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Enhancing Machinery Maintenance in the Gold Manufacturing Industry: Strategies for Overcoming Barriers and Integrating Sustainability

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Abstract

Effective machinery maintenance is critical for ensuring operational efficiency and productivity in the gold manufacturing industry. However, several barriers hinder maintenance practices, including insufficient employee accountability, limited availability of spare parts, and inadequate financial planning. This study investigates strategies to overcome these challenges and enhance maintenance processes. Risk factors were identified through a comprehensive literature review and expert consultations, and then analysed using the Fuzzy VIKOR method a multi-criteria decision-making tool that addresses complexity and uncertainty. The research highlights key barriers and proposes proactive measures for improving maintenance performance. Furthermore, the integration of sustainability principles into maintenance operations is emphasized to support economic, environmental, and social objectives. The findings underscore the importance of employee training, spare parts management, and financial planning in achieving effective and sustainable maintenance practices. This study provides valuable insights for industry professionals and decision-makers seeking to optimize machinery maintenance in the gold manufacturing sector.

Keywords: *employee training; fuzzy VIKOR machinery maintenance; maintenance barriers; proactive maintenance; risk assessment; spare parts management; sustainability in manufacturing*

1. Introduction

The gold manufacturing industry plays a vital role in the global economy, contributing significantly to production and trade. However, similar to other manufacturing sectors the industry faces persistent challenges in maintaining operational efficiency, particularly in machinery maintenance. Effective machinery maintenance (EMM) is crucial for minimizing downtime, maximizing productivity, and extending the lifespan of equipment. A major barrier to effective machinery maintenance in the gold manufacturing industry is the lack of employee accountability. Employees often fail to take ownership of maintenance tasks, leading to inadequate upkeep of machinery, increased breakdowns, and disruptions in production. This problem is compounded by a shortage of skilled technicians, which further hinders the ability to carry out routine and preventive maintenance activities. Another significant challenge is the inadequate availability of spare parts. As noted by Rathi et al., (2022), timely access to spare components is crucial for minimizing downtime and maintaining consistent production output. The difficulty in sourcing critical components highlights the need for proactive maintenance strategies, including strategic supplier partnerships and inventory management optimization.

Financial planning is another critical component of effective machinery maintenance. Alarcón et al., (2021) emphasize that integrating Maintenance Management Systems (MMS) with Enterprise Resource Planning (ERP) platforms enables organizations to allocate resources efficiently, forecast repair costs, and secure funding for both scheduled maintenance and unexpected equipment failures. Sustainability has become an increasingly important as a critical dimension in maintenance practices (Wienker et al., 2016). Integrating sustainability principles into maintenance operations can help organizations meet environmental and social objectives while enhancing operational efficiency. Proactive strategies, such as adopting energy-efficient technologies, minimizing waste in spare parts management, and aligning maintenance activities with broader sustainability frameworks, can significantly contribute to long-term success in the gold manufacturing industry. This study aims to identify and propose strategies for overcoming key barriers to machinery maintenance in the gold manufacturing industry, with particular emphasis on enhancing employee accountability, improving spare parts availability, and strengthening financial planning. By addressing these challenges and integrating sustainability frameworks, organizations can optimize maintenance processes, improve operational performance, and sustain high productivity levels. To guide this investigation, the study addresses the following research questions:

1) What strategies can be implemented to address the lack of responsibility among employees regarding machinery maintenance in gold operations?

2) What are the implications of the lack of maintenance audit on machinery maintenance in gold operations?

1.1 Problem Statement

The gold manufacturing industry faces persistent challenges in machinery maintenance, including inadequate employee accountability, limited spare parts availability, and weak financial planning. These issues lead to increased downtime, reduced productivity, and higher costs. Moreover, sustainability principles are rarely integrated into maintenance practices, limiting their environmental and operational effectiveness. Overcoming these barriers is vital to improving efficiency and ensuring long-term sustainability in the sector.

1.2 Literature Review

a. Maintenance Strategies in the Gold Manufacturing Industry

Effective machinery maintenance strategies are essential for improving productivity and reducing operational costs (Velmurugan et al., 2022). Various scholars have emphasized the role of strategies like Total Productive Maintenance (TPM), Autonomous Maintenance (AM), and Condition-Based Monitoring (CBM) in optimizing machine performance. Franciosi et al., (2020) explained how proactive maintenance approaches, such as TPM, can reduce downtime, enhance production efficiency, and align with sustainability goals. Additionally, technologies such as predictive maintenance, integrated maintenance management systems (MMS), and sensor-based monitoring are instrumental in enhancing maintenance efficiency and lowering operational costs (Rathi et al., 2022). Several studies underscored the importance of effective spare parts management in maintenance operations. Koppiahraj et al., (2021) emphasized the importance of inventory optimization and strategic supplier partnerships to address spare part shortages. Timely access to spare parts not only minimizes downtime but also supports economic and environmental sustainability. Organizations that implement predictive maintenance can anticipate equipment failures and address potential issues proactively, thereby improving operational reliability. Employee accountability is also a critical determinant of maintenance effectiveness. Franciosi et al., (2020) suggested that empowering employees through training and clear role definitions can foster a culture of ownership and responsibility. Actively involving employees in maintenance activities can enhance overall equipment effectiveness (OEE) and decrease downtime.

b. Sustainability in Maintenance Practices

Sustainability in maintenance practices has received growing attention for its role in minimizing environmental impact and supporting long-term economic performance. Sustainable maintenance typically involves reducing waste, optimizing resource use, and incorporating energy-efficient technologies. Marimuthu et al., (2021) explained that integrating sustainability principles into maintenance strategies enabled organizations to lower their carbon footprint and improve regulatory compliance. Alarcón et al., (2021) and Rathi et al. (2022) emphasized the contribution of digital tools such as Maintenance Management Systems (MMS) and Enterprise

Resource Planning (ERP) systems in promoting sustainability outcomes. These technologies facilitated data-driven decision-making, improved resource allocation, and supported predictive maintenance. Furthermore, the adoption of circular economy principles, including equipment reuse and recycling, contributed to more sustainable maintenance operations and reduced dependence on raw materials.

c. The Importance of Maintenance Audits

A well-structured maintenance audit process is essential for ensuring that machinery operates efficiently and reliably. Regular audits can identify inefficiencies, missed maintenance tasks, and potential risks. In the absence of an audit system, organizations may struggle to monitor maintenance activities effectively, resulting in increased downtime and higher repair costs. Alarcón et al., (2021) emphasized the importance of integrating real-time monitoring technologies, such as those embedded in Maintenance Management Systems (MMS) and Enterprise Resource Planning (ERP) systems, to improve audit accuracy and support informed decision-making.

Maintenance audits also play a vital role in ensuring compliance with safety standards and environmental regulations, which are particularly important in the gold manufacturing industry. Failure to conduct audits may lead to regulatory penalties, unsafe working conditions, and reputational damage. Additionally, audits can help organizations identify recurring maintenance issues and implement corrective actions. Wan et al., (2017) highlighted the value of collaborative maintenance planning systems, which leverage process knowledge and data integration to enhance maintenance efficiency. By incorporating audits into routine practices, companies can adopt a proactive maintenance approach aligned with long-term operational goals.

d. Research Gaps and Opportunities

Despite the extensive research on maintenance practices in manufacturing industries, significant gaps remain in the literature specific to the gold manufacturing sector. Much of the existing research focuses on generalized maintenance approaches, with limited attention to the unique challenges of gold manufacturing, such as the use of specialized equipment and the dependency on skilled labor. Additionally, while strategies like Total Productive Maintenance (TPM) and predictive maintenance have been examined in other industries, their implementation in gold manufacturing remains underexplored. There is also a lack of research on the integration of sustainability frameworks into maintenance practices in this sector. Existing studies frequently overlook the potential benefits of aligning maintenance strategies with sustainability objectives, including reduced environmental impact and enhanced social responsibility. This study addresses these gaps by proposing targeted strategies to improve machinery maintenance in the gold manufacturing industry, with a particular focus on employee accountability, spare parts availability, financial planning, and the integration of sustainability principles.

2. Objectives

This study aims to identify and prioritize key barriers to effective machinery maintenance in the gold manufacturing industry and to propose sustainable strategies for improvement.

The specific objectives are:

1. To identify critical maintenance risk factors through literature review and expert input.
2. To evaluate and rank these factors using the fuzzy VIKOR method.
3. To incorporate sustainability principles into maintenance decision-making.
4. To recommend practical strategies for enhancing maintenance performance and operational sustainability.

3. Methodology

3.1 Framework for this Paper

The conceptual framework developed in this study is depicted in Figure 1.

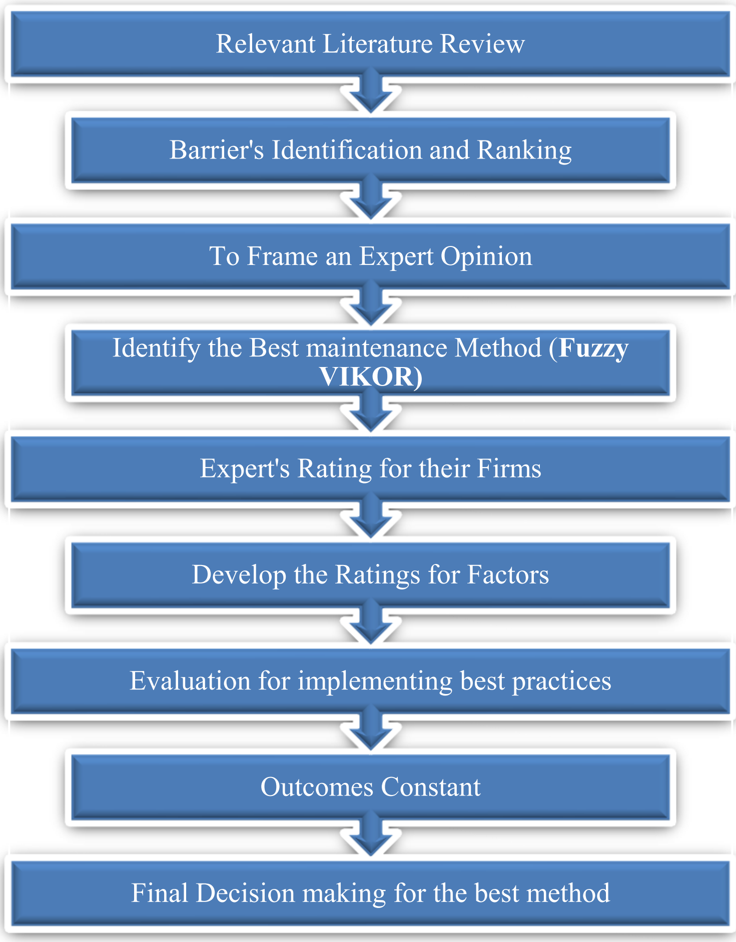

Figure 1 Framework of this paper

3.2 Fuzzy VIKOR

In the gold manufacturing industry, effective machinery maintenance is crucial for ensuring operational efficiency and productivity. To address the complex decision-making process of prioritizing machinery maintenance risk factors, the Fuzzy VIKOR method, a powerful tool in Multi-Criteria Decision-Making (MCDM), was employed. This method combines fuzzy logic theory with the VIKOR approach to handling uncertainties and complexities inherent in decision-making processes (Ighravwe et al., (2022). The VIKOR method, originally developed by Opricovic and Tzeng (2004), is a multi-criteria decision-making (MCDM) method designed to address problems with conflicting and non-commensurable criteria. The method focuses on finding a compromise solution that can assist decision-makers in situations where conflict resolution among criteria is essential (Fei et al., 2019). It evaluates alternatives based on factors R (maximum group regret), S (total group utility), and Q (compromise ranking measure), making it a powerful tool for solving decision-making problems.

Fifteen risk factors affecting machinery maintenance were identified based on relevant literature and expert opinions from the industry. Bhandari et al., (2019) stated that Organization face several barriers when implementing cleaner technologies. Measuring the influence of these barriers is essential for formulating a strategic approach to implementing cleaner technologies. Based on the literature review and expert opinions, four categories of barriers were identified: technical information, operational and strategic, financial and economic, and human barriers. Experts were allowed to independently discuss and clarify risk variables to ensure there was no external influence or bias. After completing all procedures, the priority ranking of each risk factor was established through multiple ranking methods, as presented in Table 1. Awasthi et al., (2010) presented a fuzzy multi-criteria approach using fuzzy TOPSIS to evaluate suppliers' environmental performance based on both benefit and cost criteria. The approach involved criteria identification, linguistic assessments, performance scoring, and sensitivity analysis, supported by a numerical application demonstrating its practical applicability.

Linguistic values refer to the qualitative assessment of variables using words or linguistic terms instead of numerical values. In linguistics and computational modeling, these values are commonly used to represent vague or imprecise information. This concept is central to fuzzy logic and systems that deal with human language and reasoning, where assigning precise numerical values is often challenging. Table 2 presents the linguistic values along with their corresponding fuzzy numbers.

In this study, the multi-criteria decision-making (MCDM) method, specifically VIKOR, is applied to evaluate and select the optimal choice among three gold firms. Firm factors and ratings are determined through linguistic assessment and then converted into fuzzy numbers using the VIKOR method, referred to as Fuzzy VIKOR. This approach involves evaluating both risk factors and firm alternatives using the VIKOR method to identify the most suitable option. By referencing an optimistic ideal solution, the method measures each firm's proximity to this ideal outcome. This evaluation is presented in Table 3, using the terms: very poor, poor, fair, good, and very good. The fuzzy numbers in Tables 2 and 3 are derived from linguistic assessments, with corresponding numerical values adapted from Awasthi et al., (2010). These values enable the quantification of qualitative inputs for fuzzy VIKOR analysis.

Table 1 Identified risk factors affecting machinery maintenance in the gold manufacturing industry

Risk Factors	Criteria
Availability of machinery spare parts.	C1
Skilled technician shortage.	C2
Prevention of corrosion wear	C3
Lack of data on machinery maintenance	C4
Lack of maintenance audits	C5
Unawareness of maintenance importance	C6
Fixing poor-quality spare	C7
Poor maintenance management team in the factory	C8
Long time running machinery without rest	C9
Not proper financial planning from top management	C10
Insufficient training and education for working employee	C11
Lack of technology to maintain machinery	C12
Imported spare delay	C13
Maintenance and purchasing dies	C14
Lack of responsibility and involvement among the employees.	C15

Table 2 Linguistic variables and corresponding triangular fuzzy numbers used in expert evaluation

Fuzzy Number	Terms
(1,3,3)	Very Low (VL)
(1,3,5)	Low (L)
(3,5,7)	Medium (M)
(5,7,9)	High (H)
(7,9,9)	Very High (VH)

Table 3 Normalized decision matrix derived from expert scores

Fuzzy Number	Terms
(1,3,3)	Very Poor (VP)
(1,3,5)	Poor (P)
(3,5,7)	Fair (F)
(5,7,9)	Good (G)
(7,9,9)	Very Good (VH)

Step 1: Convert the weights of risk factors and firm evaluations into crisp values by defuzzifying the parameters in the fuzzy decision matrix. According to equation (1), the fuzzy number S = (S_1 ,S_2 ,S_3) is transformed into a crisp number S, as presented in Table 4 and Table 5.

$$S=\frac{S_1+4S_2+S_3}{6} \quad (1)$$

Next Step 2: For all machinery maintenance of risk factors i=1 , 2 , ….m and firms j=1 , 2 ,…...n to find th e E_i^*(best value) and E_i^-(worst value), which is depicted in Table 6.

$$E_i^* = \max_j \{y_{ij}\} \; ; \; E_i^- = \min_j \left\{y_{ij}\right\} \text{ (Benefit group risk factor)} \quad (2)$$

$$E_i^* = \min \left\{y_j\right\} \; ; \; E_i^- = \max j \left\{y_{ij}\right\} \text{ (Cost group risk factor)} \quad (3)$$

Next Step 3: Using the equations (4) and (5) to calculate $D_j$and C_j Values.

$$D_j = \sum_{i=1}^{m} Fe_i \frac{E_i^* - y_{ij}}{E_i^* - E_j^-} \quad (4)$$

$$C_j = \max_i Fe_i \frac{e_i^* - y_{ij}}{e_i^* - e_i^-} \quad (5)$$

Next step 4: Calculating the value of K_j

$$K_j = \mu \frac{D_j - D^*}{D^- - D^*} + (1-\mu) \frac{C_j - C^*}{C^- - C^*} \quad (6)$$

Where,

$$D^* = \min_j G_j$$

$$D^- = \max_j G_j$$

$$C^* = \min_j H_j$$

$$C^- = \max_j H_j$$

And (1-μ) is the individual regret weight and μ tactic of maximum group utility weight

Next step 5: Arrange the values of D, K and C in numerical order to rank each firm's availability. The results are presented in Table 7.

Next step 6: Recommend firm M(1) as the optimal choice, as it ranks highest based on the minimum value of F, provided that the following conditions are satisfied.

F1: Acceptable advantage

$K(M2)-K(M1) \geq OQ$

Where the 2nd one on the ranking list is M(2) Firm by K and N is the number of decision-makers

$$OQ=\frac{1}{N-1}$$

F2: Decision-making acceptable stability

To rank the best firm M(1) Using C and D. In decision making a good result is stable which is the tactic of maximum group utility (when $\mu > 0.5$ is required) or $\mu \approx 0.5$ or $\mu < 0.5$

Which includes:

Firm M(1) and M(2) if only rule F2 is not satisfied or

Firm M(1),M(2),…..M(N) if rule F1 is not satisfied

To find M(N) by using K[M(N)]-K[M(1) < OQ For the maximum value of N.

3.3 Application of VIKOR in Evaluating the Factors

As illustrated in Figure 1, the study begins by identifying factors that influence machinery maintenance in the gold industry. These factors were initially identified through a narrative literature review, which is commonly used to address the risk factors in the gold industry (Jahan, & Edwards, 2013). In this study, the narrative review was used to address the research questions outlined in the introduction. The review processes involved searching academic databases including Science Direct, Google Scholar, EBSCO and Scopus to identify factors affecting machinery maintenance in the gold industry. Relevant literature was gathered using keywords combined with Boolean operators, including: 'Machinery maintenance' AND 'Operational efficiency,' 'Maintenance barriers' AND 'fuzzy VIKOR risk assessment,' 'Proactive maintenance' AND ' Sustainability in manufacturing,' and 'Employee training' AND 'Spare parts management'. The search was limited to English-language articles published after 2013. The initial search yielded 200 articles, which were analyzed in stages: starting with a review of titles, followed by examining abstracts and keywords, and concluding with a full-text assessment of core issues. Of the 200 articles, only 25 directly addressed issues relevant to the gold industry. The remaining articles mentioned the gold industry only in their titles or keywords. Following the review of the final 25 articles, 15 key factors impacting machinery maintenance in the gold industry were identified and are presented in Table 1. Industry experts independently listed risk variables, engaged in group discussions, and assigned linguistic ratings to ensure accurate and unbiased evaluations.

Table 4 Linguistic evaluations of maintenance risk factors by three firms (M1, M2, M3)

Risk factors	M1			M2			M3		
	SM1	**SM2**	**SM3**	**SM1**	**SM2**	**SM3**	**SM1**	**SM2**	**SM3**
C1	P	F	G	VG	G	F	G	VG	G
C2	VG	G	VP	G	G	F	VG	VG	VG
C3	G	P	VG	VP	P	VP	F	F	G
C4	F	F	VG	VP	VP	P	VP	VP	P
C5	VP	VG	G	VG	VG	F	G	G	VG
C6	G	P	VP	F	G	G	F	F	P
C7	VG	P	F	G	G	G	G	F	F
C8	G	G	VG	P	VP	P	F	F	F
C9	P	VP	VP	F	F	G	VG	F	F
C10	VG	VG	G	VP	P	P	P	VP	VP
C11	F	F	G	G	G	G	F	F	G
C12	VG	G	F	F	F	G	VG	G	G
C13	G	G	F	VG	VG	G	VP	P	G
C14	P	P	VP	VP	VP	P	G	G	F
C15	G	VG	F	G	G	F	VG	G	G

Table 5 Aggregated linguistic evaluations and fuzzy ratings of maintenance risk factors

Risk Factors	Linguistic Rating			Aggregate fuzzy rating	Crisp rating	Normalized crisp rating
	SM1	**SM2**	**SM3**			
C1	L	M	VH	(1,5,9)	5.00	0.060
C2	M	VH	VL	(3,8.33,3)	6.56	0.079
C3	M	L	M	(3,3,7)	3.67	0.044
C4	H	VL	L	(5,1.66,5)	2.78	0.034
C5	L	M	H	(1,5,9)	5.00	0.060
C6	L	L	VL	(1,3,3)	2.67	0.032
C7	H	VH	H	(5,8.33,9)	7.89	0.095
C8	H	M	M	(5,5,7)	5.33	0.065
C9	VH	VH	H	(7,8.33,9)	8.22	0.099
C10	H	M	M	(5,5,7)	5.33	0.065
C11	M	H	H	(3,7,9)	6.67	0.081
C12	VH	H	H	(7,7,9)	7.33	0.089
C13	VH	VH	H	(7,8.33,9)	8.22	0.099
C14	L	L	M	(1,3,7)	3.33	0.040
C15	M	M	L	(3,5,5)	4.67	0.056

Table 6 Best value of E_i^* and the worst values E_i^- for the 15 maintenance risk factors

Risk factors	Crisp ratings				
	L	**M**	**N**	**E***	**E-**
C1	5.000	7.000	7.889	5.000	7.889
C2	6.333	6.667	8.222	6.333	**8.222**
C3	4.333	2.667	5.333	2.667	5.333
C4	5.333	2.111	2.111	2.111	5.333
C5	7.222	7.333	7.000	**7.000**	7.333
C6	4.333	6.667	4.667	4.333	6.667
C7	4.333	7.000	5.333	4.333	7.000
C8	7.000	2.111	5.000	2.111	7.000
C9	1.778	5.333	5.667	1.778	5.667
C10	8.222	3.000	1.778	1.778	8.222
C11	5.333	7.000	5.333	5.333	7.000
C12	7.000	5.333	7.333	5.333	7.333
C13	6.667	8.222	3.667	3.667	8.222
C14	2.667	2.111	6.667	2.111	6.667
C15	7.556	6.667	7.333	6.667	7.556

Table 7 D_j, C_j and K_j values for maintenance decision alternatives (firms M1, M2, and M3)

	M1	M2	M3
D_j	31.106	0.523	0.533
C_j	5.833	0.999	0.099
K_j	-1.704	-0.037	0
Rankings	1	2	3

Since the collected factors are related to real-world operational experiences, expert evaluations were conducted to assess the significance of each factor. Focusing on 3 companies, expert input was gathered to assess their machinery maintenance risk factors. The linguistic assessments for the three companies (M1, M2, M3) and the aggregated fuzzy values for the 15 factors are presented in Table 4. Crisp ratings and normalized crisp values were then calculated from the fuzzy ratings using Equation (1). The best (E_i^*) and worst (E_i^-) values for each machinery maintenance risk factor were calculated, as shown in Table 6. Based on the calculated K_j, the acceptable advantage (F1) and decision making stability (F2) was analyzed.

4. Result and Discussion

To identify the risk factor affecting machinery maintenance in the gold jewelry manufacturing industry, a nominal group technique was used with a team of three in-company experts. Each expert was asked to independently compile a list of risk variables.

In addition, relevant risk factors were also collected from the literature. Experts then discussed and ranked the risk variables independently, without external influence or bias. Table 1 presents the results used to identify and analyze the major problems. This process contributes to smoother operational performance. The evaluation was conducted using the Fuzzy VIKOR method along with sensitivity analysis.

4.1 Interpretation of Best (Ideal) Fuzzy Scores in Maintenance Prioritization

The ranking of risk factors affecting machinery maintenance in the gold manufacturing industry revealed that the most influential issues are: Lack of Maintenance Audit (C5), Lack of Employee Responsibility (C15), and Shortage of Skilled Technicians (C2). The factors follow a descending order of influence as:**C5 > C15 > C2 > C11 > C12 > C1 > C6 > C7 > C13 > C3> C4> C8 > C9 > C10,** with C5 having the highest rating value of 7.000**.** In line with the second objective of this study, the absence of routine maintenance audits (C5) was identified as the most critical risk factor. This deficiency presents substantial challenges for managing machinery and equipment effectively. Without regular audits, organizations lack a structured mechanism to assess asset conditions, detect maintenance gaps, and prioritize corrective actions. As a result, undetected wear or malfunction can lead to unexpected equipment failures, increased repair costs, and significant production downtime. Moreover, the absence of audit oversight weakens accountability and limits the ability to track performance, thereby undermining efforts to optimize maintenance planning and resource allocation. To mitigate this risk, companies should integrate routine audits into their maintenance management systems. Doing so will enable proactive monitoring of asset health, reduce unplanned disruptions, and improve overall maintenance effectiveness (Marimuthu et al., 2023). By institutionalizing audit practices, organizations can foster a culture of continuous improvement and support long-term operational sustainability. Regarding the first objective, the second most critical factor Lack of Employee Responsibility (C15) also poses serious concerns. When employees fail to take ownership of maintenance tasks, equipment may be neglected, misused, or improperly handled. This behaviour can lead to more frequent machinery breakdowns, extended downtime, and elevated maintenance costs. Additionally, a lack of accountability may delay the reporting of early warning signs, allowing minor issues to escalate into major failures. Poor responsibility also contributes to inefficient resource utilization, as tasks may be deferred, overlooked, or inadequately executed. Addressing this issue requires cultivating a culture of accountability, where employees are empowered and encouraged to take proactive responsibility for equipment maintenance. Providing regular training, clear procedural guidelines, incentives, and performance feedback can enhance employee engagement and ownership ultimately leading to greater reliability, operational efficiency, and cost savings. The third most impactful factor is the Shortage of Skilled Technicians (C2), which was assigned a value of 6.333. This shortage significantly hinders timely and effective maintenance. In the absence of qualified personnel, organizations struggle to carry out essential maintenance activities, resulting in prolonged equipment downtime and operational delays. The reliance on external contractors increases both costs and scheduling complexity, reducing a firm's control over its maintenance operations. Moreover, without in-house expertise, implementing advanced strategies, such as predictive maintenance or condition-based monitoring, becomes difficult. These methods require specialized knowledge to deploy and interpret correctly. To address this skills gap, gold manufacturing firms must invest in internal workforce development. This can be achieved by establishing training programs, partnering with vocational institutions, and offering apprenticeships. In addition, competitive compensation and clear career advancement pathways are essential to attract and retain skilled talent. These strategies will help build a capable maintenance workforce and improve equipment reliability and overall operational performance.

4.2 Interpretation of Lowest Fuzzy Scores in Maintenance Prioritization

The analysis of worst-performing factors in machinery maintenance for the gold manufacturing industry identified the top three concerns as: Shortage of Skilled Technicians (C2), Inadequate Financial Planning from Top Management (C10), and Delays in Imported Spare Parts (C13). These were followed in descending order by: **C2 > C10 > C13> C1 > C15 > C5 > C12 > C7 > C8>C11>C6>C14 >C9>C3>C4**. Among these, the shortage of skilled technicians (C2) was assigned the worst value of 8.222. Employees lacking the necessary technical skills to operate and maintain machinery can cause production delays and reduce overall efficiency. This issue often arises from insufficient technical knowledge or weak problem-solving skills when equipment malfunctions occur. To address this, companies must invest in comprehensive training programs and continuous professional development. Improving employee proficiency through education and hands-on training can significantly enhance machinery operation, reduce downtime, and increase productivity. The second major challenge, inadequate financial planning from top management (C10), results in a lack of budgetary preparedness for both routine maintenance and emergency repairs. Without a structured financial plan, companies face unexpected repair or replacement costs, which can disrupt operations and increase total maintenance expenditure. Financial planning should include clear budgeting for preventive maintenance, contingency funds for unplanned failures, and periodic equipment upgrades. Sound financial management is essential to ensure maintenance continuity and reduce the risk of extended downtime. Another significant issue is the availability of machinery spare parts (C1). When spare parts are readily available, maintenance can be completed efficiently, reducing delays and minimizing production losses. However, sourcing challenges especially for imported, specialized, or outdated components can lead to extended equipment downtime. These delays not only impact productivity but may also result in financial loss and compromised safety if temporary fixes are used. To overcome this, companies should implement inventory optimization strategies, form strategic partnerships with suppliers, and invest in modern spare parts management systems. Technologies such as 3D printing and digital parts catalogues also offer innovative solutions for improving spare part accessibility and reducing procurement lead times. Ensuring consistent spare part availability can strengthen maintenance responsiveness and sustain high productivity levels across operations.

According to the findings from the Fuzzy VIKOR analysis, Firm 2 **(C6)** demonstrated the best performance among the three evaluated firms. This suggests that other firms can improve their machinery maintenance efficiency by adopting similar strategies and best practices identified in Firm 2's maintenance framework.

4.3 Managerial Implications

The findings of this study have several important managerial implications for companies operating in the gold manufacturing industry. These implications are based on the identified risk factors and suggested strategies for improving machinery maintenance practices. Ensuring the availability of spare parts is critical for minimizing downtime and maintaining operational efficiency. To address this, companies should implement proactive measures such as inventory optimization and form strategic partnerships with reliable suppliers. Investing in spare parts management systems can further streamline procurement processes and reduce lead times. Additionally, adopting technological innovations such as 3D printing and digital spare parts catalogs can enhance spare parts accessibility and improve responsiveness during maintenance operations.

Equally important is the need to foster a culture of accountability and empowerment among employees responsible for machinery maintenance. This includes providing comprehensive training programs and continuous skill development opportunities to increase technical proficiency. Encouraging employees to take ownership of maintenance tasks can help prevent breakdowns, improve productivity, and promote a sense of responsibility across the workforce.

Another critical implication relates to the development of a skilled internal maintenance workforce. Companies should invest in long-term training and collaborate with educational institutions or industry partners to create apprenticeship or vocational training programs. Offering competitive compensation and clearly defined career advancement pathways can help attract and retain skilled technicians, addressing the industry-wide shortage of qualified personnel.

In terms of financial planning, organizations must establish a well-defined budget for machinery maintenance. This includes not only regular upkeep but also contingency funds for unexpected repairs or upgrades. Involving top management in the financial planning process ensures that adequate resources are allocated and that maintenance objectives align with broader operational and sustainability goals.

Finally, the implementation of routine maintenance audits should be considered an integral part of the maintenance management system. Regular audits allow for the systematic evaluation of asset conditions, the identification of maintenance gaps, and the prioritization of improvement efforts. By addressing the lack of audit oversight, companies can enhance operational reliability, reduce maintenance-related costs, and support continuous improvement initiatives within the gold manufacturing sector.

5. Conclusion

This study has illuminated the critical barriers to effective machinery maintenance in the gold manufacturing industry. By identifying and ranking key risk factors based on their impact, the research offers valuable insights into strategies for improving maintenance practices. Enhancing employee accountability, ensuring the timely availability of spare parts, and implementing sound financial planning have been highlighted as fundamental elements in optimizing maintenance operations. Moreover, the integration of sustainability principles into maintenance activities is essential for achieving long-term economic, environmental, and social objectives. The findings underscore the significance of continuous workforce training, proactive spare parts management, and robust financial strategies in maintaining operational efficiency and sustaining productivity in the gold manufacturing sector. Moving forward, several opportunities exist for future research in this domain. One promising direction is to examine the practical implementation and effectiveness of specific maintenance strategies, such as Total Productive Maintenance (TPM) and Predictive Maintenance, within the context of the gold manufacturing industry. Additionally, further exploration of advanced technologies such as 3D printing for improving spare parts availability and minimizing lead times presents a valuable area of study. Future research could also aim to develop comprehensive frameworks for integrating sustainability into maintenance practices and establish metrics for evaluating their impact on overall operational sustainability. Collaborative efforts with industry stakeholders to apply and assess the proposed strategies in real-world settings would provide deeper insight into best practices and support the advancement of sustainable and efficient maintenance systems in the gold manufacturing industry.

6. References

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