fuzzy number in the fuzzy pairwise comparison matrix, which is called "defuzzifying" the matrix. Using the value-graded mean integration method [151], the defuzzification is done in this work. The consistency is evaluated according to Piya et al.[152]. If the CR is less than 0.10, the matrices can be considered consistent; otherwise, the pairwise comparison must be performed again.

4.2.2 FTOPSIS (Fuzzy Technique for Order of Preference by Similarity to Ideal Solution)

Hwang and Yoon [153] presented TOPSIS, and Yoon [154] improved upon it. Due to its ease of use and effectiveness, this technique is widely used by researchers across disciplines to address decision-making issues. The fuzzy TOPSIS (FTOPSIS) method was developed by fusing the standard TOPSIS approach with fuzzy set theory to deal with the information's inherent inconsistencies and fuzziness [155]. The steps of FTOPIS's methodical process are as follows:

Step 1: Development of a fuzzy decision matrix $(\widetilde{D})$

A $(\widetilde{D})$ is the matrix that uses fuzzy scoring to evaluate various FMs based on RFs.Various linguistic variables, such as very low (VL), low (L), medium (M), medium high (MH), high (H), and very high (VH) RFs, are used by decision-makers to assess newly identified FMs [156]. Following that, their equal triangular fuzzy numbers are used to create$(\widetilde{D})$.

To generate a robust ranking, multiple decision-makers' perspectives are taken into account. As a result, if there are '*m*' decision-makers, each FM's aggregate fuzzy score is computed using equation (4.4).

$$\tilde{a}_{i,j} = \frac{1}{m}(\tilde{a}_{i,j}^{1} + \tilde{a}_{i,j}^{2} + \dots\dots\dots \tilde{a}_{i,j}^{m}) \quad (4.4)$$

Where, $\tilde{a}_{i,j}$ denotes the aggregate fuzzy score for i^{th} FM for j^{th} RF and $\tilde{a}_{i,j}^{m}$ denotes the fuzzy score for i^{th} FM for j^{th} RF obtained from m^{th} decision-maker. As a result, the aggregated fuzzy score obtained is organized in rows and columns as defined by $(\widetilde{D})$ as given in equation (4.5).

$$(\widetilde{D}) = \begin{bmatrix} \tilde{a}_{1,1} & \cdots & \tilde{a}_{1,j} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{i,1} & \cdots & \tilde{a}_{i,j} \end{bmatrix}_{R\times S} \quad (4.5)$$

Where i and j can be any number from 1 to R or S. R is the number of FM and S is the number of RF.

Step 2: Normalization of $(\widetilde{D})$

The normalization technique is used to turn a wide range of criteria in various units into a comparable range. A normalization operation can be performed in a variety of ways. The TOPSIS technique, on the other hand, employs the linear scale transformation [45]. Normalization for advantageous criteria is achieved with equation (4.6), while normalization for cost criteria is performed using equation (4.7), which led to the creation of the normalized matrix given by equation (4.8).

$$\widetilde{N}_{i,j} = \left(\frac{\tilde{a}_{i,j}}{\max_i(max(a_{i,j}^{l},\ a_{i,j}^{m},\ a_{i,j}^{u})}\right) \quad (4.6)$$

$$\widetilde{N}_{i,j} = \left(\frac{\min_i(min(a_{i,j}^{l},\ a_{i,j}^{m},\ a_{i,j}^{u})}{\tilde{a}_{i,j}}\right) \quad (4.7)$$

$$\widetilde{ND} = [\widehat{N}_{i,k}]_{R\times S} \quad (4.8)$$

Where,$\widetilde{N}_{i,j}$ shows the value that has been normalized for the element $\tilde{a}_{i,j}$of the decision matrix. $\widetilde{ND}$ shows the decision matrix that has been normalized.

Step 3: Formulation of Weighted normalized fuzzy decision matrix ($\widetilde{WND}$)

Every criterion is weighted differently from the others. Weights show the importance of each condition. The weights are used to build $\widetilde{WND}$ as given by equation (4.9).

$$\widetilde{wN}_{i,j} = \widetilde{N}_{i,j} \times w_j \tag{4.9}$$

Where, $\widetilde{wN}_{i,j}$ depicts the weighted normalized value corresponding to the element $\widetilde{N}_{i,j}$ of the normalized decision matrix. w_j denotes the weight of the risk factor ' j'.

Step 4: Evaluate the distance between the positive ideal solution (ISN^+) and the negative ideal solution (ISN^-)

The TOPSIS technique ranks alternatives based on their distance from ISN^+ and ISN^-. $\widetilde{WND}$ consists of fuzzy numbers that are in the range from 0 to 1. Hence, ISN^+ and ISN^- are defined according to equations (4.10) and (4.11), respectively.

$$ISN^+ = (\tilde{l}_1^+, l_2^+, \ldots\ldots\ldots.., \tilde{l}_S^+) \tag{4.10}$$

$$ISN^- = (\tilde{l}_1^-, \tilde{l}_2^-, \ldots\ldots\ldots\ldots, \tilde{l}_S^-) \tag{4.11}$$

where, $\tilde{l}_j^+ = (1,1,1)$ and $\tilde{l}_j^- = (0,0,0)$

The distance between two fuzzy integers is estimated using the Euclidean distance formula to indicate how far away a certain solution choice is from being optimal. If $\tilde{m}$ and $\tilde{n}$ are two fuzzy numbers, then equation (4.12) is used to calculate the Euclidean distance between them.

$$d(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2]} \tag{4.12}$$

where, $\tilde{m} = (m_1, m_2, m_3)$ and $\tilde{n} = (n_1, n_2, n_3)$

With equation (4.12), the distance of an alternative from ISN^+ and ISN^- is obtained. The distance is measured for each FM, and the algebraic total is regarded as the aggregated distance of an FM from ISN^+ and ISN^-. Equation (4.13) is utilized to evaluate the distance between the alternatives from ISN^+, and equation (4.14) is used to formulate the distance from ISN^-.

$$X_i^+ = \sum_{j=1}^{Q} d(\widetilde{wN}_{i,j}, \tilde{l}_j^+) \tag{4.13}$$

$$X_i^- = \sum_{j=1}^{Q} d(\widetilde{wN}_{i,j}, \tilde{l}_j^-) \tag{4.14}$$

Step 4: Evaluation of closeness coefficient (CC_i)

The CC_i is used to determine FM ranking. Equation (4.15) is used to obtain the closeness coefficient of an alternative that is an FM in the current case.

$$CC_i = \frac{X_i^-}{X_i^+ + X_i^-} \quad (4.15)$$

The greater the value of CC_i, the closer the FM is to ISN^+ and farther from ISN^-. This means the FM with the highest CC_i value comes out on first rank and the ranks of the FMs fall as the CC_i values decrease.

4.3. Methodology implementation for hydraulic direct drive

In this section, the methodology is implemented for the risk prioritizing of the FM of hydraulic direct drives. FAHP is implemented first for assigning the risk factor weights, which is followed by the implementation of fuzzy TOPSIS for prioritization of various failure modes of hydraulic direct drive. Figure 4.2 depicts the research methodology structure.

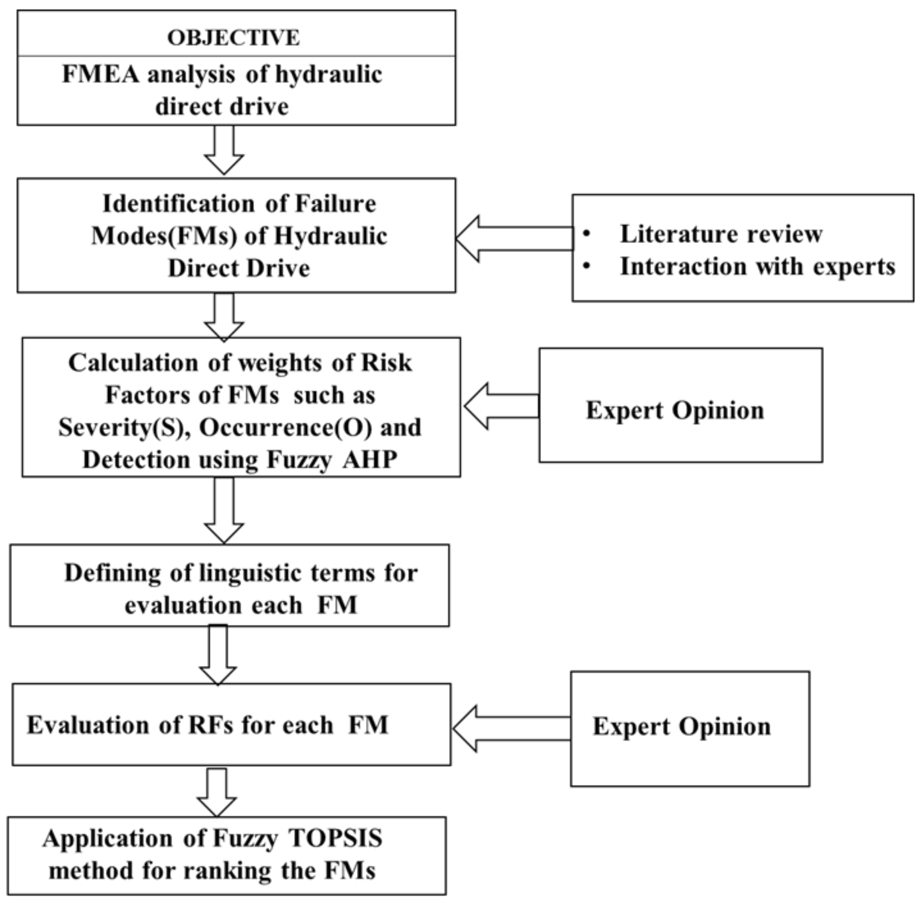

Figure 4.2 Research methodology structure

4.3.1. Implementation of FAHP

The FMs that were found were assessed utilizing three RFs, namely S, O, and D, before their ranking. These RFs are viewed as equally important in conventional FMEA, which is not the case for real-world conditions. Hence, FAHP was utilized to obtain RF weights. Initially, experts' opinions regarding pairwise comparisons of RFs in LVs were assimilated and displayed in Table 4.3.

Table 4.3 Pair-wise comparison of RFs.

Risk Factor	S	O	D
S	(EI, EI, EI, EI, EI)	(MHI, HI, HI, HI, EI)	(LI, LI, VHI, HI, MLI)
O	(MLI, LI, LI,LI, EI)	(EI, EI, EI, EI, EI)	(VHI, LI, HI, VLI, VLI)
D	(HI, HI, VLI, LI, MHI)	(VLI, HI, LI, VHI, VHI)	(EI, EI, EI, EI, EI)

The linguistic values (LVs) of the pairwise comparison matrix were converted into triangular fuzzy numbers such as; ELI: (1/10,1/9,1/8), VLI: (1/8, 1/7, 1/ 6), LI: (1/6, 1/5, 1/4), MLI: (1/4, 1/3, 1/2), EI: (1, 1, 1), MHI: (2, 3, 4), HI: (4, 5, 6), VHI: (6, 7, 8), EHI: (8, 9, 10) according to [59]. Consequently, the fuzzy pairwise comparison matrix is obtained, which is shown in Table 4.4.

Table 4.4 Fuzzy pairwise comparison matrix

Risk Factor	S	O	D
S	(1, 1, 1)	(2.63, 3.27, 3.87)	(0.7, 0.86, 1.08)
O	(0.26, 0.30, 0.38)	(1, 1, 1)	(0.57, 0.68, 0.8)
D	(0.92, 1.16, 1.43)	(0.57, 0.14, 0.33)	(1, 1, 1)

Using equation (4.2), the determination of the geometric means of the RFs was accomplished and the weight vector was calculated according to equation (4.3), as shown in Table 4.5.

Table 4.5 Weight vector

Risk Factor	The fuzzy geometric mean value	Weight	Defuzzified weight
S	(1.22,1.41,1.61)	(0.38, 0.48, 0.59)	0.485
O	(0.59,0.65,0.73)	(0.21, 0.33, 0.29)	0.277
D	(0.80,0.54,0.77)	(0.25,0.18,0.28)	0.238

Based on the results from Table 4.5, the most significant risk factor is the Severity (S) with a weight of 0.485. This indicates that hydraulic direct drive failure is a severe failure that can impact the overall functioning of the belt conveyor and eventually the power plant where this conveyor is installed. The next risk factor is the occurrence (O) of hydraulic direct drive failures with a weightage of 0.277, which is followed by the detection (D) having a weightage of 0.238.

The consistency of the comparison matrix was calculated, and it was determined to be 0.05, validating the FAHP's conclusions. A consistency of less than 0.1 indicates that the FAHP approach is effective.

4.3.2 Implementation of FTOPSIS

Using the FAHP priority of the RFs, the FTOPSIS method established the rank of the discovered FMs. The initial stage in implementing the FTOPSIS approach was the creation of a fuzzy decision matrix$(\widetilde{D})$. $\widetilde{D}$ was determined by comparing the LVs of each FM to those of the RFs. Table 4.6 is developed according to Liu et al.,[156] for converting LVs into fuzzy numbers Table 4.7 summarizes the experts' perspectives on linguistic variables for the risk factors for each of the FMs. Each expert provided a rating of FMs for each of the RFs. The ratings provided by the first, second, third, fourth, and fifth experts are listed in Table 4.7.

Table 4.6 Linguistic variables and equivalent triangular fuzzy number

Sr.No	Linguistic variables	Triangular fuzzy number
1	Very low (VL)	(0, 0, 1)
2	Low (L)	(0, 1, 3)
3	Medium low (ML)	(1, 3, 5)
4	Medium (M)	(3, 5, 7)
5	Medium high(MH)	(5, 7, 9)
6	High (H)	(7, 9, 10)
7	Very high (VH)	(9, 10, 10)

Table 4.7 Evaluation of the Failure Modes (FM) in Linguistic Variables (LV)

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Failure Mode	Occurrence (O)	Severity (S)	Detection (D)
FM1	(M,MH,MH,MH,MH)	(M,MH,MH,MH,MH)	(H,H,H,H,H)
FM2	(MH,MH,MH,MH,M)	(H,H,H,H,H)	(MH,H,MH,H,MH)
FM3	(MH,H,MH,MH,MH)	(H,H,H,H,H)	(MH,MH,MH,MH,MH)
FM4	(MH,M,M,M,M)	(MH,MH,MH,MH,MH)	(H,H,H,H,H)
FM5	(MH,MH,MH,H,H)	(VH,VH,VH,VH,VH)	(H,H,H,H,H)
FM6	(L,L,L,VL,L)	(H,MH,MH,MH,M)	(MH,H,MH,MH,MH)
FM7	(H,H,H,H,H)	(VH,VH,VH,H,H)	(H,MH,MH,MH,MH)
FM8	(H,H,H,H,H)	(VH,VH,VH,VH,H)	(H,H,MH,MH,MH)
FM9	(MH,MH,H,H,MH)	(MH,MH,MH,MH,MH)	(VH,H,H,H,H)
FM10	(MH,H,MH,H,MH)	(H,H,H,H,H)	(H,H,H,H,H)
FM11	(MH,MH,H,MH,H)	(H,H,VH,VH,VH)	(H,H,H,H,MH)
FM12	(M,MH,MH,MH,MH)	(H,H,H,H,H)	(H,H,H,H,H)
FM13	(M,L,L,L,L)	(MH,M,M,MH,MH)	(H,H,H,H,H)
FM14	(MH,MH,MH,M,M)	(H,VH,VH,VH,VH)	(H,H,H,MH,MH)

FM15	(H,H,H,H,H)	(VH,VH,VH,VH,VH)	(MH,MH,MH,MH,MH)
FM16	(MH,MH,MH,M,M)	(MH,MH,H,MH,MH)	(H,H,H,H,H)
FM17	(M,MH,MH,MH,M)	(H,H,H,H,H)	(H,H,H,H,H)
FM18	(MH,MH,MH,MH,H)	(H,H,H,H, H)	(H,MH,MH,MH,MH)

The transformation of LVs into fuzzy numbers is done according to Table 4.6, and the Fuzzy Decision Matrix for Evaluation of the FMs is shown in Table 4.8.

Table 4.8 Fuzzy Decision Matrix for Evaluation of the FMs

Failure Mode	**Occurrence (O)**	**Severity (S)**	**Detection (D)**
FM1	(4.6, 6.6, 8.6)	(4.6, 6.6, 8.6)	(7, 9, 10)
FM2	(4.6, 6.6, 8.6)	(7, 9, 10)	(5.8, 7.8, 9.4)
FM3	(5.4, 7.4, 9.2)	(7, 9, 10)	(5, 7, 9)
FM4	(3.4, 5.4, 7.4)	(5, 7, 9)	(7, 9, 10)
FM5	(5.8, 7.8, 9.4)	(9, 10, 10)	(7, 9, 10)
FM6	(0, 0.8, 2.6)	(5, 7, 8.8)	(5.4, 7.4, 9.2)
FM7	(7, 9, 10)	(8.2, 9.6, 10)	(5.4, 7.4, 9.2)
FM8	(7, 9, 10)	(8.6, 9.8, 10)	(5.8, 7.8, 9.4)
FM9	(5.8, 7.8, 9.4)	(5, 7, 9)	(7.4, 9.2, 10)
FM10	(5.8, 7.8, 9.4)	(7, 9, 10)	(7, 9, 10)
FM11	(5.8, 7.8, 9.4)	(8.2, 9.6, 10)	(6.6, 8.6, 9.8)
FM12	(4.6, 6.6, 8.6)	(7, 9, 10)	(7, 9, 10)
FM13	(0.6, 1.8, 3.8)	(4.2, 6.2, 8.2)	(7, 9, 10)
FM14	(4.2, 6.2, 8.2)	(8.6, 9.8, 10)	(6.2, 5.2, 9.6)
FM15	(7, 9, 10)	(9, 10, 10)	(5, 7, 9)
FM16	(4.2, 6.2, 8.2)	(5.4, 7.4, 9.2)	(7, 9, 10)
FM17	(4.2, 6.2, 8.2)	(7, 9, 10)	(7, 9, 10)
FM18	(5.4, 7.4, 9.2)	(7, 9, 10)	(5.4, 7.4, 9.2)

To avoid the complex normalization formula, the linear scale transformation stated in equations (4.6) to (4.8) was employed to formulate the $\widetilde{WND}$.Each column of $\widetilde{WND}$ is the normalized equivalent RF value for all FMs. Following this, each column's values were multiplied by its corresponding weight to generate weighted normalized values, as defined by equation (4.9). Table 4.9 shows the weighted normalized values that were obtained.

Table 4.9 Weighted normalized Fuzzy Decision Matrix of the FMs.

Failure Mode	Occurrence (O)	Severity (S)	Detection (D)
FM1	(0.0966, 0.2112, 0.4128)	(0.0653, 0.1373, 0.2692)	(0.2226, 0.4248, 0.698)
FM2	(0.0966, 0.2112, 0.4128)	(0.0994, 0.1872, 0.313)	(0.1844, 0.3682, 0.6561)
FM3	(0.1134, 0.2368, 0.4416)	(0.0994, 0.1872, 0.313)	(0.159, 0.3304, 0.6282)
FM4	(0.0714, 0.1728, 0.3552)	(0.071, 0.1456, 0.2817)	(0.2226, 0.4248, 0.698)
FM5	(0.1218, 0.2496, 0.4512)	(0.1278, 0.208, 0.313)	(0.2226, 0.4248, 0.698)
FM6	(0, 0.0256, 0.1248)	(0.071, 0.1456, 0.2754)	(0.1717, 0.3493, 0.6422)
FM7	(0.147, 0.288, 0.48)	(0.1164, 0.1997, 0.313)	(0.1717, 0.3493, 0.6422)
FM8	(0.147, 0.288, 0.48)	(0.1221, 0.2038, 0.313)	(0.1844, 0.3682, 0.6561)
FM9	(0.1218, 0.2496, 0.4512)	(0.071, 0.1456, 0.2817)	(0.2353, 0.4342, 0.698)
FM10	(0.1218, 0.2496, 0.4512)	(0.0994, 0.1872, 0.313)	(0.2226, 0.4248, 0.698)
FM11	(0.1218, 0.2496, 0.4512)	(0.1164, 0.1997, 0.313)	(0.2099, 0.4059, 0.684)
FM12	(0.0966, 0.2112, 0.4128)	(0.0994, 0.1872, 0.313)	(0.2226, 0.4248, 0.698)
FM13	(0.0126, 0.0576, 0.1824)	(0.0596, 0.129, 0.2567)	(0.2226, 0.4248, 0.698)
FM14	(0.0882, 0.1984, 0.3936)	(0.1221, 0.2038, 0.313)	(0.1972, 0.387, 0.6701)
FM15	(0.147, 0.288, 0.48)	(0.1278, 0.208, 0.313)	(0.159, 0.3304, 0.6282)
FM16	(0.0882, 0.1984, 0.3936)	(0.0767, 0.1539, 0.288)	(0.2226, 0.4248, 0.698)
FM17	(0.0882, 0.1984, 0.3936)	(0.0994, 0.1872, 0.313)	(0.2226, 0.4248, 0.698)
FM18	(0.1134, 0.2368, 0.4416)	(0.0994, 0.1872, 0.313)	(0.1717, 0.3493, 0.6422)

Following that, the distance between each FM and the ISN^+ and ISN^- solutions was computed using equations 10 and 11. The TOPSIS method's ranking approach is based on the fact that a critical FM is near the ISN^+ but far from the ISN^-. This fact was described using *CC*, as defined in equation (15). An FM with a *CC* value of one is considered a critical FM. This condition, however, is quite unusual. As a result, the FM with the highest *CC* value received a ranking first, while other FMs with lesser *CC* values were ranked lower. Table 10 illustrates the distance of the FMs from ISN^+, i.e., X_i^+, ISN^-, i.e., X_i^-, CC values, and the resulting rank.

Table 4.10 X_i^+, X_i^-, CC, and rank of Failure Modes

Failure Mode	X_i^+	X_i^-	CC	Rank
FM1	2.202842	0.940892	0.299291	13
FM2	2.203739	0.938939	0.29877	14
FM3	2.210058	0.934815	0.29725	15
FM4	2.232144	0.908311	0.289229	16
FM5	2.110676	1.02402	0.326673	1
FM6	2.433904	0.691575	0.22127	18
FM7	2.144932	0.992323	0.316303	5

FM8	2.127019	1.008263	0.321586	3
FM9	2.153009	0.987183	0.31437	6
FM10	2.128203	1.013089	0.322507	2
FM11	2.131927	1.005493	0.320484	4
FM12	2.160806	0.980653	0.312165	8
FM13	2.359018	0.768995	0.245841	17
FM14	2.187891	0.947456	0.302185	10
FM15	2.152396	0.983271	0.313576	7
FM16	2.200174	0.942117	0.299819	12
FM17	2.173355	0.96672	0.307865	9
FM18	2.1956	0.948396	0.301653	11

The obtained results were also compared to the usual FMEA approach based on RPN calculations. The crisp scores were generated by defuzzifying the fuzzy results obtained during the FM examination. The traditional RPN was then calculated by multiplying the crisp scores. As a result, each FM was assigned a decreasing RPN value, with the FM with the highest RPN value ranking first. Table 4.11 compares conventional RPN to the rank produced with the fuzzy TOPSIS ranking.

Table 4.11 Comparison of FM ranking using Fuzzy TOPSIS with conventional ranking

Failure Mode	Occurrence (O)	Severity (S)	Detection (D)	Conventional RPN	Rank	Fuzzy TOPSIS rank
FM1	6.6	6.6	8.6667	377.52	15	13
FM2	6.6	8.6667	7.6667	438.5334	12	14
FM3	7.3333	8.6667	7	444.8889	11	15
FM4	5.4	7	8.6667	327.6	16	16
FM5	7.6667	9.6667	8.6667	642.2964	1	1
FM6	1.1333	6.9333	7.3333	57.62368	18	18
FM7	8.6667	9.2667	7.3333	588.9482	4	5
FM8	8.6667	9.4667	7.6667	629.0075	2	3
FM9	7.6667	7	8.8667	475.8445	8	6
FM10	7.6667	8.6667	8.6667	575.8519	6	2
FM11	7.6667	9.2667	8.3333	592.0371	3	4
FM12	6.6	8.6667	8.6667	495.7334	7	8
FM13	2.0667	6.2	8.6667	111.0489	17	17
FM14	6.2	9.4667	7.1	416.7227	13	10
FM15	8.6667	9.6667	7	586.4445	5	7
FM16	6.2	7.3333	8.6667	394.0444	14	12
FM17	6.2	8.6667	8.6667	465.6889	10	9
FM18	7.3333	8.6667	7.3333	466.0740	9	11

4.3.3 Sensitivity Analysis

The validity and robustness of the study's results were evaluated through sensitivity analysis (SA). The primary objective of SA is to identify the input variables that contribute most significantly to the uncertainty observed in the model outputs [157]. By systematically modifying input parameters, the stability and consistency of the results can be assessed. Various approaches to sensitivity analysis have been documented in the literature [158] [159].

In the present study, the methodology proposed by Chen and Khan [158] is adopted, particularly the use of incremental percentage change (IPC) to adjust the weight of the most influential risk factor (RF) and examine its impact on the ranking outcomes. A variation of ±5% IPC is applied, whereby the weights are increased and decreased by 5% in successive sensitivity iterations. To maintain the normalization condition, the weights of the remaining risk factors are proportionally adjusted such that their total remains equal to unity.

The initial weights assigned to the risk factors are presented in Table 4.12. Subsequently, for each sensitivity scenario, the identified failure modes (FMs) are re-evaluated using the FTOPSIS method. The resulting variations in the ranking of failure modes are summarized in Table 4.13, while Figure 4.3 illustrates these changes graphically through a line plot depicting the relationship between percentage weight variations and corresponding rank shifts

Table 4.12 Change in RF weight in the sensitivity analysis

%age change in weight	O	S	D
-25%	(0.1575, 0.24, 0.36)	(0.1514, 0.2325, 0.3852)	(0.3391, 0.5275, 0.8591)
-20%	(0.168, 0.256, 0.384)	(0.1495, 0.2276, 0.3708)	(0.3349, 0.5164, 0.8269)
-15%	(0.1785, 0.272, 0.408)	(0.1477, 0.2227, 0.3563)	(0.3307, 0.5053, 0.7946)
-10%	(0.189, 0.288, 0.432)	(0.1458, 0.2178, 0.3419)	(0.3265, 0.4942, 0.7624)
-5%	(0.1995, 0.304, 0.456)	(0.1439, 0.2129, 0.3274)	(0.3222, 0.4831, 0.7302)
0%	(0.21, 0.32, 0.48)	(0.142, 0.208, 0.313)	(0.318, 0.472, 0.698)
5%	(0.2205, 0.336, 0.504)	(0.1401, 0.2031, 0.2986)	(0.3138, 0.4609, 0.6658)
10%	(0.231, 0.352, 0.528)	(0.1382, 0.1982, 0.2841)	(0.3095, 0.4498, 0.6336)
15%	(0.2415, 0.368, 0.552)	(0.1363, 0.1933, 0.2697)	(0.3053, 0.4387, 0.6014)
20%	(0.252, 0.384, 0.576)	(0.1345, 0.1884, 0.2552)	(0.3011, 0.4276, 0.5691)
25%	(0.2625, 0.4, 0.6)	(0.1326, 0.1835, 0.2408)	(0.2969, 0.4165, 0.5369)

Table 4.13 Rank change in the sensitivity analysis

	-25%	-20%	-15%	-10%	-5%	0%	5%	10%	15%	20%	25%
FM1	13	13	13	13	13	13	13	12	12	13	13
FM2	14	14	14	14	14	14	14	14	15	14	14
FM3	15	15	15	15	15	15	15	15	13	12	12
FM4	16	16	16	16	16	16	16	16	16	16	16
FM5	1	1	1	1	1	1	1	1	1	1	1
FM6	18	18	18	18	18	18	18	18	18	18	18
FM7	7	7	5	5	5	5	5	5	5	5	5
FM8	4	4	4	4	3	3	3	2	2	2	2
FM9	6	6	7	6	6	6	6	7	7	7	7
FM10	2	2	2	2	2	2	2	3	3	3	3
FM11	3	3	3	3	4	4	4	4	4	4	4
FM12	5	5	6	7	7	8	8	8	8	8	8
FM13	17	17	17	17	17	17	17	17	17	17	17
FM14	10	10	10	10	10	10	11	11	11	11	11
FM15	9	9	8	8	8	7	7	6	6	6	6
FM16	11	11	11	12	12	12	12	13	14	15	15
FM17	8	8	9	9	9	9	9	9	9	9	9
FM18	12	12	12	11	11	11	10	10	10	10	10

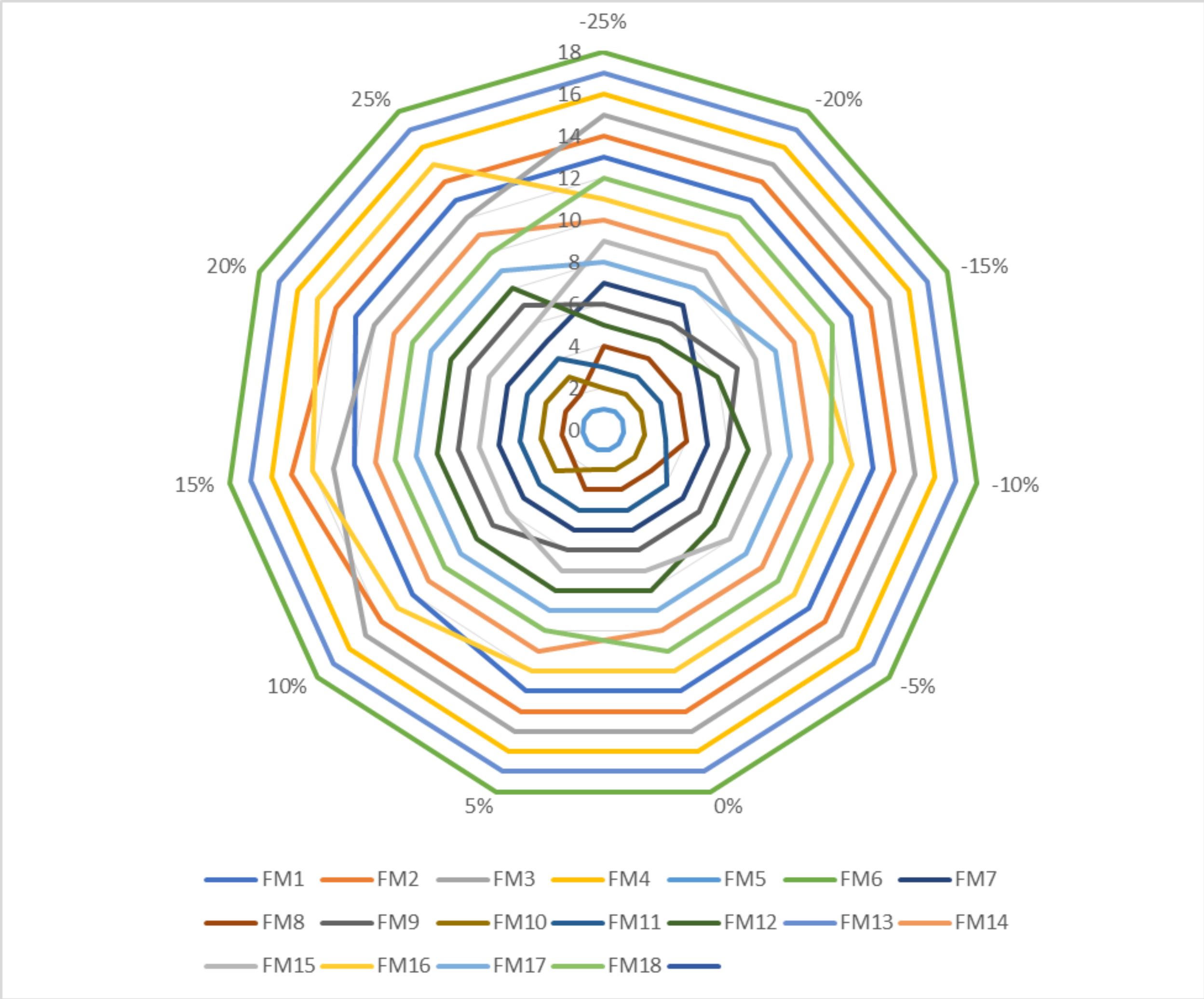

Figure 4.3 FMs rank change in the sensitivity analysis

As can be seen in Figure 4.3, in all 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.

4.4 Conclusions and recommendations

In thermal power plants, uninterrupted coal feeding is required in the boiler for electric power generation. The belt conveyor system is used to feed coal, and the hydraulic direct drive is a crucial part of the system. To enable the uninterrupted working of hydraulic direct drive, it is necessary to identify the failure modes (FMs) that result in HDD failure and to evaluate how relevant each mode is to overall plant failure.

Failure Mode and Effects Analysis (FMEA), as a systematic risk assessment tool, is effectively employed to achieve the stated objectives. Accordingly, this study demonstrates the application of FMEA in conjunction with fuzzy-based multi-criteria decision-making (MCDM) techniques, specifically the Fuzzy Analytic Hierarchy Process (FAHP) and the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS), to analyze potential failure modes (FMs) associated with hydraulic direct drives (HDDs).

The analysis commenced with the identification of relevant failure modes through expert consensus involving five domain specialists. These identified FMs were subsequently evaluated based on three key risk parameters: occurrence (O), severity (S), and detection (D). The input data required for the implementation of FAHP and FTOPSIS were collected from experts in the form of linguistic assessments, which were then converted into corresponding triangular fuzzy numbers for further analysis.

FAHP was used to compute the weights of O, S, and D, while FTOPSIS was used to compute the rankings of the FMs. The following are the major findings of the current study

- Using FMEA with FAHP and FTOPSIS to prioritize probable FMs of the Hydraulic Direct Drive is a straightforward method.
- It can be seen from Table 4.14 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

It is possible that the ranking of the FMs produced from this study will help in assessing the relative seriousness of the various FMs of the HDD. This study may help management and the necessary individuals create efficient and effective maintenance processes to avoid FMs, especially the most expensive ones. As a result, the belt conveyor system would be more reliable and able to run continuously for longer periods.

While it would be desirable to propose mitigation strategies for all 18 identified failure modes, the analysis indicates that the top five failure modes fall within the highest 25% in terms of severity. Therefore, priority should be given to addressing these critical failure modes, and the recommended corrective actions outlined in Table 4.14 may be implemented accordingly.

Table 4.14 Suggestions for proper maintenance of Hydraulic Direct Drive

Sr. No	Failure Mode	Potential Causes	Suggested Maintenance Actions
1	High temperature of the oil	1. Cooling circuit components, including the radiator, may not be working properly 2. Low level of oil in the reservoir/oil tank 3. Chock up of return line filter.	1. Check the performance of all cooling circuit components and replace them as necessary. 2. Maintain the correct oil level in the oil tank 3. Repair/Replace the filter on the return line
2	Radiator tripped	1. Blockage in the radiator	1. Remove any build-up in the radiator
3	High case pressure of Hydraulic Motor	2. Chock up of the Return/Drain line filter. 3. Improper Pressure relief valve setting	2. Check the return line filter 3. Check pressure relief settings
4	High case pressure of Hydraulic Pump	1. Faulty or incorrectly adjusted pressure control devices and Variable pump pressure compensator 2. Chock up of Return/Drain line filter. 3. Malfunctioning of the Limit switch-Suction Valve	1. Check pressure relief control and pressure compensator settings. Check the return line filter 2. Check the return line filter 3. Repair/Replace Limit switch- Suction Valve
5	High charge pressure	1. Chock up of the flush-out line filter 2. Malfunctioning of the relief valve	1. Repair /Replace flush-out line filter 2. Repair/Replace relief valve

CHAPTER 5

MAINTENANCE OUTSOURCING CHALLENGES OF BELT CONVEYOR INSTALLATIONS

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This chapter focuses on the identification and analysis of key issues related to maintenance outsourcing in belt conveyor systems. To achieve this, an integrated structural and hierarchical framework is developed using the Analytic Hierarchy Process (AHP) in conjunction with the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method. Furthermore, this research makes a meaningful contribution to the existing body of knowledge on maintenance outsourcing for heavy machinery systems by incorporating perspectives from multiple stakeholders. The outcomes of this work also serve as a foundation for the development of systematic frameworks aimed at supporting the selection of maintenance contractors for such industrial installations.

5.1. Introduction

Ensuring long-term operational safety and efficiency of belt conveyors necessitates effective maintenance practices [10]. However, findings by Siegel et al. [84] indicate that despite experiencing productivity losses due to equipment failure or downtime, approximately 61% of organizations did not revise their maintenance strategies. This highlights the critical importance of structured and proactive maintenance planning for material handling equipment (MHE), particularly belt conveyors.

Various maintenance strategies are adopted across industries for managing physical assets. Corrective maintenance (CM), also referred to as run-to-failure, involves repairing equipment after a breakdown occurs. Preventive maintenance (PM) is performed at predetermined intervals or based on usage metrics, such as operational hours or distance traveled. While PM aims to reduce failure likelihood, it often does not consider the actual condition of the system

[60]. In contrast, predictive maintenance (PdM) utilizes system condition data and historical records to determine the optimal timing for maintenance interventions, thereby minimizing unnecessary repairs and improving system responsiveness [60]. Another widely adopted approach is Total Productive Maintenance (TPM), which promotes the involvement of all organizational levels from operators to management to enhance equipment reliability and overall asset performance [160]. TPM has become a cornerstone of modern quality management practices in competitive industrial environments [161]. Maintenance philosophies have evolved significantly over time, transitioning from reactive approaches to preventive strategies and, more recently, to condition-based maintenance frameworks [12] [13]. Typical maintenance activities for belt conveyors include cleaning, lubrication of bearings, gearbox oil replacement, inspection, repair, and replacement of critical components such as belts, rollers, drums, and electrical elements [14]. Among these strategies, predictive maintenance has been identified as particularly effective in enhancing the reliability of belt conveyor systems. Additionally, in process industries, turnaround maintenance (TAM) is commonly practiced, ensuring periodic system overhauls [15]. The advent of Industry 4.0 (I4.0), often regarded as the fourth industrial revolution, has significantly transformed maintenance practices. The integration of real-time monitoring systems and advanced digital technologies has improved maintenance efficiency and effectiveness [61]. I4.0 technologies enable early fault detection and predictive capabilities, leading to reduced downtime and operational costs [62]. The implementation of intelligent systems for predictive maintenance has been shown to significantly decrease equipment downtime and service durations [63].. Furthermore, the use of Internet of Things (IoT) platforms facilitates seamless communication between devices, enabling real-time condition monitoring and maintenance forecasting [64]. The Industrial Internet of Things (IoT) forms the foundation of Cyber-Physical Systems (CPS), enabling interconnected physical assets to share and process data [65]. Such systems support advanced analytics and data-driven decision-making for maintenance activities [66]. Big data analytics further enhances maintenance strategies by enabling real-time insights and optimizing spare parts logistics [67]. Data-driven approaches, incorporating statistical methods, pattern recognition, and artificial intelligence (AI), are increasingly utilized to improve predictive maintenance models [162]. Simulation techniques also allow for the assessment of system health and failure risks based on historical data [68].

Cloud computing plays a crucial role in supporting I4.0 technologies by enabling data storage and real-time processing capabilities, thereby forming an integral component of CPS. Emerging technologies such as human-robot collaboration [163] and additive manufacturing for spare parts production [164] are further enhancing maintenance practices. Additionally, advanced techniques such as data mining (DM) and knowledge discovery in databases (KDD) are increasingly applied for fault diagnosis and prognosis in industrial systems.

Augmented reality (AR) is another rapidly growing technology with significant applications in maintenance training and operations. It enables visualization and interaction with system components, thereby enhancing the effectiveness of maintenance training programs. Prototype AR-based systems have been developed for applications such as aircraft maintenance training [69]. Furthermore, Industry 4.0 facilitates the concept of sustainable maintenance (SM), which aims to minimize environmental impact while improving equipment longevity and lifecycle management [165].

A critical aspect of modern maintenance is the estimation of the remaining useful life (RUL) of equipment using sensor data and advanced analytical models [70] [71]. Techniques such as long short-term memory (LSTM) networks and deep learning (DL) are increasingly employed for this purpose (Bruneo and De Vita, 2019). The concept of digital twins further enhances condition monitoring by creating virtual replicas of physical systems for real-time analysis [13]. Future advancements in robotics, drones, and wearable technologies are also expected to strengthen smart maintenance practices [72]. Studies suggest that the combined implementation of TPM and I4.0 technologies yields improved maintenance outcomes [166]

Emerging maintenance paradigms under the I4.0 framework include predictive, proactive, remote, and self-maintenance strategies. Predictive maintenance is expected to reduce equipment downtime by 30–50% and extend operational life by 20–40% [167]. Proactive maintenance focuses on addressing root causes of failures rather than symptoms [168], while remote maintenance leverages technologies such as AR to enable off-site diagnostics and repairs [169,170]. Self-maintenance involves continuous, automated condition monitoring, often supported by robotics for high-risk tasks [171]. Autonomous maintenance practices have also been shown to reduce lifecycle costs [172], and the adoption of I4.0 technologies can significantly minimize human errors [173].

Despite these advancements, the implementation of sophisticated maintenance strategies requires a workforce equipped with both technical and non-technical skills. Technical competencies include expertise in IoT, RFID, cloud computing, data analytics, and automation systems [18,19]. Additionally, skills such as communication, problem-solving, leadership, and critical thinking are essential for effective maintenance management [20,21]. Developing such competencies requires significant investment in training and resources.

As industrial systems become more complex and integrated, maintenance management has become increasingly challenging [16]. Turnaround maintenance (TAM) in process industries often requires additional manpower, leading organizations to outsource certain maintenance activities [17]. Consequently, outsourcing of both corrective and preventive maintenance has become a common practice [22]. Outsourcing is closely linked to the evolution of facilities management [174] and is particularly critical in asset-intensive industries such as mining, aviation, and defense, where maintaining system uptime is essential [23].

Belt conveyor systems typically operate under harsh environmental conditions, making the implementation of advanced I4.0 technologies for their maintenance particularly challenging. This complexity motivates the need to further explore maintenance strategies for such systems. While maintenance outsourcing for belt conveyors is increasing, it presents several challenges due to the safety critical nature of the equipment. These challenges span technical, managerial, economic, and legal domains [24]. Existing literature indicates a lack of comprehensive studies addressing key issues such as service provider selection, performance evaluation, and maintenance strategy optimization in outsourcing contexts [73]. Additionally, organizations face difficulties in adapting maintenance processes to align with Industry 4.0 requirements [74], particularly in the context of belt conveyor systems. Considering these research gaps, this chapter aims to:

- Identify critical challenges associated with maintenance outsourcing of belt conveyor systems in the Industry 4.0 era

- Evaluate the relative importance of these challenges using the Analytic Hierarchy Process (AHP)
- Analyze interrelationships among the challenges through the DEMATEL method
- Classify the challenges into cause-and-effect categories

The outcomes of this study are expected to assist organizations in recognizing key challenges and implementing effective mitigation strategies for maintenance outsourcing of belt conveyor systems.

5.2. IDENTIFICATION OF MAINTENANCE OUTSOURCING CHALLENGES

In the contemporary globalized and highly competitive business environment, outsourcing has become a widely accepted strategic practice [175]. Organizations increasingly concentrate on their core competencies while delegating non-core activities to external service providers [176]. The practice of outsourcing business functions has evolved and can be broadly categorized into horizontal and vertical contracting [75]. Activities such as finance, human resource management, and maintenance are typically classified under vertical contracting arrangements [75].

Among these, maintenance outsourcing, wherein maintenance responsibilities are transferred to third-party service providers under maintenance service contracts (MSCs), has gained significant traction in recent decades [76]. Organizations consider outsourcing maintenance for several reasons, including the reduction of costs associated with maintaining in-house maintenance departments and the avoidance of continuous training requirements related to technological advancements, safety standards, and environmental regulations [75]. Additionally, outsourcing may contribute to improved workforce morale by relieving employees from routine maintenance tasks, thereby allowing management to focus on more strategic priorities [78]. Similarly, it has been observed that organizations increasingly adopt outsourcing practices to optimize budgets and reduce the size of permanent staff [32].

In process industries, particularly during turnaround maintenance (TAM) operations, in-house resources are often insufficient to meet operational demands. Consequently, outsourcing TAM activities to external contractors has become a common practice [15]. With the advent of

Industry 4.0, maintenance outsourcing has become even more prevalent among organizations operating material handling equipment (MHE), including belt conveyor systems. A survey conducted by Siegel et al.[84] revealed that 45% of organizations acknowledged the need to revise their maintenance strategies, while 17% lacked awareness of various maintenance methodologies. Furthermore, a significant proportion of respondents (74%) expressed a preference for original equipment manufacturers (OEMs) to perform maintenance activities. While this preference creates opportunities for OEMs to offer maintenance and condition monitoring services, budgetary constraints often limit such engagements. As a result, organizations may opt for alternative maintenance service providers that offer cost-effective solutions. However, practical experiences indicate that outsourcing maintenance is not without challenges, and many organizations have encountered unfavorable outcomes when engaging external contractors [32]. Potential drawbacks include reduced operational control, loss of internal expertise and learning opportunities, dependency on service providers, inconsistencies in service quality, and the risk of workforce displacement [77].

Given these considerations, the selection of an appropriate contractor becomes a critical factor in ensuring the success of maintenance outsourcing arrangements [78]. This is particularly relevant in the context of belt conveyor systems, where maintenance outsourcing is inherently complex and associated with significant risks due to the critical and integrated nature of the equipment. To systematically investigate these challenges, a comprehensive literature review was conducted alongside unstructured exploratory interviews involving key stakeholders, including system owners, original equipment manufacturers, maintenance engineers, contractors, and technicians. The insights derived from this process facilitated the identification of key challenges, which are discussed in the subsequent sections.

5.2.1 Attainment of organizational strength by contractors.

The effectiveness of maintenance outsourcing is largely determined by the capabilities and robustness of the contractor’s organizational framework. Martin [75] emphasized that critical managerial functions of a maintenance contractor include achieving an appropriate scale of operations, assessing potential clients, and structuring an efficient maintenance function. Expanding on this, Judenberg [78] identified a comprehensive set of prerequisites essential for a competent maintenance organization. These include a strong track record and industry reputation, availability of skilled manpower, financial soundness, a high level of commitment and professionalism, well-established and documented procedures, and the adoption of advanced project management practices.

Further attributes contributing to organizational strength have been highlighted by [79], including effective reporting and feedback mechanisms, a culture of innovation, operational accessibility, strong administrative systems, reliability, credibility, domain-specific expertise, and the provision of auxiliary support services. Additionally, factors such as clear communication channels, effective control mechanisms, proactive operational approaches, and the ability to maintain dynamic relationships with asset owners are considered vital for successful maintenance service delivery.

From a technological perspective, Sorokin [177] underscored the importance of integrating advanced software tools within maintenance operations. These include computerized maintenance management systems (CMMS), enterprise asset management (EAM) systems, enterprise resource planning (ERP) platforms, and specialized risk assessment tools equipped with functionalities for budget monitoring, maintenance tracking, decision support, and process visualization.
Achieving such comprehensive organizational capabilities is particularly challenging in the context of belt conveyor systems, especially under the evolving paradigm of Industry 4.0, where the expectations for technological integration, operational efficiency, and service quality are significantly heightened.

5.2.2 Legal and financial challenges for contractors

Maintenance outsourcing involves a range of legal and financial considerations that must be carefully addressed to ensure effective contractual arrangements. Typically, maintenance service contracts (MSCs) are established as legally binding agreements that encompass technical, economic, and legal dimensions of the outsourcing process [76]. Martin [75] categorized maintenance contracts into three primary types: work package contracts, performance-based contracts, and facilitator contracts, each differing in terms of responsibility allocation and operational control.

In work package contracts, the asset owner retains full authority over planning and control activities, directing the maintenance contractor regarding the execution of tasks, including their timing and location. Consequently, the asset owner assumes responsibility for managing associated complexities. In contrast, performance-based contracts involve a higher level of commitment from the contractor, who guarantees specific technical outcomes or service levels, thereby increasing the contractual complexity. Facilitator contracts, on the other hand, grant greater autonomy to the contractor, wherein the asset owner is required to adhere to the operational guidelines established by the contractor to access maintenance services.

In addition to the contractual structure, several technical elements require careful specification within MSCs, including the type of maintenance activities (such as preventive maintenance (PM) and/or corrective maintenance (CM), detailed task descriptions, turnaround times, and documentation requirements [76]. Furthermore, legal aspects such as contract duration, terms and conditions, dispute resolution mechanisms, and warranty or guarantee provisions must be clearly defined to avoid ambiguities.

From a financial perspective, MSCs encompass various components, including payment structures, penalty clauses, risk-related costs, and insurance provisions. Considering the multifaceted nature of these technical, legal, and financial factors, along with the inherent risks associated with different contract types, the selection of an appropriate maintenance contract and its terms presents a significant challenge for belt conveyor system owners.

5.2.3 Attainment of necessary technician skills by contractors

The adoption of Industry 4.0 has led to transformative changes in industrial production systems, significantly elevating workforce expectations and requiring advanced skill sets among technicians and operators [178]. These developments are equally relevant to industrial maintenance practices within the Industry 4.0 framework. Traditionally, maintenance and troubleshooting activities have relied extensively on the expertise and experience of skilled personnel. However, with the emergence of Industry 4.0 technologies, cyber-physical assistance systems have been developed to support maintenance professionals in performing complex tasks more efficiently [81].

Despite these technological advancements, complete automation of maintenance processes remains unattainable, thereby maintaining the critical importance of skilled human intervention. In the context of maintenance outsourcing, the effectiveness of such arrangements largely depends on the availability of well-trained and experienced personnel employed by contractors, particularly those with long-term engagement [32]. It has also been observed that many challenges associated with the outsourcing of maintenance of belt conveyor systems arise from inadequate system inspection and condition monitoring, primarily due to a shortage of experienced technicians.

One of the major challenges faced by maintenance personnel in the Industry 4.0 environment is the ability to process and interpret large volumes of data, especially in real-time scenarios. The increasing complexity of industrial systems further complicates accurate data interpretation, often leading to difficulties in analysis and decision-making [81]. Consequently, technicians are now required to possess enhanced competencies that enable them to make prompt, data-driven decisions while simultaneously performing roles akin to data analysts. This shift reflects the transition from conventional condition-based maintenance to more advanced, integrated predictive maintenance paradigms.

In addition, modern maintenance practices demand proficiency in various technological domains, including network communication, microwave systems, and data transmission technologies. Such expertise is essential for interpreting real-time machine data, analyzing system performance, and diagnosing faults using advanced tools such as sensors and actuators. Chemweno et al. [81] further emphasized the need for specialized knowledge in utilizing digital support tools, including mobile applications and web-based platforms.

However, current industry trends indicate a significant shortage of technicians equipped with the necessary digital competencies [82], as well as expertise in knowledge management practices. This gap highlights that existing skill sets are inadequate to fully leverage Industry

4.0 technologies, thereby presenting a substantial challenge for maintenance contractors striving to meet evolving industrial requirements

5.2.4 Maintenance data acquisition and analysis challenges

The systematic recording and analysis of failure and repair information are fundamental to effective maintenance management. Data acquisition constitutes a critical initial step in maintenance activities. Murthy et al. [76], in their comprehensive study on data management in maintenance outsourcing, emphasized that accurate and well-structured data collection is essential for successful outsourcing practices. This includes clearly defining the type, scope, and level of detail of the data to be collected, as well as establishing the respective responsibilities of asset owners and maintenance contractors.

In traditional maintenance practices for belt conveyor systems, maintenance records are typically maintained through logbooks or stored within database management systems, which are generally sufficient for routine maintenance purposes. However, the transition to predictive maintenance under the Industry 4.0 paradigm necessitates more advanced data acquisition techniques. In such environments, data collection involves the use of multiple sensors integrated into machinery, along with preprocessing operations such as data fusion and signal conditioning to ensure data quality and usability.

Despite these advancements, several challenges persist. A significant limitation is the scarcity of high-quality, real-time data required for effective predictive maintenance. Additionally, maintenance datasets are often characterized by inaccuracies, incompleteness, lack of structure, missing values, and insufficient labeling, which hinder reliable analysis [83].

A survey conducted by Siegel et al. [84] further highlighted deficiencies in maintenance data practices, revealing that many organizations fail to document previous failures or update their maintenance strategies even after experiencing major breakdowns. The study reported that only a small proportion of organizations maintain maintenance history using information systems, while a majority either do not keep records or fail to utilize existing systems effectively.

Furthermore, the development and implementation of data acquisition and decision-making algorithms involve substantial costs [179]. The large volumes of data generated in Industry 4.0 environments also pose significant challenges for conventional relational database management systems (RDBMS), which are often inadequate for handling such scale and complexity. This limitation complicates the visualization and interpretation of data through tools such as charts, tables, and graphical models [13].

Effective analysis of maintenance data requires a strong foundation in statistical methodologies, while the development of predictive models necessitates expertise in reliability theory and stochastic processes [76]. Consequently, maintenance service providers must either develop in-house expertise or engage external specialists to ensure accurate data analysis and modeling [13],[76].

Considering these, it is evident that maintenance contractors for belt conveyor systems must adopt advanced practices in data acquisition, storage, and processing to align with the requirements of Industry 4.0 and to enable effective predictive maintenance strategies.

5.2.5 Facilitation with modern equipment, gadgets, and instrumentation

The transition to an Industry 4.0 environment necessitates significant investment in advanced equipment, tools, and instrumentation to effectively perform maintenance activities. As previously discussed, future maintenance strategies for belt conveyor systems rely heavily on the availability of accurate and high-quality data, thereby making precise data acquisition a critical requirement. Condition monitoring, which forms a core component of predictive maintenance, depends on the collection of signals from key locations across the conveyor system. Common signal-based monitoring techniques include vibration analysis and acoustic measurements.

In addition to these methods, the measurement of forces and torques in rotating components using wireless technologies is expected to play an important role in Industry 4.0-based maintenance. Both fixed and mobile sensors may be deployed for comprehensive condition monitoring of belt conveyor systems [10]. Existing approaches for monitoring conveyor belts often involve embedding conductive elements such as cords, arrays, or layers within the belt structure. These embedded components interact with electrical or magnetic fields, and any disruption in continuity caused by damage can be detected through appropriate sensing mechanisms, enabling early fault identification [84].Advanced techniques such as image processing have also been proposed for monitoring belt conditions, where video data captured from conveyor systems is analyzed to detect potential damage [85]. Beyond the belt itself, the drive unit, which comprises critical components such as motors, bearings, gearboxes, and braking systems, also requires continuous monitoring [84]. Various sensing technologies, including vibration sensors, strain gauges, and motor current analysis tools, are commonly used for this purpose [86, 180]. Furthermore, overall system health can be evaluated by accurately measuring parameters such as belt tension and speed using instruments like voltage and current probes, strain gauges for torque measurement, and encoders for velocity and rotational speed assessment [86].

The integration of Internet of Things (IoT) technologies has significantly enhanced capabilities for real-time condition monitoring and predictive maintenance. However, achieving full digitalization of maintenance processes requires further advancements in system capabilities and infrastructure. One of the major challenges lies in the optimal design and strategic placement of sensors to enable effective online monitoring of critical parameters. Additionally, the software platforms used to process and analyze sensor data must be user-friendly to ensure ease of use by maintenance personnel.

Augmented Reality (AR) has also emerged as a promising technology with the potential to transform maintenance practices in Industry 4.0 environments. AR systems can provide visualization of hidden or complex structures within physical systems, thereby assisting in intricate maintenance tasks [87]. Despite these technological advancements, the adoption of modern diagnostic tools remains a significant challenge in maintenance outsourcing contexts [76]. Consequently, the capability of maintenance contractors to deploy and effectively utilize advanced equipment, instrumentation, and digital technologies represents a critical factor in determining the success of maintenance operations in belt conveyor systems.

5.2.6 Service quality challenges

Maintaining a high level of service quality from external maintenance providers represents a critical challenge in outsourcing arrangements. Toosi et al. [79] categorized maintenance service quality into three principal dimensions: equipment quality, repair quality, and service orientation. Equipment and repair quality primarily relate to the technical performance of maintenance services, including system reliability and the capability of the contractor to restore equipment to its original or near-original condition. In contrast, service orientation encompasses the non-technical aspects, particularly the quality of interaction, responsiveness, and overall service experience delivered by the maintenance provider.

In addition to these dimensions, several performance-related factors significantly influence perceived service quality. These include maintenance service duration, response time, and turnaround time, which are widely recognized as key indicators of maintenance effectiveness [80]. Cohen [88] stressed the importance of incorporating structured performance evaluation elements within maintenance contracts, such as functional analysis statements, maintenance performance indicators, and system loss metrics.

Moreover, Judenberg [78] suggested that maintenance quality can be effectively assessed using quantitative measures such as mean time between failures (MTBF), frequency of incidents, and average repair time. Collectively, these indicators provide a comprehensive evaluation of maintenance performance. In the context of Industry 4.0, where operational demands and system complexities are significantly elevated, ensuring consistent service quality in belt conveyor maintenance presents a substantial challenge for maintenance contractors.

5.2.7 Health, safety, and environment-related challenges

Maintenance operations, particularly turnaround maintenance (TAM) projects, are often associated with significant health, safety, and environmental (HSE) risks, as evidenced by numerous incidents reported during shutdown periods [15]. Concerns regarding safety and environmental compliance become even more critical when maintenance activities are outsourced, as highlighted by Martin[75]. In this context, Malmen [89] identified deficiencies in safety management systems during TAM operations across several organizations, underscoring a serious challenge in the outsourcing of maintenance for systems such as belt conveyors.

To address these concerns, Hadidi [15] recommended that safety considerations should be a key criterion in the contractor selection process, beginning at the bidding stage itself. Specifically, factors such as the contractor's historical performance, including records of safety incidents, technical expertise, the competence of maintenance personnel, and the comprehensiveness of the HSE management plan play a decisive role in evaluating and selecting a suitable maintenance contractor from a safety perspective.

5.2.8 Spares supply chain management challenges

Maintenance activities play a crucial role in improving system availability, while preventive maintenance enables the timely replacement of components that have reached the end of their operational life, thereby minimizing the risk of unexpected failures. However, increased requirements for component returns and replacements can impose a significant burden on maintenance service providers, particularly in managing spare parts inventory to meet contractual obligations [90]. In addition, inventory levels for repairable components are influenced by factors such as repair capacity and the lead times associated with forward and reverse logistics [90].

In the context of outsourcing, effective coordination within the supply chain is essential to ensure mutual benefits for all stakeholders involved [181]. The profitability of maintenance contracts is highly sensitive to the policies governing critical spare parts [182]. Both asset owners and maintenance contractors aim to optimize their respective economic outcomes; however, the control of spare parts inventory significantly affects operational behavior. When the asset owner retains control over spare parts, the maintenance contractor may have limited incentives to optimize component usage beyond standard contractual constraints. Conversely, when the contractor manages the spare parts supply chain, more efficient and judicious utilization of components can be achieved [23].

Furthermore, various inventory management models have been developed to address different operational scenarios, including variations in failure and repair rates [91], time-dependent spare part demand [92], and reliability-centered maintenance conditions [93] considering these complexities, the formulation and implementation of an effective spare parts supply chain policy represents a significant challenge in the outsourcing of maintenance for belt conveyor systems.

All the above-mentioned challenges are in Table 5.1. The following section discusses the integrated methodology that will be used in this endeavor

Table 5.1 Challenges in maintenance outsourcing of belt conveyors

Sr.No	Challenges	Notation
1	Attainment of organizational strength by contractors	MOC_1
2	Legal and financial challenges for contractors	MOC_2
3	Attainment of necessary technician skills by contractors	MOC_3
4	Maintenance data acquisition and analysis challenges	MOC_4
5	Facilitation with modern equipment, gadgets, and instrumentation	MOC_5
6	Service quality challenges	MOC_6
7	Health, safety, and environmental challenges	MOC_7
8	Spares supply chain management challenges	MOC_8

5.3. Description of Integrated Methodologies

An integrated hybrid approach combining the Analytic Hierarchy Process (AHP) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) is recommended for evaluating the relative importance of challenges and examining their interrelationships [183,184,185]. The AHP technique is employed to prioritize the identified challenges by assigning appropriate weights based on their significance within the decision-making framework. In contrast, the DEMATEL method facilitates the analysis of interdependencies among these challenges by categorizing them into cause-and-effect groups.

In the present study, a combined AHP–DEMATEL framework is adopted to leverage the strengths of both methodologies. AHP is selected due to its simplicity, robustness, and widespread acceptance as a reliable tool for determining the relative importance of decision criteria. On the other hand, DEMATEL offers a distinctive advantage by enabling the construction of impact relationship maps, which help identify the most influential factors within a complex system.

Unlike conventional quantitative approaches, including AHP, which assume independence among decision criteria, DEMATEL explicitly accounts for the interrelationships and contextual interactions among variables. By integrating these two methods, a more comprehensive and realistic analysis of the problem can be achieved. A detailed description of both methodologies is presented in the subsequent sections.

5.3.1 Methodology of AHP (Analytic Hierarchy Process)

The analytic hierarchy process (AHP) is an extensively used MCDM method used to compute the priority weight of the factors, leading to their ranking. As a dynamic problem-solving tool for complex and fuzzy problems, AHP (Analytic Hierarchy Process) is ideal. Decision-making processes involving multiple criteria in a hierarchical system are a common use of this technique [186]. To establish priority scales, AHP relies on pairwise comparisons and the subjective judgments of domain experts, according to Saaty [150]. It is easier to conceptualize and structure a problem using an AHP model than without it [187].

The method for calculating the weight of each factor is explained in detail [188].

Step 1:In the first step, gather the importance of factors in a pairwise manner from experts using Saaty's nine-point scale, as shown in Table 5.2, and then create a pairwise comparison matrix.

Table 5.2 Saaty's scale for pairwise comparison

1	3	5	7	9	2,4,6,8
Equally Important	Moderately more Important	Strongly more important	Very strongly more important	Extremely more important	Intermediate values between two preferences

Each expert's pairwise comparisons are aggregated by taking the geometric mean so that the reciprocal property can be maintained [189]. The aggregated PCM is given by the equation p_{ijk} if '*i*' is considered to be more important than "*j*" by expert "*k* " (5.1).

$$PCM = \begin{bmatrix} p_{11} & \cdots & \cdots & p_{1j} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ p_{i1} & \cdots & \cdots & p_{i,j} \end{bmatrix}_{n\times n} \quad (5.1)$$

Where, $p_{ij} = \left(\prod_{k=1}^{m} p_{ij}^{k}\right)^{1/m}$, *i,j* = 1, 2, 3, ..., *n* and *k* = 1, 2, 3, ..., *m*. *n* and *m* represent several factors and experts, respectively.

Step 2: Determine the AHP weight by performing the following calculation:

- Use equation (5.2) to normalize the aggregated PCM

$$u_{ij} = \frac{p_{ij}}{\sum_{j=1}^{n} p_{ij}} \tag{5.2}$$

Where, u_{ij} represents a normalized value corresponding to the element p_{ij} of the PCM.

- Assume that each row of the normalized aggregated PCM has been normalized and aggregated, then calculate the AHP weight (w) using equation (5.3).

$$w_i^{\alpha} = \frac{s_{ij}}{\sum_{j=1}^{n} s_{ij}} \tag{5.3}$$

Where, $s_{ij} = \left(\prod_{j=1}^{n} u_{ij}\right)^{1/n}$

Step 3: Verify that the aggregated PCM is consistent by performing the following test:

- Compute the eigenvalue (λ) of the PCM using equation (5.4)

$$\lambda = \frac{r_i}{w_i^{\alpha}} \tag{5.4}$$

Where, r_i is the i^{th} entry of the vector obtained by multiplying PCM with the weight vector.

- Compute the consistency index (C.I) using equation (5.5)

$$C.I = \frac{\lambda_m - n}{n-1} \tag{5.5}$$

Where λ_m denotes the maximum value of the eigen vector

- Compute the consistency ratio (ξ^{L*}) using equation (5.6)

$$\xi^{L*} = \frac{C.I}{RI} \tag{5.6}$$

where *RI* represents the random index value for the geometric mean method. The value of RI for a matrix size of 3, 4, 5, 6, 7, 8, 9, 10 is used as 0.52, 0.87, 1.08, 1.22, 1.32, 1.39, 1.44, and 1.48, respectively, as suggested by Dijkstra [190].

5.3.2 DEMATEL Methodology

It is widely accepted that the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is an effective tool for spotting the ties that bind various elements of a large system. [191]. The DEMATEL method was developed by the Geneva Research Centre between 1972 and 1976 for categorizing factors into cause-and-effect groups effectively. An impact diagram helps to identify the most important factors in a mathematical model. Traditional quantitative tools like AHP assume that all factors are independent. DEMATEL considers all relationships among the factors through contextual relationships, unlike AHP. This methodology has been successfully implemented for upstream-downstream supply chain comparison for strategic logistics outsourcing [192], analysis of the cause-and-effect relationship among barriers to the adoption of blockchain technology in green supply chain management [193], modelling human resource dimension of international project risk management [194], analysis of IoT implementation challenges [195], etc.

5.3.2.1 Procedure of DEMATEL

Step 1: Establish A direct relation matrix (M)

As a result of the experts' ratings, a pairwise comparison matrix of attributes is generated. Table 5.3 shows a 0-5 point scale for comparing the impact of two attributes.

Table 5.3 Scale for pairwise comparison

Definition	Numerical rating
No Influence	0
Very Low Influence	1
Low Influence	2
Medium Influence	3
High Influence	4
Very High Influence	5

Due to the enormous number of specialists who have contributed to their viewpoints, it is necessary to weigh each one's contribution. For instance, if the number of experts is 'Y ' and the number of attributes is 'p,' there will be non-negative matrices of the form 'p x p' for each expert. It denotes the degree to which the attribute 'm' has an effect on the attribute 'n'. The entry 'x_{mn}' indicates the degree to which attribute 'm' influences 'n'. Now, for accommodating all responses from 'Y' experts, an average matrix 'a_{mn}' is constructed using equation (5.7)

$$a_{mn} = \frac{1}{Y}\sum_{p=1}^{Y} x_{mn}^{p} \qquad (5.7)$$

Step 2. Develop the direct relation matrix using equation (5.8)

$$B = A \times S \quad (5.8)$$

$$\text{Where, } S = \min\left[\frac{1}{max\sum_{n=1}^{p}|m_{mn}|}, \frac{1}{max\sum_{n=1}^{p}|m_{mn}|}\right] \qquad (5.9)$$

Step 3: Develop the total relation matrix (C)

The total relation matrix (C) is given by equation (5.10)

$$C = B\,(I - B)^{-1} \qquad (5.10)$$

The total relation matrix is constructed by adding all rows and columns. It is critical to notice that the elements 'Y_n' and 'X_m' respectively represent the direct and indirect impacts of other attributes on the attribute 'n'. The values of 'X_m' denote the influential power of attributes, and 'Y_n' depicts the magnitude of Correlations (Y). If one wishes to determine the prominence of an attribute, the value of (X_m+Y_n) will suffice. The difference between ' X_m ' and ' Y_n ' indicates whether an attribute is associated with a cause or effect group.

Step 4: Evaluate the threshold value

To calculate the threshold, all the factors in a total relation matrix are averaged together (C). The cause-and-effect diagram can be constructed with its help as well. The threshold value acts as a critical value because only values with a magnitude greater than the threshold value are shown in the cause-and-effect diagram. The causal diagram helps determine the interdependencies and behaviour of attributes among themselves by providing interactive relationships among the attributes.

A diagrammatic representation of the above-mentioned methodologies is shown in Figure 5.1.

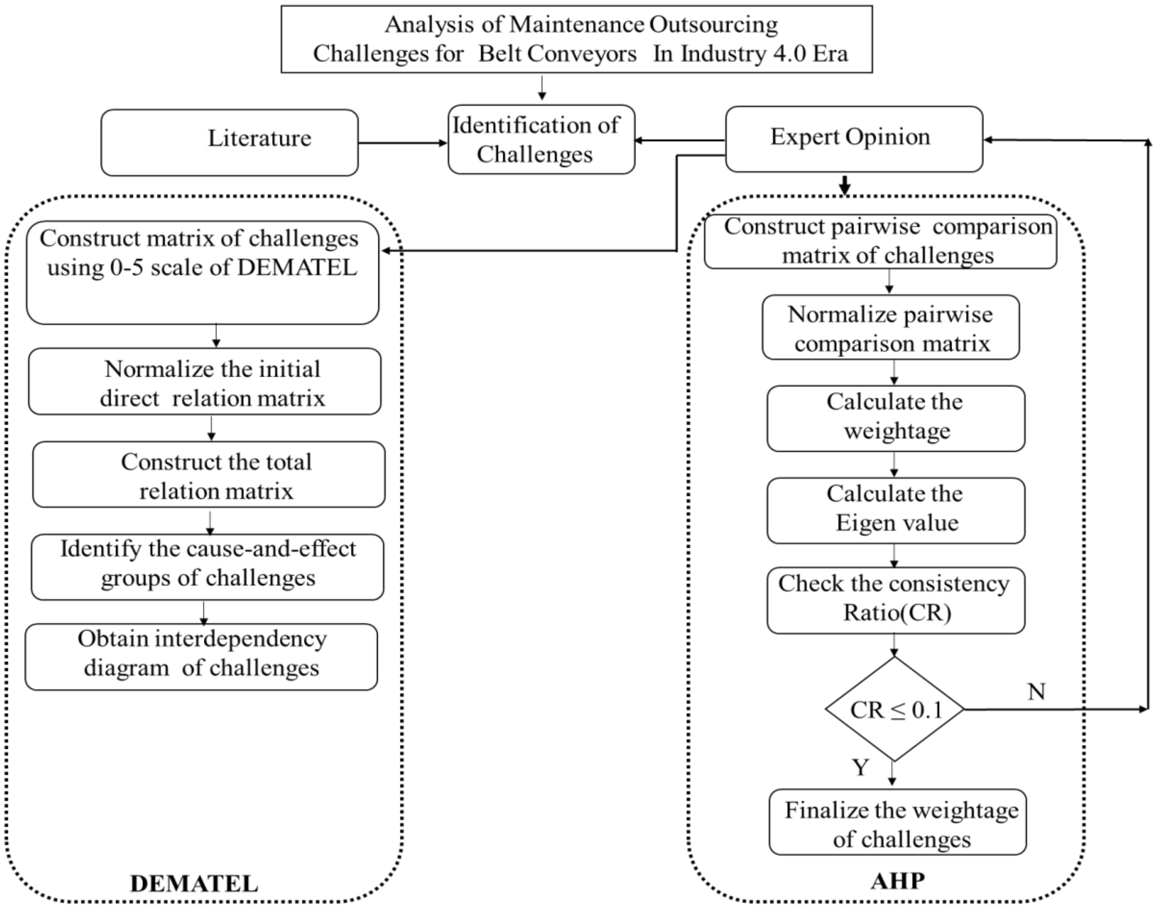

Figure 5.1 Research methodology framework

5.4. Methodology implementation

Using the integrated methodology described in the preceding section, the weight of challenges is assessed, and their relationships are established in this section. There was a total of 10 experts, including 7 from industry and 3 from academia, who were contacted for this study. All the industry experts had more than 15 years of experience in the maintenance of belt conveyors, while the other three had more than 10 years of research and teaching experience. Section 5.2 summarised the findings of a thorough literature review that identified eight main challenges of maintenance outsourcing. A questionnaire was created and sent to each expert based on the identified cluster of challenges. The evaluation scales for AHP and DEMATEL, shown in Tables 5.2 and 5.3, were used by each expert to provide their ratings. Thereafter, an average value was calculated for all 10 experts based on their ratings.

5.4.1 Implementation of the AHP model

The AHP is used to determine the weight of the challenges. Section 5.3.1 outlined the steps to follow to accomplish this. As a first step, an expert panel recommends that a pairwise comparison square matrix of the maintenance outsourcing challenges using Saaty's 1-9 scale be developed. The matrix ‘A_1’ so developed is shown in expression (5.10).

$$A_1 = \begin{array}{c} \text{Maintenance outsourcing challenges} \\ MOC_1 \\ MOC_2 \\ MOC_3 \\ MOC_4 \\ MOC_5 \\ MOC_6 \\ MOC_7 \\ MOC8 \end{array} \begin{array}{cccccccc} MOC_1 & MOC_2 & MOC_3 & MOC_4 & MOC_5 & MOC_6 & MOC_7 & MOC_8 \end{array} \begin{bmatrix} 1 & 8 & 2 & 4 & 3 & 5 & 7 & 7 \\ 1/8 & 1 & 1/6 & 1/5 & 1/6 & 1/7 & 1/2 & 1/3 \\ 1/2 & 6 & 1 & 4 & 3 & 3 & 5 & 7 \\ 1/4 & 5 & 1/4 & 1 & 1/3 & 2 & 6 & 5 \\ 1/3 & 6 & 1/3 & 3 & 1 & 3 & 3 & 4 \\ 1/5 & 7 & 1/3 & 1/2 & 1/3 & 1 & 4 & 6 \\ 1/7 & 2 & 1/5 & 1/6 & 1/3 & ¼ & 1 & ½ \\ 1/7 & 3 & 1/7 & 1/5 & 1/4 & 1/6 & 2 & 1 \end{bmatrix} \quad (5.10)$$

The normalized weights of maintenance outsourcing challenges are established by systematically following the steps outlined in section 5.3.1.1 for AHP, and they are ranked and shown in Table 5.4.

Table 5.4 AHP-based ranking of the maintenance outsourcing challenges

Challenges	**Weightage**	**Rank**
MOC_1	0.32	1
MOC_2	0.02	8
MOC_3	0.24	2
MOC_4	0.11	4
MOC_5	0.15	3
MOC_6	0.10	5
MOC_7	0.03	7
MOC8	0.04	6

5.4.2 Implementation of DEMATEL

Using DEMATEL, it is possible to establish a causal relationship between the challenges through a cause-effect diagram. Using an average of the experts' responses, the average direct relation matrix 'A' is first constructed for the challenges using equation (5.7) and shown in Table 5.5.

Table 5.5 Average direct-relation matrix (A) for the challenges

	MOC$_1$	MOC$_2$	MOC$_3$	MOC$_4$	MOC$_5$	MOC$_6$	MOC$_7$	MOC$_8$	SUM
MOC$_1$	0	4	3	3	4	5	4	4	27
MOC$_2$	1	0	0	0	0	3	2	3	9
MOC$_3$	0	0	0	4	3	5	4	0	16
MOC$_4$	0	0	0	0	0	4	2	5	11
MOC$_5$	2	0	3	4	0	5	3	0	17
MOC$_6$	5	2	0	0	0	0	4	1	12
MOC$_7$	3	3	0	0	0	4	0	0	10
MOC$_8$	3	3	0	0	0	4	0	0	10
								MAX	27

The normalized initial direct relation matrix (*B*) is developed based on equation (5.8) as shown in Table 5.6.

Table 5.6 Normalized initial direct relation matrix (*B*)

Challenges	MOC$_1$	MOC$_2$	MOC$_3$	MOC$_4$	MOC$_5$	MOC$_6$	MOC$_7$	MOC$_8$
MOC$_1$	0	0.1481	0.1111	0.1111	0.1481	0.1852	0.1481	0.1481
MOC$_2$	0.0370	0	0	0	0	0.1111	0.0741	0.1111
MOC$_3$	0	0	0	0.1481	0.1111	0.1852	0.1481	0
MOC$_4$	0	0	0	0	0	0.1481	0.0741	0.1852
MOC$_5$	0.0741	0	0.1111	0.1481	0	0.1852	0.1111	0
MOC$_6$	0.1852	0.0741	0	0	0	0	0.1481	0.0370
MOC$_7$	0.1111	0.1111	0	0	0	0.1481	0	0
MOC$_8$	0.1111	0.1111	0	0	0	0.1481	0	0

Further, the total relation matrix (C) is obtained by using equation (5.9) and shown in Table 5.7.

Table 5.7Total Relation Matrix (C)

Challenges	MOC$_1$	MOC$_2$	MOC$_3$	MOC$_4$	MOC$_5$	MOC$_6$	MOC$_7$	MOC$_8$	X_m
MOC$_1$	***0.163511***	***0.265644***	***0.150287***	***0.179554***	***0.18907***	***0.417549***	***0.310481***	***0.250604***	1.9267
MOC$_2$	0.104704	0.059166	0.013524	0.016158	0.017014	***0.185052***	0.126475	***0.143043***	0.665136
MOC$_3$	0.106231	0.074465	0.026222	***0.18306***	0.129763	***0.316209***	***0.248111***	0.069623	1.153683
MOC$_4$	0.084357	0.067878	0.010896	0.013018	0.013708	***0.229018***	0.12963	***0.216117***	0.764622
MOC$_5$	***0.177835***	0.086481	***0.13547***	***0.19411***	0.041398	***0.336211***	***0.23272***	0.084354	1.28858
MOC$_6$	***0.256349***	***0.159279***	0.033112	0.03956	0.041657	***0.134557***	***0.230323***	0.105022	0.999858
MOC$_7$	***0.17889***	***0.170798***	0.023107	0.027607	0.02907	***0.235038***	0.082673	0.059297	0.806479
MOC$_8$	***0.17889***	***0.170798***	0.023107	0.027607	0.02907	***0.235038***	0.082673	0.059297	0.806479
Y_n	1.250767	1.054509	0.415724	0.680674	0.49075	2.088674	1.443084	0.987357	

Additionally, the mean values of all the factors in Table 5.7 are used to determine the threshold value for each major challenge, which is presented in Table 5.8. The threshold value (α) is calculated as 0.131. It is used to study the relationships between the challenges and to determine whether one has a direct effect on the others.

Table 5.8 Relative importance, Cause/effect grouping with value (CE), and Prominence Ranking (PR) of challenges

Challenges	Y_n	X_m	X_m+Y_n	PR	X_m-Y_n	Cause and Effect	CE
MOC_1	1.250767	1.9267	3.177467	1	0.675933	Cause	3
MOC_2	1.054509	0.665136	1.719645	6	-0.38937	Effect	6
MOC_3	0.415724	1.153683	1.569407	7	0.737959	Cause	2
MOC_4	0.680674	0.764622	1.445296	8	0.083948	Cause	4
MOC_5	0.49075	1.28858	1.77933	5	0.797831	Cause	1
MOC_6	2.088674	0.999858	3.088532	2	-1.08882	Effect	8
MOC_7	1.443084	0.806479	2.249563	3	-0.6366	Effect	7
MOC_8	0.987357	0.806479	1.793836	4	-0.18088	Effect	5
Threshold value							0.131

Interaction values above the threshold value are considered significant values and are highlighted in bold italics in Table 5.7. The values of Influential power (X_m) and Correlations (Y_n) are respectively represented in Table 5.7. The strength of the relationship of a particular challenge with other challenges is directly proportional to the corresponding value of (X_m+Y_n). A prominence rank (PR) is assigned based on the higher (X_m+Y_n) value, as shown in Table 8. The Cause-Effect (CE) value is calculated as 'CE = (X_m-Y_n)'. The challenges having a negative CE value are treated as 'Effect' while the challenges having a positive CE value are treated as 'Cause'. A higher CE value indicates the strong causal influence of the corresponding challenge. A causal diagram is represented in Figure 5.2. The factors above the horizontal axis are 'Cause', while the factors below the horizontal axis are 'Effect'. Apart from these, an interdependency diagram is plotted that shows the interdependencies among challenges based on the total relation matrix (C), which is shown in Figure 5. 3.

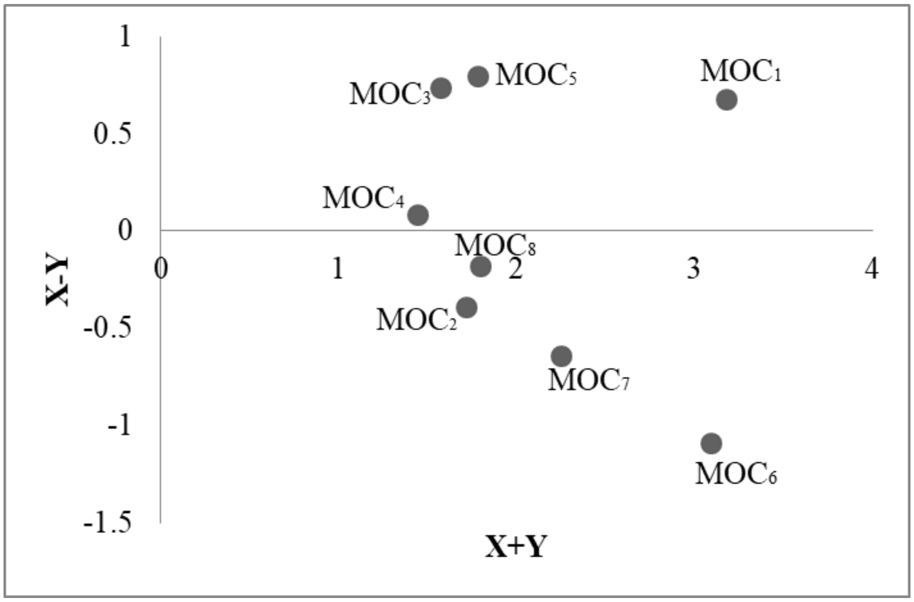

Figure 5.2 Cause-and-Effect diagram of challenges

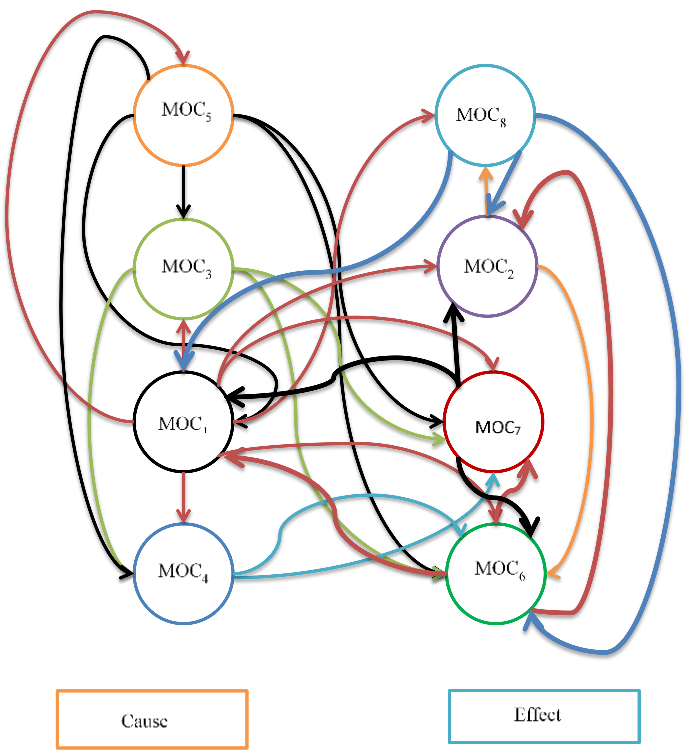

Figure 5.3 Interdependency diagram of challenges

5.5. Results

According to Table 5.8, the strongest and most sought-after 'Cause' to drive the challenges in maintenance outsourcing of belt conveyor installations in the era of Industry 4.0 is 'Facilitation with modern equipment, gadgets, and instrumentation (MOC_5)'. The AHP ranking for this challenge is three with a weightage of 15%. The challenge 'Attainment of necessary technician skills by contractors' decorates the second position in the CE ranking of the 'Cause' category. The AHP ranking of this challenge is also second. The challenge of attainment of organizational strength by contractors (MOC_1) ranked top in the AHP analysis with 32 percent of the weightage, and the DEMATEL study projected it in a 'Cause' category with a CE ranking of three. The last challenge in the cause category is 'Maintenance data acquisition and analysis challenges' with an AHP ranking of four. Apart from the categorization of the challenges into 'Cause' and 'Effect' groups, the DEMATEL methodology has also established the interrelationships among the challenges. A prominence rank (PR) was established using the DEMATEL methodology. Prominence ranking signifies the supremacy of a challenge in influencing other challenges. According to this, the challenge 'Attainment of organizational strength by contractors' has the highest prominence ranking, which has an impact on all other challenges. The second challenge in the prominence ranking is the service quality challenge. The theoretical and practical implications of the results are discussed in the forthcoming section.

5.6. Discussions

The outcomes of the study have both theoretical and practical implications, which are separately addressed.

5.6.1Theoretical Implications

The research has utilized structural models such as AHP and DEMATEL. These structural models used have their limitations, such as the high reliance on the judgments of the experts on the topic, the possibility of subjectivity in evaluations, etc. However, these shortcomings were alleviated to the minimum level by incorporating the support of experienced experts in the domain and using the consensus of all experts in the evaluation to avoid subjectivity. The inputs from the experts were successfully modeled using the structural models, and the theoretical results obtained were highly consistent with the practical scenario.

5.6.2 Practical Implications

According to the results, the prominent challenge in the cause category is 'Facilitation with modern equipment, gadgets, and instrumentation (MOC_5). This indicates that failure to address this challenge will have a cascading effect on the proliferation of other challenges. This is because the Industry 4.0 regime requires more sophistication in all operations, and hence the need for modern equipment, gadgets, and instrumentation for condition monitoring is highly justifiable. Hence, maintenance contractors need to procure and use modern equipment, gadgets, tools, etc. 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 whom the authors consulted while developing the literature. 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. Since the maintenance in the Industry 4.0 regime requires a more sophisticated approach from the technicians, the inefficiencies of the in-house maintenance crew would be a bottleneck that paves 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 constitute the organizational strength of a contractor, must be strong for any maintenance service firm to get the contract. Maintenance data acquisition and analysis challenges were the fourth ones in the cause category. Data acquisition and analysis are the cornerstone activities in predictive maintenance in the Industry 4.0 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.

Challenges in the ‘Cause’ category, if not addressed promptly, would lead to the proliferation of challenges that belong to the category of ‘Effects’. It is to be noted that challenges in service quality, health safety, environment, and spare supply chain management are closely linked with hardcore maintenance activities of the belt conveyor system. Hence, such challenges should not arise as maintenance has a lot of implications for the reliability and safety of the conveyor systems. Moreover, legal and financial challenges would escalate if the ‘Cause’ category challenges are inadequately addressed by maintenance contractors. Hence, organizations that are venturing into the business of maintenance services will have to strengthen their organization through robust procedures, management tools, etc. The poor level of attainment of service quality would weaken the organizational strength of contractors, which would lead to a loss of repute and goodwill, which may eventually lead to legal and financial troubles. Inadequate service quality will also be reflected through the occurrence of problems in managing the health and safety of the maintenance crew and the protection of the environment. Challenges having PR ranking three and four, i.e., the health, safety, and environment, as well as spares supply chain management-related challenges, can adversely affect organizational strength, lead to legal problems, and affect service quality. Failures to fulfill the legal and financial challenges by the maintenance contractor would lead to quality issues in the maintenance processes and chaos in the spare supply chain. Inadequacies in the skill set of the maintenance crew with the contact will lead to problems in maintenance data acquisition, service quality, and spare management. It has already been mentioned that maintenance data acquisition is essential in the era of Industry 4.0, and hence, lacunae in that will adversely affect service quality and spare supply chain management. The lack of modern equipment, gadgets, and instrumentation available with the maintenance contractor derails the organizational objectives and cripple the service technicians. Moreover, the maintenance data acquisition and analysis will be adversely affected, and all such effects will ultimately culminate in poor service quality.

5.7 Conclusions

According to the findings of this paper, challenges to the maintenance outsourcing of belt conveyors have been identified through a literature review as well as interactions with conveyor owners and maintenance professionals, which have assisted in better understanding and assimilation of challenges. The use of a hybrid methodology combining AHP and DEMATEL has aided in the analysis of the maintenance outsourcing challenges and the identification of the most significant challenges. This discovery is extremely important in the context of implementing Industry 4.0 practices, including in maintenance. The AHP technique has ranked the challenges according to their significance. The DEMATEL methodology has classified the challenges into the ‘Cause’ and ‘Effect’ categories. This form of categorization and prioritizing would aid owners and operators of belt conveyor installations, maintenance engineers, and maintenance service contractors in understanding challenges that fall under the cause category. This will assist them in developing more focused methods and tactics that are aimed at reducing the most significant challenges. According to the findings of the study, the most significant challenges are the attainment of organizational strength by contractors, the attainment of necessary technician skills by contractors, facilitation with modern equipment, gadgets, and instrumentation, and maintenance data acquisition and analysis challenges. AHP had ranked the above challenges in the top four slots, and DEMATEL had categorized them into the 'Cause' category. This gives a clear indication to the organizations who are already functioning or willing to venture into the business of undertaking maintenance contracts that they need to develop organizational strength in all dimensions, recruit people with adequate skills and train them to be ready for the Industry 4.0 environment, procure modern gadgets that help the technicians in performing tasks as well as maintenance data acquisition and analysis. Belt conveyor maintenance contractors can use the study's findings to craft more comprehensive, comprehensive, and profitable plans for bagging more contracts and their successful execution. The future scope of this work includes the development of a framework for maintenance contractor selection.

CHAPTER 6

CONTRACTOR SELECTION FOR OUTSOURCED MAINTENANCE SERVICES

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This chapter deals with the development of a framework for selecting a suitable contractor for the outsourcing of maintenance of belt conveyor installations. To pick the best contractor among options, a hybrid structural methodology incorporating AHP and PROMETHEE-II is used. This will assist the organizations that own and operate these installations in making informed decisions about the hiring of suitable maintenance contractors.

6.1. INTRODUCTION

Traditionally, maintenance operations were performed internally by the owning organizations without reliance on external support. However, with the increasing integration of automation, digitalization, and intelligent systems under the paradigm of Industry 4.0, maintenance management has become significantly more complex [16]. Advanced maintenance strategies such as PdM demand specialized technical expertise and sophisticated tools. Consequently, maintenance personnel are now required to possess competencies in emerging technologies, including the Internet of Things (IoT), radio-frequency identification (RFID), machine learning, cloud computing, data analytics, cybersecurity, automation, middleware systems, and collaborative software platforms [12,18, 19, 196].

In addition to technical capabilities, Industry 4.0 necessitates a broad set of non-technical skills such as effective communication, adaptability, accountability, teamwork, organizational ability, analytical reasoning, critical thinking, emotional intelligence, and continuous learning. Developing these competencies requires substantial investment in workforce training and development. In response to these challenges, organizations increasingly adopt outsourcing strategies, particularly for corrective and preventive maintenance functions [22]. As a result, a growing proportion of maintenance activities in process industries is delegated to external service providers [17, 197, 198].

Ahmed [95] highlighted that the outsourcing trend is further driven by a shortage of skilled maintenance professionals, as well as limitations in internal resources and infrastructure. Similarly, Godoy et al. [23] emphasized that asset-intensive sectors such as mining, aviation, and defense, characterized by complex equipment and stringent uptime requirements, often necessitate significant maintenance investments, making outsourcing a viable and sometimes essential option. Typical candidates for outsourced maintenance include general equipment, electronic systems, environmental control systems, transportation assets, facilities, and large-scale plant overhauls [96].

Belt conveyor systems are frequently integral components of power plants and process industries, where maintenance activities such as TAM are critical and resource intensive. These operations are often complex, high-cost, and require meticulous planning, scheduling, coordination, and execution involving multiple stakeholders, including clients, partners, contractors, and technology providers [97]. Consequently, the outsourcing of belt conveyor maintenance is becoming increasingly prevalent, particularly in industries such as mining.

Despite its advantages, outsourcing maintenance for safety-critical systems like belt conveyors presents several challenges. These include technical, managerial, economic, and legal issues that may arise during implementation [24]. To achieve optimal outcomes and mitigate associated risks, the selection of an appropriate contractor is of paramount importance [77]. However, identifying and evaluating suitable contractors from multiple alternatives remains a complex decision-making problem for system owners and operators [24].

Accordingly, the primary objective of this study is to develop a structured framework for selecting maintenance contractors for outsourced conveyor services using a hybrid decision-making approach. The selection criteria are identified through a combination of expert opinions and literature review, incorporating both primary and secondary data sources. For this purpose, site visits were conducted across multiple industries employing belt conveyor systems, and domain experts were consulted through an unstructured exploratory survey. The questionnaire focused on identifying key criteria relevant to contractor selection for outsourced maintenance services.

To ensure objectivity and eliminate bias, expert responses were kept confidential until all inputs were collected. Subsequently, similar responses were grouped into distinct criteria and sub-criteria, which were further validated through an extensive literature review. The relative importance (weights) of the identified criteria was determined using the Analytic Hierarchy Process (AHP). Thereafter, the PROMETHEE-II method was applied to rank and select the most suitable contractor from a set of alternatives. Finally, the effectiveness and applicability of the proposed hybrid framework were demonstrated through a case study.

6.2. IDENTIFICATION OF CRITERIA FOR MAINTENANCE CONTRACTOR SELECTION.

In this section, the selection criteria for maintenance contractors for belt conveyor installations have been identified. For this, the authors have conducted visits to various belt conveyor installations in industries including mining, power plants, and fertilizer units. An unstructured exploratory survey was conducted among the owners and operators, and gathered information regarding their preferences while selecting a maintenance contractor. Moreover, this information was integrated with the available literature. The various selection criteria and sub-criteria that have been revealed through these interactions and literature have been segregated under different headings that are described in the forthcoming sub-sections.

6.2.1 Economic Factors

Economic considerations play a pivotal role in the selection of contractors for outsourced maintenance operations, as highlighted by Kusi-Sarpong et al. [199]. Maintenance activities are inherently cost-intensive, involving significant labor hours, consumption of materials, utilization of spare parts, and deployment of specialized equipment [200]. In many instances, actual maintenance expenditures may surpass the allocated budget due to unforeseen circumstances [201]. Consequently, the pricing structure proposed by a contractor becomes a critical determinant in the selection process.

Beyond direct costs, outsourced maintenance is associated with substantial financial risks [202]. These risks may arise from unexpected requirements such as urgent procurement of spare parts, extensions in maintenance timelines, delays in payments from asset owners, and immediate financial obligations toward suppliers. Such factors can impose additional financial strain on contractors. Therefore, the financial robustness of a contractor is a key consideration, encompassing aspects such as overall financial stability, revenue generation, profitability, liabilities, obligations, and shareholder equity [203].

In a similar context, Morkunaite et al. [204] emphasized the importance of evaluating financial indicators such as contractor income, the value of previously awarded contracts, outstanding receivables, pre-tax profits, and financial performance ratios during the selection process. Furthermore, contemporary maintenance contracts often incorporate penalty clauses, wherein contractors incur financial penalties for delays in project completion [198]. Additionally, contractors are typically responsible for bearing insurance-related costs. Hence, preference should be given to contractors who demonstrate transparency and well-defined policies regarding penalty provisions and insurance liabilities.

6.2.2 Organizational strength

The capability and effectiveness of a maintenance organization are fundamental to the success of maintenance outsourcing initiatives [177]. Core managerial responsibilities of a maintenance contractor include determining the appropriate scale of operations, assessing prospective clients, and structuring an efficient maintenance function within the organization [75]. In this context, Judenberg [78] conducted an extensive analysis and identified essential organizational requirements, such as a high level of commitment and professionalism, clearly documented procedures, and the adoption of advanced project management tools.

Further, Toosi et al. [79] highlighted several organizational competencies that contribute to contractor effectiveness, including efficient reporting and feedback mechanisms, a culture of innovation, accessibility, strong administrative practices, reliability, credibility, and domain-specific expertise. Additional attributes include the provision of auxiliary support systems, effective communication, operational control, proactive decision-making, and the ability to maintain dynamic relationships with asset owners. Similarly, Ghazali et al.[203] emphasized that contractor management capabilities should be evaluated based on prior performance, quality standards, the presence of a formal quality control policy, and the implementation of structured quality and project management systems.

Tong et al. [98] recommended that maintenance contractors adhere to internationally recognized standards, including ISO 9000 for quality management, ISO 14001 for environmental management, and ISO 45001 for occupational health and safety. In terms of technological infrastructure, Chemweno et al. [80] stressed the importance of adopting advanced software solutions such as computerized maintenance management systems (CMMS), enterprise asset management (EAM) systems, enterprise resource planning (ERP) platforms, and customized risk assessment tools. These systems typically incorporate functionalities for budget monitoring, maintenance operations tracking, decision support, and process visualization.

Accurate data collection and analysis are also critical components of effective maintenance outsourcing. Murthy et al. [76] underscored the importance of systematic data acquisition, particularly for tracking equipment failures and repair histories. In conventional belt conveyor maintenance, this is often achieved through maintenance logbooks or database management systems. However, with the advent of Industry 4.0, there is an increasing need for advanced data acquisition techniques, including sensor-based monitoring systems for predictive maintenance. Consequently, maintenance contractors must adopt modern data management practices encompassing efficient data collection, storage, and retrieval mechanisms.

To ensure accurate interpretation and modeling of maintenance data, contractors must either employ skilled in-house experts or engage external specialists [14, 76]. Additionally, belt conveyor maintenance often necessitates the replacement of components that have reached the end of their operational life. However, frequent replacement demands can impose logistical and financial challenges, particularly in maintaining adequate spare parts inventory to meet contractual obligations [90]. In this regard, Godoy et al. [23] observed that when contractors effectively manage the spare parts supply chain, optimized component utilization can be achieved, thereby benefiting asset owners. This underscores the importance of robust and efficient supply chain management capabilities within maintenance contracting organizations.

6.2.3 Service Track Record

Maintenance contractors are generally expected to demonstrate a strong and reliable service track record [205]. According to Ghazali et al.[203], this record can be assessed through several indicators, including the contractor's prior experience, the number and financial scale of completed projects, duration of industry involvement, and the profile of previous clients served. In addition to historical performance, the evaluation should also consider the contractor's current workload, such as ongoing projects and backlog. This includes factors like the number, size, and geographical distribution of projects, as well as capacity utilization, project progress, and anticipated completion timelines.

Furthermore, Cao et al. [206] emphasized the importance of relational aspects, including the contractor's level of cooperation with client organizations, as well as their interactions with subcontractors and suppliers. Performance indicators such as project success and failure rates also provide valuable insights into the contractor's reliability and operational effectiveness. Therefore, a comprehensive assessment of the contractor's service track record is essential when selecting a suitable partner for outsourced maintenance of belt conveyor systems.

6.2.4 Maintenance service quality

The quality of services delivered by a maintenance provider constitutes a critical consideration in the outsourcing decision-making process for conveyor system owners [79]. Ghazali et al [203] categorized maintenance service quality into three primary dimensions: equipment quality, repair quality, and service orientation. Equipment and repair quality pertain to the technical proficiency of the service provider, including system reliability and the capability to restore equipment to an optimal or near original operating condition. In contrast, service orientation relates to the nontechnical aspects of service delivery, encompassing interpersonal interactions and the overall responsiveness of the provider.

In addition to these dimensions, key performance metrics such as maintenance service duration, response time, and turnaround time play a significant role in evaluating service quality [80]. Cohen [88] further emphasized the importance of incorporating structured performance measurement components within maintenance contracts, including functional analysis documentation, maintenance performance indicators, and system loss metrics. Moreover, Judenberg [78] suggested that maintenance quality can be effectively assessed using indicators such as mean time between failures (MTBF), frequency of incidents, and the average time required to resolve faults.

Therefore, a comprehensive evaluation of maintenance service quality is essential when selecting a contractor for outsourced maintenance activities, particularly in the context of belt conveyor systems

6.2.5 Maintenance technician skills

The role of maintenance technicians in achieving technical and organizational objectives has received significant attention in maintenance engineering research [207]. The effectiveness of maintenance outsourcing largely depends on the contractor's ability to deploy a skilled, experienced, and stable workforce [208]. A shortage of qualified specialists has been identified as a key challenge, particularly in the context of outsourcing belt conveyor maintenance. Therefore, the selected contractor must possess not only a thorough understanding of the technical scope of work but also access to adequately trained and specialized personnel [203].

Ighravwe [209] emphasized that technician competency forms the foundation for successful maintenance execution. In line with evolving industrial practices, Windelband [81] highlighted that modern technicians are expected to operate at an advanced skill level, enabling them to make real-time, data-driven decisions while also functioning as data analysts. This shift reflects the transition from traditional condition-based maintenance toward more integrated and predictive maintenance paradigms.

Existing literature consistently identifies education and practical experience as critical determinants of technician capability [210, 211]. Furthermore, additional essential attributes include formal training, hands-on experience, physical endurance, mental alertness, and cognitive competence. Consequently, maintenance contractors employing technicians with these competencies are more likely to deliver superior performance and are therefore preferable in the contractor selection process.

6.2.6 Tools and equipment support

Industrial maintenance activities typically require a wide range of tools, including basic hand tools, measuring instruments, cutting tools, vibratory tools, and pneumatic equipment, along with supporting infrastructure such as lifts, ladders, and hoisting systems [212]. In the specific context of belt conveyor maintenance, additional specialized tools and equipment, such as those used for lifting, clamping, cutting, and skiving, are essential for effective operation and servicing.

Leading manufacturers, including belt conveyor [213], recommend the use of dedicated belt handling systems to enhance maintenance efficiency. These systems comprise equipment such as belt winders, pullers, turning and guiding mechanisms, cable winches, heavy-duty clamping systems, braked let-off stands, vulcanizing units, and belt flaking devices. Accordingly, maintenance contractors are expected to possess not only standard tools and equipment but also access to advanced and specialized machinery, either in-house or through external arrangements when required.

Furthermore, the implementation of predictive maintenance strategies necessitates the use of condition monitoring systems capable of capturing operational data from critical points along the conveyor system. This typically involves the deployment of both fixed and mobile sensors [10]. Modern conveyor monitoring systems often incorporate embedded conductive elements, such as cords or layers, combined with electrical and magnetic field-based detection mechanisms. The integration of Internet of Things (IoT) technologies further enhances condition monitoring capabilities, enabling more efficient predictive maintenance practices, although it also demands increased digitalization and technical sophistication.

Murthy et al. [76] emphasized that the adoption of advanced maintenance approaches requires the use of sophisticated diagnostic and analytical tools. Therefore, contractors equipped with comprehensive and modern toolsets, along with the capability to utilize advanced technologies, are better positioned to deliver effective maintenance services and are thus preferred in the contractor selection process.

6.2.7 Health, safety, and environmental practices

Health and safety considerations in maintenance activities have been extensively investigated in prior research [214, 215]. In practical settings, maintenance operations, particularly turn-around maintenance (TAM) projects, are often associated with significant health, safety, and environmental (HSE) challenges [15]. Through an industry-wide survey, Lind and Neonen [214] identified several primary causes of safety-related incidents, including the absence of clearly defined procedures, insufficient provision of personal protective equipment (PPE), lack of technical expertise and experience, unfavorable working conditions, deficiencies in job planning, and inadequate safety management systems.

Given these concerns, Hadidi and Khater [15] advocated for the incorporation of safety-related criteria throughout the contractor selection and bidding process. Supporting this perspective, Tong et al. [98] observed that, particularly in industries such as petrochemicals, decision-makers tend to favor maintenance service providers demonstrating strong sustainability performance, including adherence to HSE standards. From a safety standpoint, critical evaluation parameters include the contractor’s work history, particularly records of incidents, technical capabilities, workforce competency, and the presence of a comprehensive HSE strategy [15]. Hence, preference should therefore be given to contractors who strictly enforce PPE usage, provide regular safety training, comply with fire safety standards, and ensure the availability of first-aid facilities. Adherence to regulatory frameworks, such as Occupational Safety and Health Administration (OSHA) standards, further strengthens the safety performance of contractors.

In addition to safety considerations, environmental sustainability has emerged as a critical concern in maintenance operations. Belt conveyor maintenance activities involve energy consumption and generate waste, including discarded components that may contribute to environmental degradation [3, 216]. Consequently, contractors should be evaluated based on their ability to implement sustainable practices, including energy-efficient operations and environmentally responsible waste management.

The criteria and sub-criteria outlined for selecting contractors for outsourced belt conveyor maintenance were identified through an exploratory survey conducted among industry owners and operators. Their insights regarding contractor selection preferences were systematically collected and subsequently integrated with findings from existing literature to establish a comprehensive evaluation framework. The various selection criteria and sub-criteria that had been revealed through these interactions and literature are consolidated and presented in Table 6.1.

Table 6.1Criteria and Sub-criteria for maintenance contactor selection of belt conveyors

Sr.No	Selection Criteria	Notation	Sub-Criteria	Notation
1	Economic Factors	EC	Contract rate	EF_1
			Net worth	EF_2
			Pre-tax profit	EF_3
			Financial accounting ratios	EF_4
			Value of previous contracts	EF_5
			Policy on penalty cost	EF_6
			Policy on insurance cost	EF_7
2	Organizational strength	OS	Project management system	OS_1
			Quality management system	OS_2
			Management communication	OS_3
			ERP system	OS_4
			Maintenance data management system	OS_5
			Spare supply chain management	OS_6
3	Service Track Record	STR	Relations between subcontractors and vendors	STR_1
			Project success rate	STR_2
			Years of expertise	STR_3
			Clientele base	STR_4
			Number of completed projects	STR_5
			Value of completed projects	STR_6
4	Maintenance Service quality	MSQ	Record of adherence to promised delivery time	MSQ_1
			Response time promptness	MSQ_2
			Turnaround time	MSQ_3
			Incidents of maintenance errors	MSQ_4
5	Personal skills	PS	Education and training of technicians	PS_1
			Experience of technicians	PS_2
			Mental and physical fitness of technicians	PS_3
			Cognitive skills of technicians	PS_4
6	Tools and equipment support	TES	Provision of general equipment and tools	TES_1
			Provision of belt handling equipment	TES_2
			Provision of sophisticated diagnostic and condition monitoring tools	TES_3

7	Health, safety, and environment	HSE	The practice of OSHA laws	HSE_1
			Safety training	HSE_2
			Display of safety instructions	HSE_3
			Personal protective equipment (PPE) provision	HSE_4
			First aid facility	HSE_5
			Fire extinguisher provision	HSE_6
			Energy efficiency in maintenance	HSE_7
			Dedicated waste disposal system	HSE_8
			Practices of repair/remanufacturing of replaced parts	HSE_9

6.3. ELABORATION OF THE HYBRID MODEL

The assessment of weightages of various selection criteria for maintenance contractors and selection of the best maintenance contractor for belt conveyor installations form a complex evaluation system. There are different methodologies for the evaluation of weights, such as the Delphi method [217], the expert evaluation method [218], etc. However, they involve a lot of subjectivity. Hence, AHP methodology is implemented in this work, which can add the intangible and tangible components to the model, along with the subjectivity and uncertainty that are intrinsic to decision making [219]. After assessing the criteria weights, the methodology of PROMETHEE-II is implemented for selecting the best contractor among the alternatives. The primary reason for the selection of this model is its easily comprehensible nature and demonstrated efficacy in addressing practical problems. Another benefit of PROMETHEE-II is the provision of a comprehensive ranking [220]. The combined methodology of AHP and PROMETHEE-II has been successfully implemented for selecting and evaluating logistics outsourcing decisions [221], identifying the best locations for water harvesting [222], supplier selection [223], etc. The methodologies are described in detail in the subsections that follow.

6.3.1 Analytic Hierarchy Process (AHP) method.

The AHP (Analytic Hierarchy Process) is a problem-solving tool that is applied to solving fuzzy problems. It is mainly applied in subjective decision-making processes, which are based on multiple criteria in a hierarchical system [224]. In AHP, the building of priority scales is based on pairwise comparisons and subjective judgments of domain experts [150]. The AHP approach allows for evaluations, both qualitative and quantitative, of variables while considering the decision maker's priorities [225]. The AHP approach has been effectively used in the domain of maintenance, including the ranking of total productive maintenance pillars [226], selection of maintenance strategy for optimum efficiency application in a structural steel fabrication construction company [227], maintenance strategy selection in the oil and gas industry [228], etc. In this study, AHP is used to examine the weightages of the selection criteria of maintenance contractors.

According to Saaty's scale, as shown in Table 6.2, pairwise comparisons and pairwise comparison matrices for the criteria at each level are obtained. Based on the formula CI= (λ_{max} – N) / (N-1), the consistency index is calculated where λ_{max} is the largest eigenvalue. After that, by taking values of the random index (RI) from Table 3, the consistency ratio is computed using the equation CR = CI/RI to see if the relative estimation is feasible for each matrix. The CR values should be less than or equal to 0.10.

Table 6.2 Satty's scale for assigning value to pair-wise comparisons of matrix elements

Verbal judgment of relative importance between elements '*i*' and '*j*'	Numerical rating
is equally important as	1
slightly important than	3
is strongly more important than	5
very strongly more important than	7
extremely more important than	9

Table 6.3 Values of Random Index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.85	0.9	1.12	1.24	1.32	1.41	1.45	1.51

6.3.2 PROMETHEE Methodology

Brans and Vincke [229] proposed the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE). This study uses the PROMETHEE-II approach [229, 230] since it completes the whole ranking of the evaluated factors, which is essential in this work. This methodology has been used for performance evaluation of sustainable maintenance suppliers in the petrochemical industry [98], selecting the optimal contractor for construction projects, supplier selection for industries [231], Development of an integrated RCM framework for transportation machines used in mines [94], maintenance prioritization in health care systems [232], etc. The steps for putting the PROMETHEE-II technique into practice are as follows.

6.3.2.1 Procedure of PROMETHEE-II

Step 1: Normalization of the decision matrix (D)

After gathering advice from experts, the decision matrix (D) is created, which serves as the PROMETHEE's initial matrix. Following that, using the expression, matrix D is normalized to yield a normalization matrix (R) using equation (6.1). Normalization is performed for transforming the values of criteria into a common scale.

$$R_{ab} = \frac{D_{ab} - \min(D_{ab})}{\max(D_{ab}) - \min(D_{ab})} \qquad (6.1)$$

Step 2: Pairwise comparison to determine the deviation

The evaluation of the distinction between the i^{th} alternative and the others occurs in this step. This necessitates the pairwise evaluation of the disparities in criterion values among different alternatives. The pairwise deviation is calculated by subtracting the value of one criterion from the value of the other using the normalized matrix (R) using equation (6.2).

$$d_b(x,y) = r_b(x) - r_b(y) \qquad (6.2)$$

Where $d_b(x,y)$ is the difference between the value x and y on each criterion, and r_b is the value of the Normalization matrix (R).

Step 3: Calculate the preference function

This step of developing a preference function helps in characterizing the difference in the decision maker's preference between pairs of alternatives with respect to each criterion. A preference function is obtained based on equation (6.3)

$$P_b\,(x, y) = F\,[d_b\,(x, y)] \qquad (6.3)$$

Where, $F(d) = 0$, if $d < 0$ and $F(d) = d$, if $d > 0$, i.e. if the deviation of pairwise comparison is negative, the function '*F*' deduces its value to 0, and if the obtained deviation is positive, the function '*F*' will retain its actual value in matrix $P(x,y)$.

Step 4: Calculate the aggregated preferences.

This step considers the weight of each criterion and integrates it with the preference function. Aggregated preferences or Global preferences are calculated by multiplying the criteria weight (W_b) that is obtained from the AHP method with the values of $P(x,y)$ as given in equation (6.4).

$$\sigma(\mathrm{x},\mathrm{y}) = \sum_{b=1}^{k} P(\mathrm{x},\mathrm{y})\, W_b \qquad (6.4)$$

Step 5: Determination of the outranking flows/partial ranking

Leaving outranking flow (ϕ+) and entering outranking flow (ϕ-) are calculated by taking the mean values of the rows and columns, respectively, of matrix **σ(x, y)**. They are used to denote the partial ranking by the PROMETHEE-I method. However, PROMETHEE-II involves a step to obtain the complete ranking of the alternatives. This step is performed for evolving the net outranking flow as a balance between negative and positive flows.

Leaving outranking flow (ϕ^+) is determined by using equation (6.5).

$$\phi^+ = \frac{1}{n-1}\sum_{c\in A}\sigma(\mathrm{x},\mathrm{c}) \qquad (6.5)$$

Entering outranking flow (ϕ^-) is determined by using equation (6.6).

$$\phi^- = \frac{1}{n-1}\sum_{c\in A}\sigma(\mathrm{c},\mathrm{x}) \qquad (6.6)$$

Step 6: Obtaining the complete ranking

Obtain the net outranking flow $\phi(x)$ by subtracting 'Entering outranking flow (ϕ^-)' from 'Leaving outranking flow (ϕ^+) as per equation (6.7). This step ensures the final ranking of alternatives.

$$\phi(x) = \phi^+ - \phi^- \qquad (6.7)$$

The net outranking flow $\phi(x)$ determines the final ranking of the alternatives. The higher the value of the $\phi(x)$ of an alternative, the greater its ranking is in the net ranking.

6.4. IMPLEMENTATION OF THE METHODOLOGY

In this section, the method proposed previously, i.e., in section 6.3, is implemented for the selection of maintenance contractors for belt conveyors installed at a 2270 MW thermal power station in Western India. There are four different potential contractors designated as C_1, C_2, C_3, and C_4, and the power plant management has to choose the best alternative with the help of a team of experts that includes maintenance engineers and managers, technicians, finance managers, operation managers, and academic scholars. Each expert has more than 8 years of experience in the respective domains. They provided the feedback required for the determination of the weight of seven criteria and also evaluated the four different contractors against each criterion in order to select the best one. Results of the study are presented in the following section:

6.5. RESULTS AND DISCUSSION

The following sections provide results about the criteria weight determination using AHP and contractors' ranking using PROMETHEE-II methods:

6.5.1 Results of AHP

The Analytical Hierarchy Process (AHP) was employed to determine the normalized weight of all selection criteria discussed in Section 6.2. This step would help the evaluators to understand the significance of each criterion quantitatively. The experts were provided with details of the selection criteria and were asked to prepare a pairwise comparison matrix of the selection criteria as per Saaty's 1-9 scale (Table 6.2). The matrix so developed is presented as 'B' given in equation (6.8).

$$B = \begin{array}{l} \text{Selection Criteria} \\ \text{EF} \\ \text{OS} \\ \text{STR} \\ \text{MSQ} \\ \text{PS} \\ \text{TES} \\ \text{HSE} \end{array} \begin{array}{c} \begin{array}{ccccccc} \text{EF} & \text{OS} & \text{STR} & \text{MSQ} & \text{PS} & \text{TES} & \text{HSE} \end{array} \\ \begin{bmatrix} 1 & 4 & 2 & 1 & 6 & 7 & 8 \\ 1/4 & 1 & 1/6 & 1/5 & 1/4 & 1/4 & 3 \\ 1/2 & 6 & 1 & 1/6 & 1 & 1 & 3 \\ 1 & 5 & 6 & 1 & 6 & 6 & 7 \\ 1/6 & 4 & 1 & 1/6 & 1 & 1 & 6 \\ 1/7 & 4 & 1 & 1/6 & 1 & 1 & 4 \\ 1/8 & 1/3 & 1/3 & 1/7 & 1/6 & 1/4 & 1 \end{bmatrix} \end{array} \qquad (6.8)$$

The steps of AHP, described in section 6.3.1.1, were implemented, and the normalized weights of selection criteria and their rank were determined, which are shown in Table 6.4.

Table 6.4 Normalized weights of selection criteria and their rank

Sr No.	Selection Criteria	Weight (W)	Rank
1	Economic Factors (EF)	0.30	2
2	Organizational Strength (OS)	0.04	6
3	Service Track Record (STR)	0.11	3
4.	Maintenance Service Quality(MSQ)	0.34	1
5.	Personal Skills (PS)	0.09	4
6.	Tools and Equipment Support (TES)	0.08	5
7.	Health, Safety, and Environment(HSE)	0.03	7

The consistency ratio (CR) was found to be 0.10, which indicates that the pairwise comparison is consistent and the weights of the criteria determined using the AHP method are reliable. It can be seen from Table 4 that maintenance service quality (MSQ) and health, safety, and environment (HSE) are the most important and the least significant criteria for contractor selection for outsourced maintenance services, as their ranks are 1 and 7, respectively. The criteria in decreasing order of importance, as revealed from Table 6.4, are MSQ>EF>STR>PS>TES>OS>HSE.

6.5.2 Results of PROMETHEE-II

After establishing the weight of selection criteria, another method of MCDM, i.e., PROMETHEE-II, was applied to select the best contractor. For this purpose, all sub-criteria need to be evaluated qualitatively first. For this purpose, Rao and Davim [233] suggested the use of fuzzy set theory, in which the linguistic term established by an expert can be translated into fuzzy numbers and then to their corresponding numerical values. They have also proposed an 11-point scale (Table 6.5) ranging from 0 to 1 for the same.

Table 6.5 Linguistic variables and equivalent numerical values

Sr.No.	Qualitative description of the linguistic variable	Assigned values
1	Exceptionally High	0.955
2	Extremely High	0.865
3	Very High	0.745
4	High	0.665
5	Above average	0.590
6	Average	0.500
7	Below average	0.410
8	Low	0.335
9	Very low	0.255
10	Extremely low	0.135
11	Exceptionally low	0.045

Once all the sub-criteria were quantitatively evaluated, the cumulative scores of all sub-criteria of each criterion were calculated using the expression $C_i = \Sigma C_{ij}$, where i = 1,2,...6 and j = 1,2,....n. Table 6.6 shows the result of the evaluation of various criteria by the team of experts.

Table 6.6. Evaluation of criteria												
Sr. no.	**Criteria**	**Sub –Criteria**		**Contractor 1**		**Contractor 2**		**Contractor 3**		**Contractor 4**		
			Notations	Sub-Criteria Score	Sum	Sub-Criteria Score	Sum	Sub-Criteria Score	Sum	Sub-Criteria Score	Sum	
1	Economic Factors (EF)	Contract rate	EF_1	0.745	5.02	0.865	5.095	0.745	5.11	0.745	5.055	
		Net worth	EF_2	0.745		0.745		0.665		0.745		
		Pre-tax profit	EF_3	0.59		0.665		0.59		0.665		
		Financial accounting ratios	EF_4	0.665		0.665		0.665		0.745		
		Value of previous contracts	EF_5	0.865		0.745		0.955		0.745		
		Policy on penalty cost	EF_6	0.745		0.745		0.745		0.745		
		Policy on insurance cost	EF_7	0.665		0.665		0.745		0.665		
2	Organizational strength (OS)	Project management system	OS_1	0.745	4.63	0.745	4.185	0.665	3.82	0.665	4.065	
		Quality management system	OS_2	0.865		0.865		0.745		0.745		
		Management communication	OS_3	0.665		0.665		0.745		0.745		
		ERP system	OS_4	0.865		0.745		0.665		0.745		
		Maintenance data management system	OS_5	0.745		0.665		0.5		0.5		
		Spare Supply chain management	OS_6	0.745		0.5		0.5		0.665		
3	Service Track Record (STR)	Relations between subcontractors and vendors	STR_1	0.745	4.71	0.745	4.59	0.665	4.07	0.865	4.71	
		Project success rate	STR_2	0.865		0.745		0.665		0.745		
		Years of expertise	STR_3	0.745		0.865		0.745		0.865		

		Clientele base	STR_4	0.865		0.745		0.665		0.745	
		Number of completed projects	STR_5	0.745		0.745		0.665		0.745	
		Value of completed projects	STR_6	0.745		0.745		0.665		0.745	
4	Maintenance service quality (MSQ)	Record of adherence to promised delivery time	MSQ_1	0.865		0.745		0.745		0.865	2.355
		Response time promptness	MSQ_2	0.865		0.865		0.665		0.745	
		Turnaround time	MSQ_3	0.865	2.595	0.745	2.355	0.745	2.155	0.745	
5	Personal skills(PS)	Education and training of technicians	PS_1	0.745	2.98	0.865	3.22	0.865	3.1	0.865	3.1
		Experience of technicians	PS_2	0.745		0.865		0.745		0.745	
		Mental and physical fitness of technicians	PS_3	0.745		0.745		0.745		0.745	
		Cognitive skills of technicians	PS_4	0.745		0.745		0.745		0.745	
6	Tools and equipment support(TES)	Provision of general equipment and tools	TES_1	0.745	2.475	0.865	2.685	0.865	2.595	0.865	2.745
		Provision of belt handling equipment	TES_2	0.865		0.955		0.865		0.865	
		Provision of sophisticated diagnostic and condition monitoring tools	TES_3	0.865		0.865		0.865		0.745	
7	Health, safety and environment(HSE)	The practice of OSHA laws	HSE_1	0.865	5.51	0.745	5.235	0.865	5.755	0.745	5.395
		Safety training	HSE_2	0.745		0.745		0.745		0.745	
		Display of safety instructions	HSE_3	0.665		0.665		0.745		0.665	

		PPE provision	HSE_4	0.745		0.745		0.745		0.665	
		First aid facility	HSE_5	0.745		0.745		0.745		0.745	
		Fire extinguisher provision	HSE_6	0.745		0.665		0.745		0.665	
		Dedicated waste disposal system	HSE_7	0.665		0.59		0.665		0.665	
		Practices of repair/remanufacturing of replaced parts	HSE_8	0.335		0.335		0.5		0.5	

Based on the results of Table 6.6, the evaluation/decision matrix was developed as shown in Table 6.7

Table 6.7 Evaluation/ Decision Matrix

	EF	OS	STR	MSQ	PS	TES	HSE
C_1	5.02	4.63	4.71	2.595	2.98	2.475	5.51
C_2	5.095	4.185	4.59	2.355	3.22	2.685	5.235
C_3	5.11	3.82	4.07	2.155	3.1	2.595	5.755
C_4	5.055	4.065	4.71	2.355	3.1	2.475	5.395

The normalized decision matrix was evaluated following further steps mentioned in section 6.3, and the result is displayed in Table 6.8.

Table 6.8 Normalized Evaluation/Decision Matrix

	EF	OS	STR	MSQ	PS	TES	HSE
C_1	1	1	1	1	0	0	0.529
C_2	0.166	0.451	0.813	0.455	1	1	0
C_3	0	0	0	0	0.5	0.571	1
C_4	0.611	0.302	1	0.455	0.5	0	0.308

The difference between i^{th} alternative with respect to other alternatives was evaluated and tabulated in Table 6.9 as directed in step 2 of section 6.3.2.1. Then, Preference function values were calculated such that if the respective difference obtained in the previous step is zero or negative, then the preference value of that entity/cell is zero otherwise, the same value will be considered as the preference function value (Table 6.10).

Table 6.9 Pairwise deviation matrix

	EF	OS	STR	MSQ	PS	TES	HSE
$D(C_1-C_2)$	0.833	0.549	0.1875	0.545	-1	-1	0.528
$D(C_1-C_3)$	1	1	1	1	-0.5	-0.571	-0.471
$D(C_1-C_4)$	0.388	0.697	0	0.545	-0.5	0	0.221
$D(C_2-C_1)$	-0.833	-0.549	-0.1875	-0.545	1	1	-0.528
$D(C_2-C_3)$	0.166	0.450	0.8125	0.4545	0.5	0.428	-1
$D(C_2-C_4)$	-0.444	0.148	-0.1875	0	0.5	1	-0.307
$D(C_3-C_1)$	-1	-1	-1	-1	0.5	0.571	0.471
$D(C_3-C_2)$	-0.166	-0.450	-0.8125	-0.454	-0.5	-0.428	1

D(C3-C4)	-0.611	-0.302	-1	-0.454	0	0.571	0.692
D(C4-C1)	-0.388	-0.697	0	-0.545	0.5	0	-0.221
D(C4-C2)	0.444	-0.148	0.187	0	-0.5	-1	0.307
D(C4-C3)	0.611	0.302	1	0.454	0	-0.571	-0.692

Table 6.10 Preference Function Matrix

	EF	OS	STR	MSQ	PS	TES	HSE
P(C1-C2)	0.833	0.549	0.187	0.545	0	0	0.528
P(C1-C3)	1	1	1	1	0	0	0
P(C1-C4)	0.388	0.697	0	0.545	0	0	0.221
P(C2-C1)	0	0	0	0	1	1	0
P(C2-C3)	0.166	0.450	0.812	0.454	0.5	0.428	0
P(C2-C4)	0	0.148	0	0	0.5	1	0
P(C3-C1)	0	0	0	0	0.5	0.571	0.471
P(C3-C2)	0	0	0	0	0	0	1
P(C3-C4)	0	0	0	0	0	0.571	0.692
P(C4-C1)	0	0	0	0	0.5	0	0
P(C4-C2)	0.444	0	0.187	0	0	0	0.307
P(C4-C3)	0.611	0.302	1	0.454	0	0	0

Multiplying the normalized weight of each attribute by the performance preference function value followed by adding all elements of each row, led to the generation of the aggregate preference function, which is shown in Table 6.11.

Table 6.11 Aggregate Preference Function

W * P	EF	OS	STR	MSQ	PS	TES	HSE	$\Sigma(w_j*P_j) / \Sigma W_j$
P(C1-C2) * Wb	0.25	0.021	0.020	0.190	0	0	0.015	0.499
P(C1-C3) * Wb	0.3	0.04	0.11	0.35	0	0	0	0.8
P(C1-C4) * Wb	0.116	0.027	0	0.190	0	0	0.006	0.342
P(C2-C1) * Wb	0	0	0	0	0.09	0.08	0	0.17
P(C2-C3) * Wb	0.05	0.018	0.089	0.159	0.045	0.034	0	0.395
P(C2-C4) * Wb	0	0.005	0	0	0.045	0.08	0	0.130
P(C3-C1) * Wb	0	0	0	0	0.045	0.045	0.014	0.104
P(C3-C2) * Wb	0	0	0	0	0	0	0.03	0.03
P(C3-C4) * Wb	0	0	0	0	0	0.045	0.020	0.066
P(C4-C1) * Wb	0	0	0	0	0.045	0	0	0.045
P(C4-C2) * Wb	0.133	0	0.020	0	0	0	0.009	0.163
P(C4-C3) * Wb	0.183	0.012	0.11	0.159	0	0	0	0.464

Using the aggregate preference function values, a partial ranking matrix was formed and displayed in Table 6.12. Then, using step 5 in section 6.3.2.1, the Leaving and Entering outranking flow was determined. This was followed by calculating the net outranking flow by subtracting the Entering outranking flow from the Leaving outranking flow. These results are shown in Table 6.13.

Table 6.12 Partial ranking matrix

	C_1	C_2	C_3	C_4
C_1	0	0.499	0.8	0.342
C_2	0.17	0	0.395	0.130
C_3	0.1048	0.03	0	0.066
C_4	0.045	0.163	0.464	0

Table 6.13 Net outranking flows and Ranks of Alternatives

	ϕ^+	ϕ^-	$\phi(x)$	**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

Finally, alternatives were ranked according to their net outranking flow values. The higher the value of the net outranking flow implies better the alternative. Based on the result from Table 6.13, contractor 1 was found to be best suited for outsourcing the maintenance contract of belt conveyors installed at the power station.

This study proposed a decision-making framework that comprised the implementation of a hybrid MCDM, i.e., AHP-PROMETHEE-II approach, and demonstrated its application in the selection of the best contractor for outsourcing the maintenance services of the belt conveyor installation of a thermal power plant. Selection of the best contractor, out of several competing contractors, constitutes a multi-criteria decision-making problem that requires evaluation of the available alternatives based on suitable criteria. Consequently, this study considered the seven most suitable selection criteria and determined their weights, reflecting their importance, using the AHP method, and subsequently, ranked the competing contractors using the PROMETHEE-II method. Results of the present study are discussed in light of the findings of the studies available in the literature, carried out by past researchers addressing problems related to the outsourcing of different services. For instance, it has been reported that “improvement of service quality” is the most important factor that influences the outsourcing maintenance decision in thermal power plants [234]. The factors such as cost and personal skills have been reported to be the most significant factors for maintenance offshoring [235]. Another study has reported that service track record reflected by the past performance is the most important criterion for the selection of maintenance contractors [236]. Another study by [237] revealed that price/quality and financial stability are the most important criteria for selection of the most suitable outsourcer. It is worth mentioning that the application of the proposed framework is not only limited to the selection of the best contractor for outsourcing maintenance services of belt conveyor installation, but also can be used by industries such as manufacturing, automobile, heavy machine, etc., to select the best contractor for outsourcing their services.

6.6. RESEARCH AND MANAGERIAL IMPLICATIONS

The significance of this study is that it presents a framework to assist belt conveyor operators in selecting appropriate outsourcing maintenance contractors who can effectively perform the maintenance task efficiently so as to accomplish the task within the stipulated time with 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 linked to outsourced maintenance can be approached through targeted initiatives concerning economic, environmental, and safety safeguards. The present study becomes more relevant and important in the context of the adaptation to Industry 4.0 requirements, which acknowledge the necessity for contemporary contractors to be adept in innovative technologies like 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 the context of thermal power plant operations. The framework mitigates risks associated with financial instability, safety infractions, or service inefficiencies by assessing contractors based on specific sub-criteria, such as punishment policies and environmental standards.

As managerial implications, the decision makers may find this study useful in addressing the problem of contractor selection by implementing clearly defined and prioritized evaluation criteria. Further, they may resolve the issue of guaranteeing contractor reliability by integrating track records and evaluations of organizational robustness. In addition, findings of this study may be used by decision makers to formulate a strategic, systematic, and adaptable framework for belt conveyor operators, improving their capacity to make educated and successful decisions on outsourced maintenance services.

6.7. CONCLUSIONS

The selection of the best contractor for outsourcing maintenance activities of belt conveyors is essential for the optimal performance of those installations. However, the presence of numerous criteria and sub-criteria related to maintenance contractor selection makes this job challenging. This research paper aimed to establish a framework to select the best alternative that deals with all the details of various selection criteria. One of the strong points of this framework is the flexibility of evaluation. All selection criteria have been ranked by using the AHP method as per their emphasis on decision-making. The importance and consequences of each criterion and sub-criterion have been discussed in detail, which will convince the owners of belt conveyor installations to identify the best contractor to whom the maintenance services can be outsourced. The PROMETHEE-II has been applied for the selection of the best contractor based on their attainment of selection criteria requirements through evaluation by a team of experts. This helped in the ranking of various contractors. This methodology will help conveyor operators to determine the important criteria pertaining to the maintenance contractor selection and assist them in making decisions while outsourcing the maintenance activities.

CHAPTER 7

EVALUATION OF SAFETY PERFORMANCE OF BELT CONVEYOR SYSTEMS

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This chapter deals with safety and its index. Under safety, the understanding in the context of belt conveyor systems, the need for its evaluation, and how it can be enhanced, and are described. This is followed by the development of its index using the structural methodology of graph theory and matrix approach for safety performance measurement of belt conveyor systems.

7.1 SAFETY AND ITS EVALUATION

Chinniah [25] pointed out that machinery throughout its lifecycle, encompassing stages such as installation, commissioning, operation, cleaning, fault diagnosis, disassembly, repair, and maintenance, is inherently associated with multiple safety hazards. Belt conveyors are no exception and present significant safety risks in various industrial applications [26,28]. These risks are primarily linked to the presence of moving components, which can lead to incidents ranging from personal injuries to fire-related accidents, thereby elevating safety concerns associated with their use.

Safety, as defined by Pethaperumal and Sivakumar [238], represents a workplace condition that safeguards individuals from both physical harm and psychological stress. Globally, industries have increasingly recognized the social, economic, and environmental consequences of safety-related incidents and injuries [29], prompting a strong emphasis on achieving zero-accident objectives and improving overall safety performance [30]. Consequently, ensuring the safety of belt conveyor systems requires a comprehensive and systematic approach spanning design, manufacturing, installation, operation, and maintenance phases [31].

Despite the acknowledged risks, existing design standards for belt conveyors often inadequately address safety concerns, particularly in quantitative terms, and such considerations are rarely incorporated into tender specification documents [32]. Although numerous design guidelines are available [33], they primarily focus on prescribing safety factors for individual components rather than providing a holistic assessment of system safety. Additionally, general safety guidelines for conveyor systems exist [34]; however, there remains a lack of comprehensive methodologies for systematically evaluating and quantifying conveyor safety levels [35]. This gap underscores the need for a multidimensional framework for analyzing belt conveyor safety.

To address this limitation, a structured framework has been developed to evaluate the safety of belt conveyor systems through the computation of a safety index. This index is derived from multiple safety factors encompassing both design-related attributes and operational contextual conditions within industrial plants. Based on an extensive review of the literature and consultations with industry professionals, seven key safety factors were identified. These interdependent factors were modeled using a graph theory and matrix-based structural approach, enabling the calculation of a belt conveyor system Safety Performance Index (SPI) and its corresponding Safety Performance Index Ratio (SPIR).

The proposed framework was validated through its application in case studies involving a fertilizer plant. Sensitivity analysis indicated that system design is the most influential factor affecting the safety performance index. The developed model serves as a practical decision-support tool for conveyor operators and maintenance personnel, facilitating the interpretation of safety performance metrics and enabling a reassessment of prevailing operational conditions to enhance workplace safety.

7.2 DEVELOPMENT OF SAFETY PERFORMANCE INDEX

This is developed in the rest of the chapter. The purpose of this index is to help in the evaluation of safety quantitatively, which has been emphasized above. The belt conveyor system safety performance index (SPI) provides meaningful insights into system safety and guides strategic maintenance planning, design improvements, and resource allocation to bolster system safety in material handling operations.

The index is also likely to be useful in comparing and analyzing various alternatives of the belt conveyor system. Some of the prominent work includes that of Kecojevic et al. [27], who developed a methodology for risk assessment of belt conveyor systems based on the injury and fatality data related to belt conveyors in US mines from 1995 to 2006. Similarly, Hills [180] performed a safety analysis of belt conveyor systems based on the injury and fatality data of the past three decades. Jocelyn [99] also tried to estimate the safety probability of belt conveyor systems based on accident data. However, Hiewijks and Rogova [32] lamented that no research had been undertaken to explore the safety of belt conveyors. Eventually, they developed a safety integrity level model (SIL) for safety assessment of the belt conveyor system based on the reliability and maintenance data. However, the model has not considered the design factors, human factors, operational environment, etc. Abbaspour et al. [28] also pointed out that the existing safety studies on belt conveyor systems are predominantly statistical analyses of previous data and lack a multivariable-based safety analysis of belt conveyor systems. It is also already mentioned that safety is a function of both design and operating contextual factors, and hence, the safety performance index should reflect both. The system design is unique to each belt conveyor system, while operating contextual factors vary for different belt conveyor systems. In view of this, the process can be represented in terms of structural type relations, i.e., composed of the system design and the contextual factors at the belt conveyor systems, and their interrelations. The literature review suggested the use of the digraph model and matrix approach to develop this index on this line. For initiating the development of the index, safety factors are identified first and described in the next section.

7.3 SAFETY FACTORS

It is essential to establish the safety factors and sub-factors of belt conveyor systems. An unstructured exploratory study has been undertaken across 5 different belt conveyor installations, as well as two belt conveyor manufacturers in western India. The interviewees comprised design engineers of belt conveyor systems, plant operating managers, maintenance engineers, supervisors, and both operating and maintenance technicians. Additionally, a comprehensive literature analysis was done to validate the survey results. The identified safety factors include System Design (SD), Installation Accuracy (IA), Management Practices (MP), Operating Practices (OP), Human Factors (HF), Operating Environment (OE), and Maintenance System (MS). Each of the safety factors is constituted by several sub-factors. The next sub-section will elaborate on those in detail.

7.3.1 System Design (SD)

The process of ensuring machine safety fundamentally originates at the design stage [127]. In this regard, Sadeghi et al.[124] introduced the concept of Design for Human Safety *(DfHS)*, which emphasizes the integration of safety principles directly into the design process. Historically, safety considerations in conveyor systems have been guided by standards issued by the American Society of Mechanical Engineers (ASME) and the American National Standards Institute (ANSI) since the 1940s, which continue to serve as essential references for designers and manufacturers [34].

Effective design must prioritize human safety during the operation of belt conveyor systems, primarily through the incorporation of robust safety mechanisms. These systems should be capable of mitigating various hazards inherent in conveyor operations. A hazard may be defined as a latent condition within a system that has the potential to cause an adverse event when triggered [239]. In belt conveyor systems, mechanical hazards arising from moving components represent the most significant risk. Additional hazards include thermal effects, sharp edges, poor ergonomic configurations, excessive noise [99, 240], as well as material-related, height-related, electrical, and location-specific risks [129].

While certain safety features can be embedded during the design and manufacturing phases, others depend on installation conditions, supporting structures, and operational practices [34]. Sadeghi et al.[124] emphasized that hazard identification and risk mitigation should be proactively addressed during early design stages through the integration of safeguards, barriers, and safety mechanisms. Supporting this view, Backstrom [241] asserted that machinery should not be certified as safe unless appropriate safeguarding systems are implemented, a principle particularly relevant to belt conveyor installations.

Safeguards, defined as mechanical means of isolating hazardous zones, play a critical role in risk reduction. Chinniah [25] identified unguarded nip points between moving belts and rollers as a major cause of accidents in conveyor systems. Various types of safety guards have been documented, including fixed guards (such as enclosing and barrier guards), interlocked guards, and interlocked guards with locking mechanisms [14]. Fixed guards restrict or prevent access to hazardous areas, while interlocked systems are designed to halt conveyor operation upon access. Additional protective measures include deterrent devices such as guardrails and roller side plates, and protective installations like plates, meshes, gutters, and restraining devices that prevent hazards associated with falling materials or component failures [129]. These measures are especially important in installations where personnel pathways are located adjacent to or beneath conveyor systems.

Control systems also play a crucial role in ensuring safe conveyor operation. Malfunctioning control devices can pose serious risks to the entire system. Conveyor start-up mechanisms must require deliberate operator action, particularly in interconnected systems where synchronization between feeding and receiving conveyors is essential. Interlocking devices are therefore necessary to ensure sequential start-up and prevent overloading [129]. Additionally, accessible emergency stop mechanisms must be installed at strategic locations, ensuring visibility, ease of operation, and immediate responsiveness. Emergency pull cords serve as supplementary safety measures in case primary stop systems fail.

Advanced safety standards such as ISO 13849-2[130] and IEC 62061 [131] advocate the integration of electronically controlled safety devices, including limit switches, safety position switches, programmable logic controllers (PLCs), safety relays, light curtains, and surface detection systems. Recent advancements also explore the application of wireless Internet of Things (IoT) technologies to enhance safety monitoring and control in conveyor systems [242].

Ergonomic design is another critical aspect influencing safety, particularly in relation to the positioning and usability of safety controls, maintenance access points, and lubrication systems. Poor ergonomic design that fails to account for human limitations can significantly compromise safety [124. Key ergonomic considerations include accessibility, visibility, and operability of safety devices. Chinniah [25] identified several design deficiencies, such as inaccessible safety switches, improper placement of controls, poorly located lubrication points, and unsafe adjustment mechanisms, all of which can lead to increased risk. Adequate spatial clearance for safe operation and maintenance must also be ensured.

System reliability is equally important in industries reliant on bulk material handling [3]. Reliability is influenced by both design characteristics and operating conditions and is typically evaluated using metrics such as Mean Time to Failure (MTTF), which reflects the frequency of system breakdowns [126]. Closely related to reliability is the concept of maintainability, which represents the ease with which a system can be inspected, diagnosed, repaired, and restored [127,128]. Key design attributes supporting maintainability include accessibility, ease of disassembly, simplicity, standardization, clear component identification, diagnosability, and modular design.

An effective belt conveyor design should incorporate these attributes to facilitate maintenance activities such as lubrication, adjustments, monitoring, cleaning, and fault clearance, ideally performed outside hazardous zones with minimal disruption to safety systems [14]. Additionally, protective measures such as lightning protection systems are necessary to mitigate electrical hazards.

Safe installation practices are equally important, with manufacturers typically specifying appropriate erection equipment that must be adhered to during installation [31]. Structural elements, including foundations and support systems, should be designed and constructed to withstand operational loads and environmental conditions.

Despite the implementation of various safety measures, accidents may still occur due to factors such as inadequate safeguarding, intentional bypassing or disabling of safety systems, improper use, or equipment malfunction [241]. These challenges highlight the need for continuous monitoring, evaluation, and improvement of safety systems in belt conveyor operations.

7.3.2 Installation Accuracy

The safety performance of belt conveyor systems is significantly influenced by the precision and quality of their installation at the operational site. Wei and Yuan-Chi [243] narrated one incident from a coal mine where the installation angle of bolts was improper, which led to accidents. Installation inaccuracies can lead to variations in belt linear speed, which may disrupt material handling efficiency and compromise belt control mechanisms, thereby adversely affecting overall system safety [244].

To mitigate such risks, conveyor installation must strictly adhere to the guidelines and procedures specified by manufacturers. Installation drawings typically assign identification numbers to individual components to facilitate correct assembly, and careful attention must be paid to ensure proper matching of these components during installation [245]. Furthermore, the structural framework of the conveyor system must be level, and precise alignment of key components such as pulleys, idlers, and return rollers must be ensured [31].

Compliance with national and local regulatory standards governing mechanical and electrical installations is also essential [245]. Upon completion of installation, a comprehensive inspection is required, including verification of elevation levels, fastening integrity, electrical connections, gearbox oil levels, bearing lubrication, and belt tension characteristics. Additionally, conducting a no-load trial run is a necessary step to validate system performance before full-scale operation [245].

Accurate installation and alignment not only enhance operational safety but also contribute to improved energy efficiency by reducing unnecessary power consumption [246]. Domek [244] further observed that operational issues such as excessive noise, improper belt tracking, and meshing irregularities are often attributable to pulley misalignment during installation. Therefore, precise installation practices are indispensable for ensuring both the safety and efficiency of belt conveyor systems.

7.3.3 Management Practices

The operational safety of belt conveyor systems within industrial environments is fundamentally dependent on proactive management initiatives aimed at ensuring safety across all activities. To achieve this, organizations should establish a dedicated safety committee comprising representatives from various hierarchical levels and functional departments, along with clearly defined policies governing safety practices. Recognizing the importance of such measures, the Occupational Safety and Health Administration (OSHA) began developing conveyor safety standards during the 1970s [34]. These standards emphasize the necessity of employing competent personnel possessing adequate knowledge, skills, and experience for the operation and maintenance of conveyor systems.

Kecojevic et al. [27] highlighted that inexperienced workers are more susceptible to occupational injuries and illnesses compared to their experienced counterparts, thereby underscoring the importance of structured training programs. Effective safety training is essential for fostering a strong safety culture and enhancing workers' awareness and competencies [247]. In this context, Panchapakesan and Prabhakar[248] suggested that conducting safety mock drills serves as an effective training approach for reinforcing safety-related knowledge, skills, and preparedness.

In addition to training, periodic safety audits conducted by external agencies during both operation and maintenance phases are crucial for identifying potential hazards, evaluating preventive measures, and minimizing accident occurrences [249]. The strategic placement of safety instructions and warning signs throughout the facility further contributes to improved safety awareness. Organizations may also implement incentive-based programs to encourage employee participation in achieving zero-accident goals, thereby enhancing motivation and reinforcing safe practices.

Furthermore, appropriate fire protection systems must be installed to address various classes of fire hazards (A, B, C, and D), tailored to the nature of materials handled and associated risks. Collectively, these management-driven initiatives play a vital role in strengthening the operational safety of belt conveyor systems.

7.3.4 Operating Procedures

The implementation of safety devices plays a significant role in reducing hazards; however, adherence to established safety procedures and the proper use of personal protective equipment (PPE) further enhance risk mitigation [129]. The Occupational Safety and Health Administration (OSHA) has issued comprehensive operational guidelines for conveyor safety, emphasizing that improper handling of conveyor systems without adequate precautions can result in severe hazards. Accordingly, all operational and maintenance activities must be governed by well-defined Standard Operating Procedures (SOPs), which must be strictly followed by all personnel involved [250].

Key safety practices outlined by CCA [250] include the clear identification and labeling of start/stop controls, as well as ensuring that all personnel are familiar with the location and functioning of emergency systems. Additional recommendations encompass maintaining proper housekeeping in conveyor areas, controlling hazardous energy sources, and implementing isolation and tagging procedures before performing maintenance or repair tasks. Unsafe practices, such as riding, climbing, or passing beneath operating conveyors, must be strictly prohibited.

Chinniah [25] emphasized the critical importance of rigorously implementing lockout procedures during maintenance, repair, and unjamming operations. These procedures should be designed in accordance with the specific hazard levels associated with the system. Giraud et al. [129] recommended comprehensive lockout practices, including the complete isolation of all energy sources, such as mechanical, electrical, hydraulic, pneumatic, thermal, chemical, and gravitational, and the release of stored energy through methods such as reservoir purging, removal of counterweights, and unloading of springs. Additionally, personal locking devices should be applied to all energy isolation points to ensure individual safety.

Supervisory personnel must ensure that all workers operating or working near conveyor systems are equipped with appropriate PPE corresponding to the nature of their tasks and working environment. PPE, including protective clothing, footwear, and respiratory equipment, should be selected based on a thorough hazard assessment and in compliance with relevant occupational health and safety standards [129]. Strict monitoring of PPE usage by safety officers is essential to ensure compliance.

Maintaining detailed records of operational activities, maintenance interventions, and accident occurrences is also recommended for effective safety management. Furthermore, belt conveyor systems are designed to operate within specified load limits; therefore, proper loading practices must be enforced to prevent overloading [129]. Exceeding design load capacities can induce excessive mechanical stresses and lead to material accumulation at critical points, thereby increasing the likelihood of hazardous conditions. Consequently, strict adherence to prescribed loading limits is essential for ensuring safe and efficient conveyor operation.

7.3.5 Human Factors

Human factors, encompassing elements such as education, training, experience, physical capability, and mental condition, play a crucial role in ensuring safety during the installation, operation, and maintenance of belt conveyor systems [124]. In addition to task-specific training, personnel involved in conveyor-related activities must receive dedicated instruction on preventive measures, standard operating procedures (SOPs), and all relevant safety protocols [26].

Work experience is a particularly significant determinant of safety performance. Chinniah [25] reported that a substantial proportion of accidents involved workers with limited experience, with approximately 30% of incidents occurring among individuals with less than one year of experience and 46% involving those with fewer than five years of experience. These findings highlight the need to compensate for limited experience through comprehensive and continuous training programs.

However, certain worker attributes extend beyond the scope of formal training. Physical fitness, mental aptitude, and cognitive abilities are equally important in ensuring safe operations. Physical capability includes sufficient strength, particularly in limbs and back, for handling operational tasks, as well as the endurance to perform physically demanding activities such as lifting heavy loads and maintaining strenuous postures over extended durations [251]. Additionally, workers must be capable of operating effectively in challenging environments characterized by exposure to fumes, chemicals, dust, noise, and elevated temperatures.

Mental abilities, including alertness, concentration, memory, and composure, are essential for maintaining safety during conveyor operations and maintenance. Cognitive competencies further enhance safety performance by enabling effective interpretation of technical information, fostering appropriate attitudes toward safety, and supporting clear communication among team members. These skills are critical for understanding technical documentation such as manuals, specifications, and diagrams, and for executing tasks with precision [251]. Moreover, intuitive judgment is often required in situations where standard procedures may not fully address complex or unforeseen conditions.

7.3.6 Operating Environment

The operating environment of belt conveyor systems is a critical determinant of their safety performance. Bluff [240] emphasized that end-use conditions, including site location and workplace layout, significantly influence safety outcomes, a consideration particularly relevant for conveyor systems deployed across diverse industrial settings. The complexity of environmental impacts is heightened by the wide range of applications of belt conveyors, spanning industries such as mining and air cargo handling.

In environments where conveyors are used to transport fine or powdered materials, airborne dust generation becomes a major concern. This can lead to multiple adverse effects, including air pollution, increased fire risk, and health hazards for workers. Such risks can be mitigated through measures such as installing protective enclosures along the conveyor path, applying moisture to transported materials to reduce dust dispersion, and erecting barriers to minimize wind effects. Furthermore, international standards such as ISO 13849-2 [130] and IEC 62061[131] recommend that safety devices, including safety position switches, be adequately protected from harsh environmental conditions that could impair their functionality and lead to system failures.

Environmental factors such as temperature and humidity also have a direct impact on worker health, system efficiency, and overall safety. Maintaining favorable ambient conditions is essential to protect both personnel and equipment from extreme temperatures, excessive humidity, noise, and air pollution [238]. Conveyor systems operating in outdoor environments are exposed to additional challenges, including rain, snowfall, and fog. Such conditions can reduce ambient temperatures, potentially leading to health risks such as hypothermia among workers.

Workplace design considerations, including adequate spacing and proper illumination, are essential for safe operation. Poor visibility can reduce reaction times, thereby increasing the likelihood of accidents [252]. This risk is further exacerbated during nighttime operations, where reduced lighting conditions impair depth perception and obscure hazards. Therefore, sufficient lighting must be provided to ensure safe working conditions.

Additionally, workplace cleanliness plays a vital role in safety. Sanni-Anibire [253] identified poor housekeeping and inadequate flooring conditions as primary contributors to slip, trip, and fall incidents. Maintaining a clean and organized work environment can significantly reduce such risks. The adoption of systematic housekeeping practices, such as the 5S methodology, is recommended to ensure a safe and well-maintained workplace.

7.3.7 Maintenance System

The inherent reliability of engineering systems tends to degrade over time, necessitating maintenance interventions to restore and sustain their operational performance. Vatn and Aven [110] noted that appropriate maintenance of systems and components contributes significantly to improving reliability, which in turn enhances overall safety. Within the lifecycle of belt conveyor systems, regular maintenance is essential to ensure their reliability, safety, and operational efficiency. In this context, Liu et al. [3] advocated the adoption of predictive maintenance strategies to achieve higher levels of reliability in conveyor operations.

Given that maintenance activities require coordinated efforts across engineering, managerial, and administrative functions, careful planning and systematic scheduling are crucial. Routine maintenance tasks, including conveyor cleaning, bearing lubrication, gearbox oil replacement, inspection and condition assessment, as well as repair or replacement of components such as belts, rollers, drums, bearings, electrical cables, and mounting structures, must be executed in accordance with established maintenance plans and schedules [14]. Additionally, maintaining an adequate inventory of spare parts for critical and replaceable components is essential to minimize downtime during unexpected failures.

Although maintenance activities are intended to enhance safety, Vatn and Aven [110] highlighted a paradox wherein maintenance processes themselves can introduce risks, as errors occurring during maintenance may lead to accidents. Such incidents are often associated with human errors, workplace conditions, and managerial shortcomings [25]. However, these risks can be mitigated through effective workforce deployment and continuous skill development of maintenance personnel through training programs.

Furthermore, systematic documentation of maintenance activities is vital for effective maintenance management. The analysis of historical data related to failures, repairs, and component replacements enables more informed decision-making in maintenance planning. This, in turn, helps reduce equipment downtime and Mean Time to Repair (MTTR), while also facilitating the identification of critical or failure-prone components, thereby supporting efficient spare parts inventory management

All the above safety performance factors and sub-factors of belt conveyor systems are consolidated in Table 7.1.

Table 7.1 Factors and sub-factors of the safety performance of belt conveyor system

Factor No.	**Factor Description**	**Sub-factor No.**	**Sub-factors Description**
F_1	System Design (SD)	F_{11}	Provision of barriers/guards
		F_{12}	Provision of deterrents
		F_{13}	Provision of protective devices
		F_{14}	Adequacy of control system safeguards
		F_{15}	Use of advanced electronic safety devices
		F_{16}	Ergonomics of safety devices and controls
		F_{17}	System Reliability
		F_{18}	System maintainability
		F_{19}	Earthing and lightning protection
		F_{20}	Foundation and structural strength
F_2	Installation Accuracy (IA)	F_{21}	Adherence to installation drawings and planning
		F_{22}	Use of proper erecting equipment
		F_{23}	Alignment accuracy
		F_{24}	Conformance to regulatory norms
		F_{25}	Inspection and trial run
F_3	Management Practices (MP)	F_{31}	Safety committee and policies
		F_{32}	Adherence to OSHAS standards
		F_{32}	Deployment of competent persons for

			operation and maintenance
		F_{34}	Safety training and drills
		F_{35}	Safety audit
		F_{36}	Safety instructions display
		F_{37}	Safety incentives
		F_{38}	Fire safety provision
F_4	Operating Practices (OP)	F_{41}	Existence of SOP and adherence
		F_{42}	Provision of PPE and its enforcement
		F_{43}	Record keeping and follow up
		F_{44}	Practice of overloading
F_5	Human Factors(HF)	F_{51}	Education and training
		F_{52}	On the job experience
		F_{53}	Physical capacity
		F_{54}	Mental abilities
		F_{55}	Cognitive skills
F_6	Operating Environment(OE)	F_{61}	Site location and layout
		F_{62}	Site ambient conditions
		F_{63}	Site illumination
		F_{64}	The practice of 5S at the site
F_7	Maintenance System(MS)	F_{71}	Existence of a maintenance plan and schedule
		F_{72}	Spare availability
		F_{73}	Maintenance crew skills
		F_{74}	Training for the maintenance crew
		F_{75}	Upkeep of maintenance records

7.4 SAFETY PERFORMANCE MODELING

Safety performance modeling of belt conveyor systems requires the identification of factors that influence safety, along with their mutual interrelationships. Modeling of these safety performance factors and their structural interrelations is conceivable by a graph-theoretical approach [254] through a digraph model. The digraph model is best suited for assimilating interrelationships among factors [255]. The basic assumptions behind this development of the framework for the measurement of safety performance are as follows.

(1) The safety performance factors are identifiable and measurable.

(2) There is a mutual interrelationship/influence among safety performance factors

A digraph is made up of nodes or vertices along with a collection of directed edges or arcs that connect them. Different system factors, variables, states, etc., are depicted by nodes in a digraph, while their mutual interactions are expressed by the arcs or edges. A visual picturization of the system structure is achieved through a digraph, and this methodology is applied for the safety performance modeling of belt conveyor systems.

A belt conveyor system safety performance digraph is designated; B_d = (F, C), where F= {F_1, F_2…, F_N}, represents a set of nodes and C= {c_{ij}, ……….,c_{NN}}, a set of directed edges, with i,j= 1,2,…,N. The nodes depict the safety performance factors, e.g., F_1 denotes the safety factor '1', whereas the edges represent the interaction/interrelationship among safety attributes, e.g. the edge 'c_{12}' shows the relationship of safety factor 1 on factor 2.

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.

The interrelations among safety performance factors are established with the support of literature and the opinion of experts from the domain. For example, the system design factors influence some of the other safety performance factors in different ways, which are elaborated here. The installation accuracy is dependent on the system design and tolerance and is denoted by an edge from nodes 1 to 2. A more complex design necessitates competent human resources for its operation and maintenance and hence system design factors influence management practices of deployment of personnel and conducting their training, etc. This is depicted by an edge from nodes 1 to 3. The operating practices are dictated by the design requirements [34]. This influence is represented by a directed edge from nodes 1 to 4. The maintenance of the system depends highly on the system design and is indicated by an edge between nodes 1 and 7. Similarly, interrelationships among other nodes are also developed and shown in the digraph in Figure 7.1.

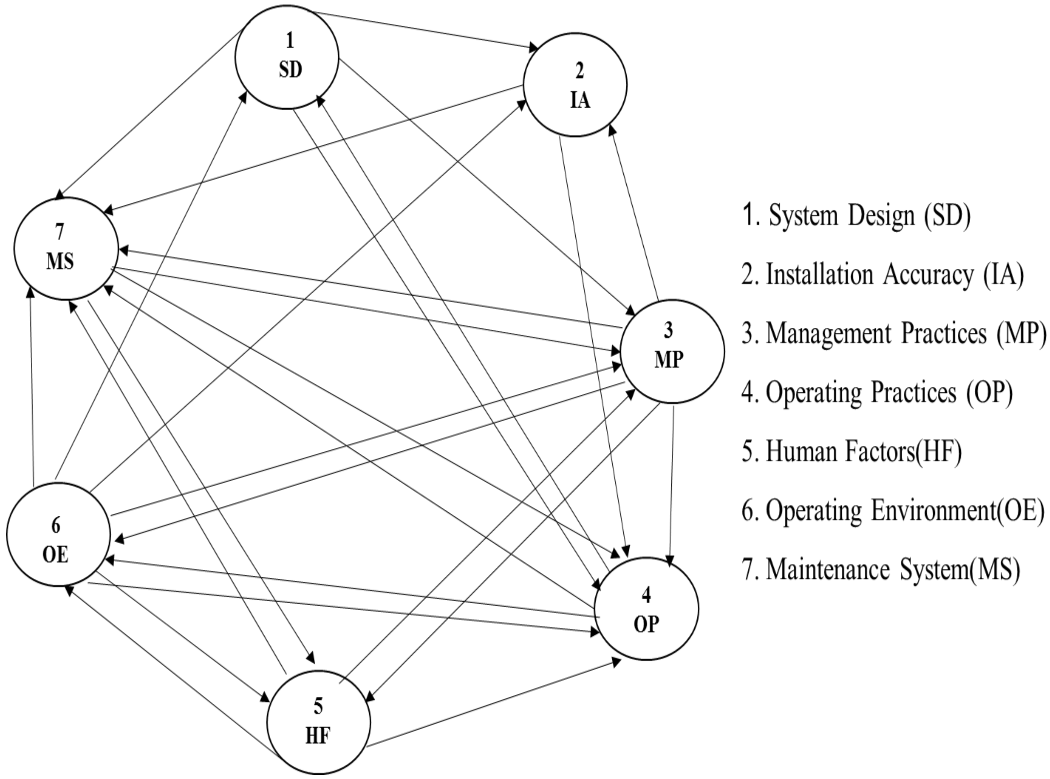

Figure 7.1 Safety performance digraph of belt conveyor system

7.4.1 Equivalent matrix of safety performance digraph

A matrix that is equivalent to the digraph in Figure 7.1 is to be generated for its analysis. This matrix will yield a numerical expression that shows the idiosyncrasies of the belt conveyor system. The matrix, which shows all the possible influences, is tiled as the safety performance matrix (SPM) of belt conveyor systems with the notation 'S_D' and is shown in expression (7.1)

$$S_D = \begin{bmatrix} F_1 & c_{12} & c_{13} & c_{14} & 0 & 0 & c_{17} \\ 0 & F_2 & 0 & c_{24} & 0 & 0 & c_{27} \\ 0 & c_{32} & F_3 & c_{34} & c_{35} & c_{36} & c_{37} \\ c_{41} & 0 & 0 & F_4 & 0 & c_{46} & c_{47} \\ 0 & 0 & c_{53} & c_{54} & F_5 & c_{56} & c_{57} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & F_6 & c_{67} \\ 0 & 0 & c_{73} & c_{74} & c_{75} & 0 & F_7 \end{bmatrix} \quad (7.1)$$

Per (S_D), which is the permanent of the above 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 function as a standard matrix function [135], which consists of only positive terms [136]. Singh and Bapat [256] postulated that the positive nullity of the digraph is best demonstrated through the permanent of a square matrix. The nullity of graphs concept has its applications in several technology domains as well as social network theory. The theory of permanents was found apt for modeling random variables in order statistics [257]. The digraph and matrix methodology has been applied by several researchers, including evaluation of supply chain collaboration [258], modeling and evaluation of mean time to repair during the design stage, evaluating a sustainability index for logistics service providers [259], etc.

For deriving a general expression for SPF, and SPM having 'N' safety performance factors is chosen for deriving a general expression for SPF. This is represented as a matrix expression (7.2). The SPF of the matrix is represented as equation (7.3).

$$S_{D\,[NxN]}=\begin{bmatrix} F_1 & c_{12} & .. & .. & c_{1N} \\ c_{21} & F_2 & .. & .. & c_{2N} \\ c_{i1} & c_{i2} & .. & .. & .c_{iN} \\ .. & .. & .. & .. & .. \\ r_{N1} & r_{N2} & .. & .. & F_N \end{bmatrix} \qquad (7.2)$$

$$\begin{aligned} Per(S_{D[NxN]}) = \; & \prod_{i=1}^{N} F_i + \sum_i \sum_j \sum_k \sum_l \sum_m \dots\dots \sum_N (c_{ij} c_{ji}) F_k F_l F_m \dots\dots F_N \\ & + \sum_i \sum_j \sum_k \sum_l \sum_m \dots\dots \sum_N (c_{ij} c_{jk} c_{ki} + c_{ik} c_{kj} c_{ji}) F_l F_m \dots\dots F_N \\ & + \Bigg\{ \sum_i \sum_j \sum_k \sum_l \sum_m \dots\dots \sum_N (c_{ij} c_{ji}) (c_{kl} c_{lk}) F_m \dots\dots F_N \\ & + \sum_i \sum_j \sum_k \sum_l \sum_m \dots\dots \sum_N (c_{ij} c_{jk} c_{kl} c_{li} + c_{il} c_{lk} c_{kj} c_{ji}) F_m \dots\dots F_N \Bigg\} \\ & + \Bigg[\sum_i \sum_j \sum_k \sum_l \sum_m \dots\dots \sum_N (c_{ij} c_{ji}) (c_{kl} c_{lm} c_{mk} + c_{km} c_{ml} c_{lk}) F_n \dots\dots F_N \\ & + \sum_i \sum_j \sum_k \sum_l \sum_m \dots\dots \sum_N (c_{ij} c_{jk} c_{kl} c_{lm} c_{mi} + c_{im} c_{ml} c_{lk} c_{kj} c_{ji}) F_n \dots\dots F_N \Bigg] \\ & + \cdots \end{aligned} \qquad (7.3)$$

Each 'F_i' in equation (3) represents i^{th} safety factor and each 'c_{ij}' epitomize the degree/level of interrelationship/influence of the i^{th} safety factor on j^{th} factor, where i, j = 1, 2,3,……, N. SPF accommodate all attainable terms consisting of 'F_i's, 'c_{ij}'s and their combinations from a combinatorial perspective.

Certain off-diagonal elements are zero in the matrix 'S_D'. This is on account of the non-existence of any edges between the factors in the digraph shown in Figure 7.1. As a result of this, certain elements of the general expression (7.3) may vanish. The forthcoming section describes the evaluation of the safety performance index.

7.4.2. Safety Performance Measurement

It is revealed from the discussions in the previous section that SPF expression represents belt conveyor system safety performance. Following these, safety performance measurements of the belt conveyor system has evolved from SPF, that containing terms consisting of F_i's andc_{ij}'s. This requires numerical values of both diagonal elements, i.e., F_i's and off-diagonal elements(c_{ij}'s) in the SPM that may be either quantitative or qualitative. The preference may be given for quantitative evaluation for computational ease and interpretation.

7.4.2.1 Quantification of diagonal elements of SPM

The diagonal elements of the SPM, i.e, F_i's, are usually quantified initially. Each safety factor (F_i) is made up of its sub-factors(F_{ij}), where i = 1,2,…,7 and j = 1,2,3,…,m, and are listed in Table 2. The attainment level of sub-factors varies with different belt conveyor designs and operating contexts. Therefore, it is mandatory to consider these aspects in the quantification of 'F_i's.

The quantification can be initiated by assigning a score 'S_{ij}' to the j^{th} sub-factor of the i^{th} safety factor, with i = 1,2,…,7 and j = 1,2,3,…,m. The sub-factors fall into two classes, i.e. favorable and unfavorable. A sub-factor becomes favorable if its level of existence promotes higher safety, e.g., provision of barriers/guards, and is non-beneficial otherwise, e.g., practice of overloading. This is to be considered while assigning the S_{ij} score. Wang and Ruxton [260] suggested a qualitative analysis of safety performance factors during the design process for implementing precautionary measures. Contemporary literature in this context by Jocelyn et al. [99] also revealed that most of the machinery-associated risk and safety assessments were based on qualitative tools, even though they involve subjective decision-making. There is often a concern of arising subjectivity in such score assignments. However, this can be minimized by employing a team of experts for this task. The team is constituted by academicians and professionals from belt conveyor design, manufacture, operations, and maintenance, as well as safety professionals from industry, right from top management to the operator level. It can be observed from Table 7.1 that it includes a mix of both qualitative and quantitative factors and sub-factors. Hubbard and Evans [261] advocated for the allocation of a quantitative value to the verbal labels of assessment. Rao and Davim [233] suggested the use of fuzzy set theory, where the value of the factors/attributes could be initially evaluated in terms of linguistic terms, followed by their conversion into corresponding fuzzy numbers, which can be finally translated into the crisp values. In this regard, Chen and Hwang [262] developed a numerical approximation scheme to convert linguistic terms to their corresponding fuzzy numbers. This methodology has been successfully adopted by several researchers [263]. Later, an 11-point scale was suggested by Rao and Davim [233] for converting linguistic terms to fuzzy numbers. Several researchers have adopted this scale, and some of the notable works include the selection of bus chassis for large fleet services [141], identification and assessment of influential factors of human reliability in maintenance [264], etc. Considering the significance of this scale, it has been implemented in this paper, and based on this scale, the experts were asked to express their evaluations of selection criteria in 11 levels, ranging from exceptionally high to exceptionally low. For computational and evaluation purposes, the linguistic terms need to be converted to a numerical value, e.g. a fuzzy numerical value in the range [0, 1]. To accomplish this, the 11-point scale shown in Table 7.2 is used.

Table 7.2 Linguistic variable and corresponding numerical values

Sr. No.	Qualitative description of the linguistic variable	Assigned values
1	Exceptionally High (EXH)	0.955
2	Extremely High (EH)	0.865
3	Very High (VH)	0.745
4	High (H)	0.665
5	Above average (AA)	0.590
6	Average (A)	0.500
7	Below average (BA)	0.410
8	Low (L)	0.335
9	Very low (VL)	0.255
10	Extremely low (EL)	0.135
11	Exceptionally low (EXL)	0.045

Since the contribution of each factor towards safety is different, it would be appropriate to assign weights (W_i) to each safety factor during quantification of 'F_i'. Accordingly, F_i value is evaluated according to equation (7.4).

$$\boldsymbol{F_i} = \mathbf{W}_{\boldsymbol{i}}(\sum \mathbf{S}_{\boldsymbol{ij}}) \qquad (7.4)$$

where i=1, 2,…,7 and j=1,2,…, m.

Literature provided several methodologies for assigning the weights (W_i) for each factor. The most befitting in this context is the AHP (Analytic Hierarchy Process) procedure developed by [140], which is adapted for assigning weight for the safety performance factors of the belt conveyor system.

7.4.2.2 Quantification of off-diagonal elements of SPM

The next step to be executed is the quantification of off-diagonal elements (c_{ij}'s) that depict the degree of influence among different safety performance factors. A scale of '0' to '1' is chosen for assessment here. The extremity levels are high and none. An additional three levels, such as above average, average and minor exist in between, e.g., system design highly influences operating practices as well as reliability and maintenance, whereas it has above the average influence on management practices and installation accuracy. System design does not influence human factors and the operating environment. Similarly, the level of influence among other factors is established by the team of experts and shown in Table 7.3.

Table7.3 Degree of influence among belt conveyor safety performance factors

S. No.	Safety performance factors	Degree of influence among factors(c_{ij})				
		High (c_{ij}=1)	Above average (c_{ij}=0.75)	Average (c_{ij}=0.5)	Minor (c_{ij}=0.25)	None (c_{ij}=0)
1	System Design (SD)	4,7	2,3			5,6
2	Installation Accuracy (IA)		4.7			1,3,5,6
3	Management Practices (MP)	4,5	2,7	6		1
4	Operating Practices (OP)	7	1		6	2,3,5
5	Human Factors(HF)	7	3,4		6	1,2
6	Operating Environment(OE)	1,4,7	5	2,3		
7	Maintenance System(MS)	4		3,5		1,2,6

7.4.2.3 Safety Performance Index

Safety Performance Index (SPI) of belt conveyors is a quantitative measurement of the safety performance of a belt conveyor system functioning in a plant or a site. This evolved from the SPF. A higher value for this index denotes a higher safety performance for the belt conveyor system.

The numerical value of SPI can be huge and at some point, even unreasonable depending on the scale chosen for 'F_i' and 'c_{ij}'. However, this can be handled by the introduction of an ideal safety performance index (ISPI) and safety performance index ratio (SPIR) of belt conveyor systems. The ideal implies a belt conveyor system that is utmost safe with all its safety performance factors that are in perfect place. In such a situation, 'S_{ij}' score for all the sub-factors attains the maximum value, i.e. a value of 0.955 as per Table 7.3. SPIR is delineated as the ratio of the safety index of a belt conveyor system to the safety index of an ideal belt conveyor system.

$$\text{SPIR} = \frac{\text{SPI}}{\text{ISPI}} \quad (7.5)$$

If the SPIR value reaches '1', it is slated to be an ideal condition. The SPIR ranges between '0' and '1'. A value nearer to unity is expected from an engineering viewpoint for ensuring maximum safety.

7.5. CASE STUDY

To illustrate the developed model, the safety performance measurement of a belt conveyor system used in a fertilizer plant located in western India is presented as a case study. The conveyor was installed in the year 2012. 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 horizontal length of the first conveyor is 70 m, which takes the material out of the wharf and transfers it to another large conveyor, which takes the material into the storage silo. The horizontal length of the large conveyor is 127 m. The transfer part of the conveyor system is housed inside a structure called a junction house. Both the conveyors run inside a conveyor gallery with a side-cladding roof to protect the conveyor from rain and wind. Walkways are provided inside the gallery on both sides of the conveyors for inspection and maintenance. The height of the junction house is 16.5m from the ground, and the height of the discharge point of the conveyor above the silo is 45.65 m above ground level. The bulk density of rock phosphate is 1.73 t/m^3. The capacity of the belt conveyor system is 770 t/h with a maximum belt speed of 2m/s.

The above belt conveyor system is designated as 'B' for all assessment purposes. The weights (W_i) for each safety factor are established first with the procedure of AHP [140]. A pairwise comparison matrix of the safety performance factors is prepared based on expert opinion for this as per Saaty's 1-9 scale. This is represented as matrix 'K_{7x7}' in expression (7.6).

$$K_{7x7} = \begin{array}{c} \text{Safety factors} \\ SD \\ IA \\ MP \\ OP \\ HF \\ OE \\ RM \end{array} \begin{array}{c} \begin{array}{ccccccc} SD & IA & MP & OP & HF & OE & RM \end{array} \\ \begin{bmatrix} 1 & 8 & 7 & 7 & 8 & 7 & 5 \\ 0.12 & 1 & 0.5 & 0.12 & 0.14 & 0.1 & 0.12 \\ 0.14 & 2 & 1 & 1 & 0.33 & 0.2 & 0.17 \\ 0.14 & 8 & 1 & 1 & 1 & 0.3 & 0.25 \\ 0.12 & 7 & 3 & 1 & 1 & 1 & 0.5 \\ 0.14 & 7 & 5 & 3 & 1 & 1 & 0.5 \\ 0.2 & 8 & 6 & 4 & 2 & 2 & 1 \end{bmatrix} \end{array} \quad (7.6)$$

Normalized relative weights of the safety performance factors are obtained through the AHP procedure and are displayed in Table7.4.

Table 7.4 Normalized relative weights of safety performance factors

Safety performance factors	Normalized relative weight (W_i)
System Design (SD)	0.493
Installation Accuracy (IA)	0.021
Management Practices (MP)	0.039
Operating Practices (OP)	0.067
Human Factors(HF)	0.089
Operating Environment(OE)	0.117
Maintenance System (MS)	0.175

Every safety factor is evaluated by the team experts based on their laid-down evaluation scheme on a linguistic scale from ‘exceptionally high’ to ‘exceptionally low’. Further, this linguistic evaluation is converted into fuzzy numeric values as per Table 7.2 and displayed in Table 7.5.

Table 7.5 Evaluation of safety performance factors for conveyor ‘B’

Safety performance factors			Sub-factor (F_{ij})	Evaluation	Subfactor Score(S_{ij})	$\sum S_{ij}$
Factor (F_i)	Abbreviation	Description				
F_1	SD	System Design	F_{11}	H	0.665	5.32
			F_{12}	A	0.500	
			F_{13}	A	0.500	
			F_{14}	BA	0.410	
			F_{15}	L	0.335	
			F_{16}	L	0.335	
			F_{17}	H	0.665	
			F_{18}	H	0.665	
			F_{19}	A	0.500	
			F_{20}	VH	0.745	
F_2	IA	Installation Accuracy	F_{21}	H	0.665	3.565
			F_{22}	VH	0.745	
			F_{23}	H	0.665	
			F_{24}	VH	0.745	
			F_{25}	VH	0.745	
F_3	MP	Management Practices	F_{31}	AA	0.590	3.65
			F_{32}	AA	0.590	
			F_{32}	VH	0.745	
			F_{34}	H	0.665	
			F_{35}	VL	0.255	

			F_{36}	L	0.335	
			F_{37}	EL	0.135	
			F_{38}	L	0.335	
F_4	OP	Operating Practices	F_{41}	A	0.500	2.165
			F_{42}	A	0.500	
			F_{43}	A	0.500	
			F_{44}	H	0.665	
F_5	HF	Human Factors	F_{51}	A	0.500	3.32
			F_{52}	VH	0.745	
			F_{53}	H	0.665	
			F_{54}	H	0.665	
			F_{55}	VH	0.745	
F_6	OE	Operating Environment	F_{61}	A	0.500	1.835
			F_{62}	A	0.500	
			F_{63}	A	0.500	
			F_{64}	L	0.335	
F7	MS	Maintenance System	F_{71}	H	0.665	2.91
			F_{72}	AA	0.590	
			F_{73}	VH	0.745	
			F_{74}	A	0.500	
			F_{75}	BA	0.410	

The evaluation process of factors for conveyor 'B' is shown for the factor 'System Design' as an example. Table 7.5 provides the sub-factors scores of the 'System Design'. As per expression (7.4), the 'System design' factor value of conveyor 'B '= 0.493 x 5.32=2.623, with W_i = 0.493 (Table 7.4) and $\sum S_{ij}$ = 2.2725 (Table 7.5). Similarly, the evaluation of other factors is also done. Based on these, the system safety digraph of the belt conveyor 'B' has been prepared and displayed in Figure 7.2. In Figure 7.2, the nodes in the digraph carry the numeric values of the safety performance factors, and edges that depict the interrelation among safety performance factors are represented by lines in varying thickness based on 'c_{ij}' as per Table 7.3.

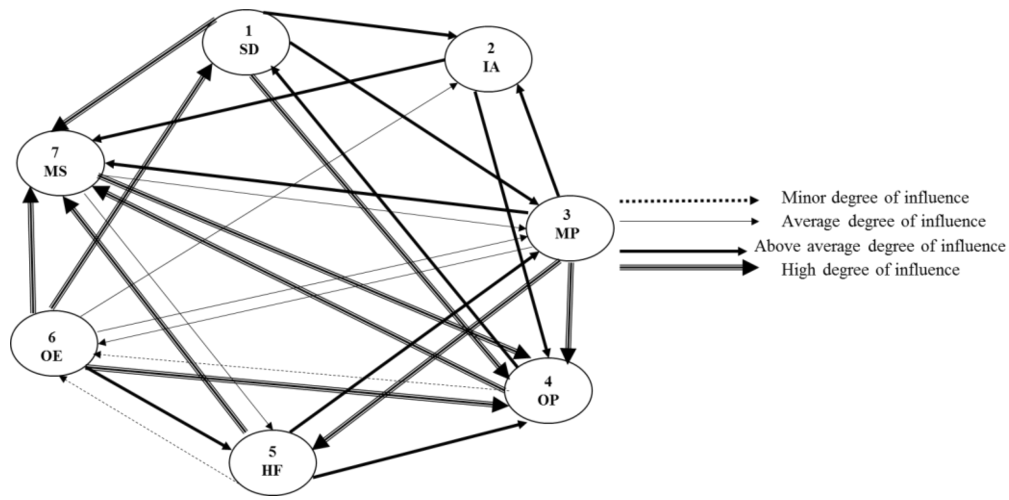

Figure 7.2 Safety performance digraph of conveyor system 'B'

The safety performance matrix of conveyor 'B', i.e. 'S_{DB}', is obtained from the safety performance digraph shown in Figure 7.2.

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

The SPF for conveyor 'B' is obtained from the permanent of the matrix 'S_{DB}' using equation (7.3) and obtained as:

Per (S_{DB}) = 7.278

i.e., safety performance index (SPI) of conveyor 'B' =7.278

To evaluate SPIR, the ISPI must be obtained. This mandates safety performance measurement 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. The evaluation of the factor 'System Design' of an ideal belt conveyor system is given. The 'System Design' consists of ten sub-factors, and according to the evaluation criteria, the highest score for each sub-factor is '0.955' as per Table 7.2. Consequently, if each of the sub-factors of 'System Design' attained the highest score, the total sub-factor score would be '9.55'. This gets multiplied by '0.493, which is the relative weight of 'System Design' according to Table 7.4. Thus, the ideal system design factor value (F_1) is

$$F_1 = \mathrm{W}_i(\sum \mathrm{S}_{ij}) = 0.493 \times 9.55 = 4.708$$

The same procedure has been applied to other factors for their evaluation. An equivalent matrix for an ideal belt conveyor system is evolved, with maximum 'F_i' and is shown as '$S_{D\ ideal}$'.

$$S_{Dideal} = \begin{bmatrix} 4.708 & 0.75 & 0.75 & 1 & 0 & 0 & 1 \\ 0 & 0.100 & 0 & 0.75 & 0 & 0 & 0.75 \\ 0 & 0.75 & 0.298 & 1 & 1 & 0.5 & 0.75 \\ 0.75 & 0 & 0 & 0.256 & 0 & 0.25 & 1 \\ 0 & 0 & 0.75 & 0.75 & 0.425 & 0.25 & 1 \\ 1 & 0.5 & 0.5 & 1 & 0.75 & 0.559 & 1 \\ 0 & 0 & 0.5 & 1 & 0.5 & 0 & 0.836 \end{bmatrix}$$

Per (S_{Dideal}) =11.835

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

The safety performance index ratio for conveyor 'B', i.e., $SPIR_B$ is shown as:

$$SPIR_B = \frac{\text{SPI of conveyor B}}{\text{ISPI}} = \frac{7.278}{11.835} = 0.614$$

A threshold value 'SPIR' is proposed by the team of experts for guiding the conveyor operators in taking the necessary corrective actions for the enhancement of safety performance. The threshold value of 60% or below is considered dangerous and requires serious interventions for system up-gradation, repair, overhaul, etc. A threshold value between 60-70% 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 will provide guidelines for the necessary action plan.

7.5.1 Sensitivity analysis of SPI

Sensitivity analysis is essential for validating the robustness of the proposed safety performance index. It also serves as a tool to examine how variations in one or more input parameters of a mathematical model influence the resulting output. Such variations may be either positive or negative in nature. This technique is commonly applied in decision-support models to identify the variables that exert the most significant influence on outcomes.

By systematically evaluating the response of the model to input fluctuations, sensitivity analysis helps in determining the critical factors that drive decision-making. Various approaches to sensitivity analysis have been reported in the literature, including differential sensitivity analysis, factorial analysis, and Monte Carlo simulation [141]. An ideal sensitivity analysis framework should consider multiple sources and levels of uncertainty within the problem domain [265].

In this work, a generic method for examining factor sensitivity is utilized. A feasible range of deviations in the safety performance factors is specified in terms of a bounded set of discrete percent changes of 10% from the safety performance factor value, which is used for the base run. A series of evaluations is performed by altering the scores of safety performance factors that are the diagonal elements of the safety performance matrix one at a time and observed its impact on the safety performance index. The percentage change in both the output and input is computed. The sensitivity is evaluated by dividing the percentage change in output by the percentage change in input. In the case study, each factor score is given an increment of 10% and the corresponding change in percentage of the safety performance index of conveyor 'B' is calculated. Table 7.6 shows the outcomes of the sensitivity analysis

Table 7.6 Result of sensitivity analysis

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

According to the sensitivity analysis, the safety performance factors are arranged in descending order according to their impact on the safety performance index for conveyor system 'B'. The order sequence is System Design (SD), Installation accuracy (IA), Human Factors (HF), Operating Environment (OE), Maintenance System (RM), Management Practices (MP), and Operating Practices (OP). From the results of the sensitivity analysis and its impact on the safety performance index shown in column 3 of Table 7.6, it can be concluded that immediate safety improvement of belt conveyor ‘B’ can be practically done by fortifying its system design for safety. Since the conveyor belt is an old installation, suitable retrofitting may be required for installing contemporary electronic safety devices. Though the impact of installation accuracy is high, reinstallation of the complete system is practically infeasible. The other practicable solutions for safety improvement include analysis of human factors and their enhancement and improvement in the operating environment through proper guarding of the worksite and housekeeping of the area. The maintenance practices can also be re-examined for any improvements.

7.6 CONCLUSIONS

A framework for the safety performance measurement of belt conveyor systems is developed by using a structural methodology in this work. The various safety performance factors were identified through literature, field visits, and interaction with experts. The AHP methodology assisted in weight assessment for various safety performance factors according to the expert’s opinion. The graph theory and matrix approach were used in developing a safety performance index for belt conveyor systems. Validation of the evolved methodology is accomplished with the help of a case study. The robustness of the model is tested by sensitivity analysis, which also assisted in identifying the factors that require more attention to enhance safety. Though the framework involves rigorous qualitative evaluation steps followed by mathematical formulations, it offers the advantage of maximum flexibility in modeling safety performance factors and their interrelationships. Another advantage is that the feasibility of inclusion or exclusion of safety performance factors according to the practical conditions is easy in this model. However, the risk associated with this methodology is the involvement of subjectivity in the evaluation of safety performance factors. This can be avoided to a greater extent by accomplishing the task at the team level using proven group technology methodologies. Moreover, this methodology can produce accurate results if the qualitative evaluation of safety performance factors is performed diligently. Using this framework, the belt conveyor designers can simulate the factors that enhance safety performance. Additionally, threshold values of the safety performance indicator ratio have been proposed, which will guide conveyor operators for improvements. The methodology guides belt conveyor operators and maintenance professionals in gaining inferences from the safety performance index to have a relook at the contextual factors existing at the worksite and their enhancement. Moreover, design engineers can make use of this index for enhancing the design features that fortify the safety performance index.

CHAPTER 8

CONCLUSION, CONTRIBUTIONS, LIMITATIONS, AND FUTURE SCOPE OF WORK

8.1 CONCLUSION

Belt conveyor systems play a vital role in the transportation of bulk materials across various industries. The reliability, maintenance, 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 a sugar plant 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.

8.2. MAJOR CONTRIBUTIONS

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. Also applied to evaluate the conveyor reliability of 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 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 costliest 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 has been created. This will assist the organizations that own and operate these installations in making informed decisions about the hiring of suitable maintenance contractors. Also applied to select a contractor for the maintenance of the conveyor belt at the Thermal Power Plant.
- 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 and apply it to evaluate the belt conveyor safety of a fertilizer plant.

8.3 LIMITATIONS

The following are the limitations of the research.

- The proposed reliability, maintenance, and safety frameworks were validated using limited case studies (sugar plant, fertilizer plant, and thermal power plant conveyor systems), which may limit the generalizability of the results to other industries, such as ports, cement plants, or underground mining operations.
- The study heavily relies on expert opinions for assigning weights and scores in AHP, FAHP, DEMATEL, and digraph-based models. Such judgments are inherently subjective and may introduce bias despite consistency checks.
- The developed digraph and matrix-based indices represent a static snapshot of system behavior and do not explicitly capture time-dependent variations in operating conditions, degradation, or maintenance effectiveness.
- Although Industry 4.0 aspects are conceptually discussed, the models do not directly integrate real-time sensor data, condition-monitoring signals, or historical failure databases for dynamic reliability prediction.

8.4 SCOPE OF FUTURE WORK

The research has presented some new ideas and philosophies related to the reliability, maintenance, and safety of belt conveyor systems. However, one can go beyond this and explore more of these ideas. Some of the possible future expansions of this work are mentioned below.

- Development of user-friendly software based on the proposed structural methodology for reliability, maintenance, and safety of belt conveyor systems for designers and practicing engineers
- Integration with real-time and data-driven techniques, the structural models can be hybridized with machine learning, digital twins, and IoT-based condition monitoring to enable dynamic and predictive reliability, maintenance, and safety assessment.
- Based on the economic and sustainability impact assessment, future work may incorporate life-cycle cost analysis, carbon footprint, and sustainability metrics to evaluate the long-term economic and environmental implications of reliability- and safety-oriented design decisions.

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APPENDIX-A

QUESTIONNAIRE-1

Criteria for Contractor Selection for Outsourced Maintenance Services of Belt Conveyor Systems

Section A: Respondent Profile

Name (Optional): ________________________

Organization Type:

☐ Mining ☐ Power Plant ☐ Fertilizer ☐ Cement ☐ Manufacturing ☐ Others: ______

Designation: ________________________

Years of Experience:

☐ <5 ☐ 5–10 ☐ 10–15 ☐ >15

Experience with Belt Conveyor Maintenance:

☐ Yes ☐ No

Experience with Outsourced Maintenance:

☐ Yes ☐ No

Section B: Expert Opinion

(1) What are the most critical factors when selecting a contractor?

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(2) Major challenges in outsourced conveyor maintenance:

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(3) Suggestions for improving contractor selection:

Responses are incorporated in Table 6.1

QUESTIONNAIRE-2

Ranking of Main Criteria

Section A: Respondent Profile

Name (Optional): ___________________________

Organization Type:

☐Mining ☐Power Plant ☐Fertilizer ☐Cement ☐Manufacturing ☐Others: ______

Designation: ___________________________

Years of Experience:

☐<5 ☐5–10 ☐10–15 ☐>15

Experience with Belt Conveyor Maintenance:

☐Yes ☐No

Experience with Outsourced Maintenance:

☐Yes ☐No

Section B: Expert opinion

Instruction: Satty's scale for assigning value

Verbal judgment of relative importance between elements '*i*' and '*j*'	Numerical rating
is equally important as	1
slightly important than	3
is strongly more important than	5
very strongly more important than	7
extremely more important than	9
Intermediate importance	2,4,6,8

Criteria	Code
Economic Factors	EC
Organizational Strength	OS
Service Track Record	STR
Maintenance Service Quality	MSQ
Personnel Skills	PS
Tools & Equipment Support	TES
Health, Safety & Environment	HSE

	EC	OS	STR	MSQ	PS	TES	HSE
EC							
OS							
STR							
MSQ							
PS							
TES							
HSE							

Responses are presented in pairwise matrix 6.8

APPENDIX-B

List of Publications

1. N.J.Parmar, Ajith Tom James (2023). 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.
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.
3. N.J.Parmar, Ajith Tom James, Mohammad Asjad, Zahid A Khan (2026). 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.3, pp.761-783.