

Development of a Novel Reliability-Centered Framework and Maintenance Strategies for the Asset Management and Sustainability of Rotary Equipment

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KEY WORDS	ABSTRACT
IoT in Maintenance Preventive Maintenance Condition Based Maintenance Equipment Reliability Rotary Equipment Optimization Unified Maintenance Framework	This study investigates the integration of Internet of Things (IoT) and Artificial Intelligence (AI) technologies into maintenance practices to enhance equipment reliability and advance sustainability within oil refineries in Pakistan. At present preventive maintenance remains the dominant strategy; however, its inherent inefficiencies, including premature equipment replacement and unplanned downtime demonstrate the need for a transition toward predictive approaches. The findings indicate that IoT and AI, when combined with effective workforce training, substantially improve maintenance performance. Real-time monitoring facilitates early fault detection, reduces unplanned downtime, and enhances overall equipment reliability. Quantitative analysis further reveals strong correlations between IoT adoption and improvements in key performance indicators, particularly operational efficiency, sustainability integration, and reliability. Moreover, measurable sustainability benefits are observed, including increased energy efficiency and reductions in carbon emissions. Nonetheless, barriers to implementation persist. High initial investment requirements and a shortage of skilled personnel present significant challenges to large-scale adoption. Addressing these barriers requires phased financial strategies, targeted workforce development programs, and the incorporation of sustainability metrics into maintenance performance evaluations. The results of this research confirm that IRSO is more than a monitoring tool; it is a comprehensive engineering framework that predicts, validates, and resolves root causes before catastrophic failure. Its implementation on rotary equipment has demonstrated measurable improvements in reliability, sustainability, and life cycle optimization, which were not achievable under conventional approaches.

1. Introduction

Oil refineries are considered to be critical facilities as they convert the crude oil into diesel, gasoline, and aviation fuels. Refineries utilize rotary equipment, for example, pumps, turbines, and compressors, for their proper operation. However, the reliability of this equipment is an issue due to unfavourable working conditions, such as high temperature, high pressure in addition to the corrosive environments. Maintenance management plays an important role in enhancing the overall productivity and efficiency in the operational environment of oil refineries. Condition-based maintenance and other prognostic methods are widely

encouraged in many research works that focus on improved performance and less downtime.

The Integrated Reliability, Sustainability, and Optimization Framework for Rotary Equipment (IRSO) has been investigated in this study. This focuses on ideas such as predictive maintenance, IoT with keen concentration on sustainability for improved efficiency. This research aims to identify the asset management improvement and sustainability perspective of the rotary equipment of the oil refineries in Pakistan to formulate a framework for evaluating their reliability. There are a number of limitations while utilizing new technologies like predictive maintenance, IoT and AI [1]. The

constraints of traditional methods have also led to the emergence of new approaches towards maintenance. These technologies allow for real time applications, early identification of faults and optimum use of resources in up keeping procedures, which conforms to recent sustainability strategies. Therefore, they should incorporate the aforementioned strategies into the (IRSO) framework.

Pakistan is geared up to adopt these new methods of maintenance [2]. It would be worthwhile to mention Pakistan has set the target to emphasize the importance

of introducing such strategies, as the demand for energy in this country also increases. If the refineries have increased dependability on the rotary equipment and can achieve improved performance, minimal pollution, and meet the set national energy security goals. The primary aim of this research is to propose a framework that integrates risk based, predictive, and condition-based maintenance strategies using IRSO [3]. In light of the challenges outlined in the preceding section, this research establishes the foundation for the development of the IRSO. The prioritized CSFs of Reliability strategy plan are shown in Figure 1.

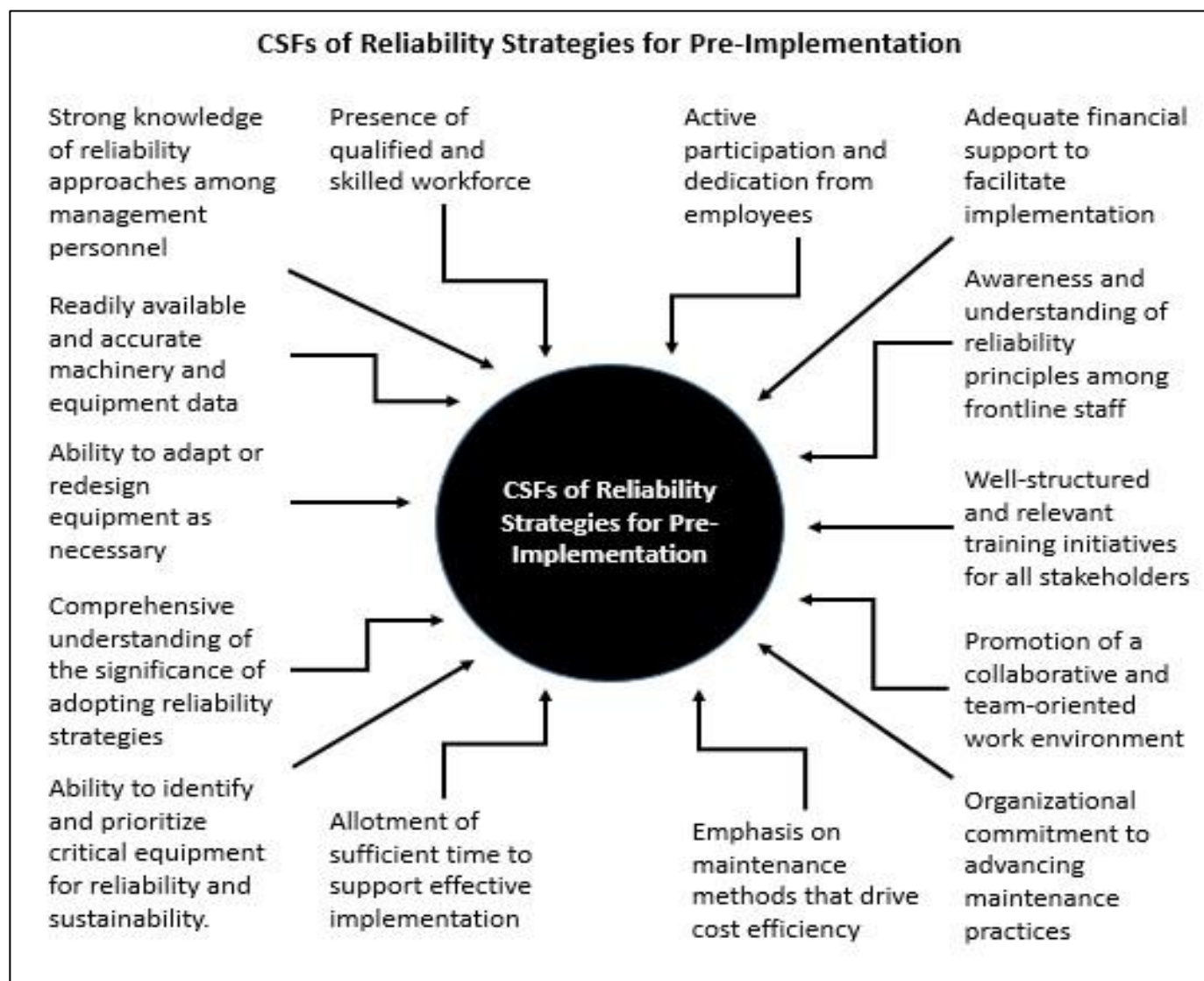


Fig. 1. The prioritized CSFs of Reliability strategies in the pre-implementation phase

Critical success factors of reliability strategies, in the context of the oil and gas industry, are of utmost importance with particular emphasis on their contribution to operational reliability. Predictive maintenance with the support of AI and IoT can be more beneficial. Likewise, [4] presents a systematic literature review on the implementation of the CBM, discussing its effectiveness on avoiding unscheduled downtime and maximizing asset productivity. Overall, these studies postulate appreciable ideas, although additional empirical grounding is needed

concerning the concurrent extensive cost trip and adaptability across different operational environments. There are current forms of maintenance such as RCM, FMEA, APM, PdM, CBM, RAM, and RBD; each of which has its benefits, but is not synchronized. Asset management frameworks enable organizations to ensure that the industrial assets are provided with the necessary care in order to have a long and efficient service life, especially given the conditions usually met in the oil refineries. Several works propose various methods for classifying and

enhancing the system of asset management. The strategic view of asset management with a focus on decision and supply, as mentioned in Figure 2.

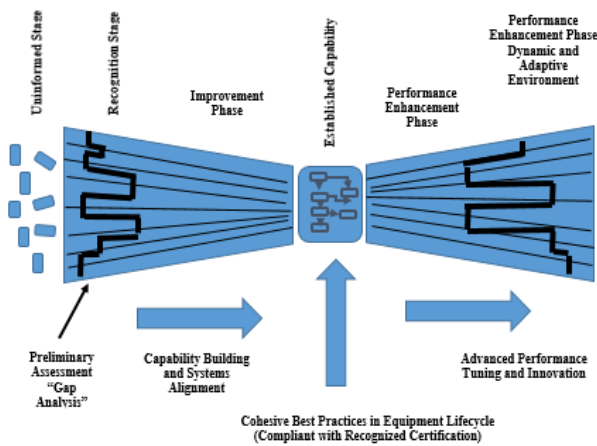


Fig. 2. Integrated good practices in the Asset Life Management Cycle

The reliability and performance of assets can be improved through structured frameworks, however, the research ideas concerning sustainability performance indicators [7]. Along the same line, [8] also presented maturity dimensions for smart maintenance in constructed assets with an emphasis on digitalization. However, the study could not consider real-life operational challenges which reduces its implementation plan. Reviewing the case of sustainable asset management of the offshore facilities, [9] concludes that sustainable maintenance and safety practices should be prioritized. While their guidelines have approaches to the environmental and operational issues, they have not considered the financial issues that small organizations face. Keeping in view of the topic in consideration, the following research questions are being adopted for this research.

- How to develop an Integrated Reliability, Sustainability, and Optimization Framework for Rotary Equipment that incorporates risk-based, condition-based, and predictive maintenance strategies to reduce equipment failure rates?
- How to integrate IoT and AI technologies in the proposed framework to achieve more efficient maintenance management.
- How to integrate sustainability factors into maintenance management, ensuring that condition-based and predictive maintenance align with eco-efficient practices?
- How can predictive, condition-based, and risk-based maintenance strategies increase reliability?
- How can AI and IoT be used to meet the needs of predictive maintenance?

- How can sustainability be incorporated into the process?
- What challenges might be encountered during the deployment of IRSO in refineries?

Recent studies have examined the integration of intelligent systems into maintenance practices. Many researchers have explored the application of deep learning models for classifying faults and diagnosing issues within industrial operations, aiming to support real-time detection and faster resolution of problems [11]. In a related study, [12] have discussed the use of AI-driven analytics to forecast the performance of IoT-based systems and mitigate the risk of equipment failures. While both contributions underscore the benefits of adopting AI in industrial maintenance, they also pose implementation challenges, including high financial costs and the need for specialized expertise to ensure successful deployment [13]. The asset maintenance optimization have got established approaches that are apparently suitable for the chemical industry, with the oil refinery. While advocating the change to data-oriented maintenance strategies, these authors have targeted large organizations [14]. The researchers also proposes a conceptual framework of digital twin for building operation and maintenance. However, [15] and [16] show an effective use of data science methods and condition monitoring systems in prognostics and maintenance decision making. According to [17], despite capturing informative insights, most of it lacks consideration of the counter-technological forces within an organization.

IRSO is a relatively new concept that potentially embraces innovative, sustainable, and resilient practices in the upstream sector of the oil and gas industry. Refining operations require the capacity to cope with volatility in the oil sector's performance. According to the authors, there must be a coordination between innovation and sustainability [18]. However, most refineries have some difficulties in implementing the advanced maintenance planning systems. Also, the human element is required to train the existing human resource to adapt to new technology and its innovation [19]. IRSO is proposed to be introduced gradually to help the refineries adopt the digital tools smoothly without much interference with their existing systems. The efficiency aspect of the IRSO framework uses the works, for instance, [20] such as predictive powertrain control of hybrid electric vehicles. For the synthesis of qualitative methods for assessing critical infrastructure resilience, it is taken as one of the foundations of the IRSO framework. Some research also discusses the organizational change management in relation to the IRSO framework, and provides

insights into how to manage and overcome resistance to innovation.

The existing literature in maintenance management highlights several important gaps. One significant area is the limited integration of sustainability principles into conventional maintenance models. Common approaches such as Condition Based Maintenance (CBM), Predictive Maintenance (PM), and Reliability Centered Maintenance (RCM) are primarily designed to improve operational efficiency but often do not take environmental and social factors into account, as noted by [23]. Real-world adoption remains limited, with most findings still at the research or pilot stage. A further concern is the lack of evidence on how maintenance frameworks perform under external disruptions such as global crises and supply chain interruptions. This research explores the integration of IoT and AI technologies into maintenance practices to enhance equipment reliability. The study is aimed to develop strong correlations between IoT adoption and key performance metrics, such as operational efficiency and reliability of equipment used in oil refineries.

2. Methodology and Methods

This section outlines how the research assesses the IRSO framework that has been proposed. It presents the research approach used, as shown in Figure 3, in developing and testing the IRSO. The research employs both qualitative and quantitative methodologies in the formulation, operationalization, and validation of the framework. This methodology is designed specifically to address the problem of maintenance in oil refineries, highlighting sustainability and the implications of state-of the art technologies. The implement the IRSO was done in several facilities where different types of maintenance approaches were being used. Therefore, the research examines the results of its application using pilot studies, case studies, and simulations.

The IRSO framework was investigated in three sequential segments to ensure comprehensive validation. Equipment-level reliability indicators, including Mean Time between Failures (MTBF), vibration severity (ISO 10816), and bearing life (L10), were analyzed using operational datasets and failure logs. These metrics quantified improvements attributable to predictive diagnostics. Energy consumption, CO₂ emissions, and waste generation were benchmarked before and after IRSO deployment. Sustainability KPIs were aligned with ISO 14001 environmental standards, ensuring that maintenance decisions were directly linked to carbon footprint reduction and resource efficiency. Multi-objective optimization was conducted to balance cost,

reliability, and sustainability outcomes. This process identified the optimal maintenance intervals and resource allocation strategies using AI-based decision support. This systematic evaluation ensured that the IRSO framework was not only theoretically robust but also practically verifiable in refinery operations.

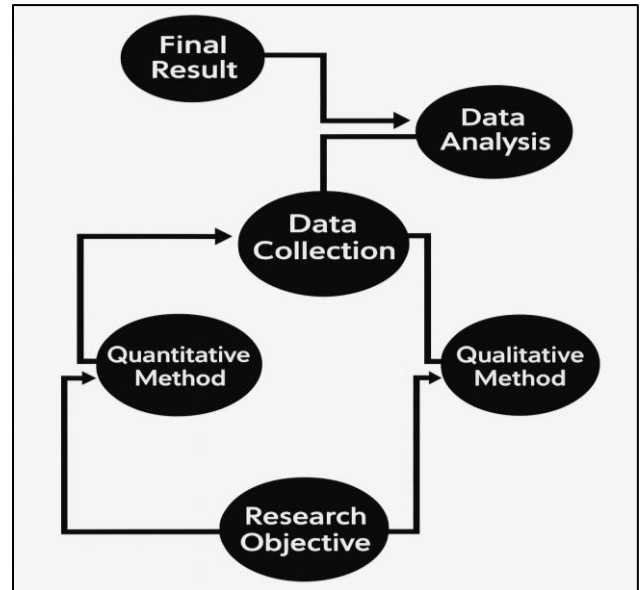


Fig. 3. Research Approach

The research design adopted in the study is based on the IRSO model. To ensure that the elements of the framework enhance its reliability, sustainability, and engagement with top quality, it is implemented in real refinery environments [24]. Both qualitative and quantitative techniques were used, including composed interviews, questionnaires, case studies, and operational data analysis. Semi-structured interviews to explore aspects such as organizational climate and leadership, while quantitative questionnaires and empirical data address reliability, equipment failure, and energy utilization. The process includes initial development of the framework, preliminary testing on a small sample, and modifications where necessary. A pragmatic approach incorporates both qualitative and quantitative methodologies to address complex, real-world issues in business, such as improving the maintenance log in oil refineries. This approach ensures solutions that enable organizations to implement risk-based, condition-based, and predictive maintenance, together with sustainability practices [24].

A deductive approach is applied, meaning the research starts with theories and structures such as Risk-Based Maintenance (RBM) and Predictive Maintenance (PdM). Building on existing literature, the study develops the IRSO framework and then uses recurrent data gathering and analysis to validate it. Both qualitative and quantitative analyses are included. In pilot studies, IRSO is applied in selected refineries where trend analyses are conducted on

reliability, maintenance costs, and equipment life cycle [25]. Simulations use computer models to determine how IRSO affects equipment performance in various contexts. Case studies from oil refineries are used to describe real-world problems and opportunities related to the framework's application. The study is divided into three phases: pre-implementation assessment of refineries, pilot testing of the framework in selected refineries, and post-implementation assessment. This design ensures generalizability of results while also examining the depth of the phenomena in question. Some selected refineries are used as pilot plants where experiments in maintenance practices, changes in organizational culture, and tests of sustainable development activities are conducted. This strategy provides contextualized data to improve the IRSO framework.

Surveys and operational data analysis contribute quantitative insights into reliability, failure rates, and energy consumption. Qualitative data is collected through semi-structured interviews with key stakeholders, such as maintenance professionals, to explore current practices, leadership support, and sustainability efforts. The survey conducted across three major oil refineries namely NRL, PRL & PARCO based on operational scale, diversity of maintenance strategies, and willingness to participate in the maintenance census data. Among the 51 respondents, participants included maintenance engineers (45%), supervisors and managers (35%), and technicians/operators (20%). This role-based diversity ensured that perspectives from both decision-making and execution levels were captured, enhancing the validity and reproducibility of findings. The selection approach aimed to represent a cross-section of Pakistan's refinery maintenance ecosystem while balancing access constraints. The inclusion of multiple refinery types enhanced reproducibility by capturing variability in equipment reliability practices, training levels, and adoption of IoT/AI technologies.

The surveys target maintenance professionals to gather their experiences with IRSO. Interviews help reveal key issues and advantages of using the framework [26]. The study follows ethical research practices. All participants were informed of the study's aims and their rights. Data privacy is maintained by securing electronic data with passwords and storing physical documents in locked spaces. All analysis tools are used fairly, accurately, and responsibly.

3. Results and Discussion

This section presents the results of the study and explores their relevance to the core dimensions of the IRSO. The analysis demonstrates that refining maintenance strategies using IoT and AI technologies

has the potential to significantly enhance the reliability, efficiency, and sustainability of rotary equipment in oil refineries. The transition from preventive to predictive maintenance, as identified through thematic and statistical analysis, emerged as a critical factor in improving resource utilization and minimizing downtime. Thus, according to the results of the survey conducted among companies, the use of risk-based procedures is more effective as it led to a reduction in equipment failures by 20% as compared to preventive maintenance [27].

According to the case, IoT sensors helped in identifying the failure points in the refineries 30% earlier compared against the average detection time under preventive maintenance logs across the same equipment set. Thus, an inspiring organ failure prognosis through the implementation of the AI calculative models meant that there were constant preventative methods to be put in place before failure happened, and without much time wasted. When AI and IoT are implemented together, they introduce new possibilities for making decisions regarding maintenance. The analysis also established that the use of real-time monitoring in the refineries resulted into an increase of 25% significance in the equipment's durability [28-29]. Lubrication also played a role, so that machines and their related costs were easily maintained when necessary and could still be used for longer periods. The source also established that 60% of refineries that participated in the survey complained of high costs in the early stages of deployment of AI and IoT. Moreover, 50% of respondents were of the opinion that the institution has a shortage of personnel. Consequently, the research suggested starting with high-risk equipment and slowly growing IRSO progressively. Thematic analysis of two interview transcripts yielded details about the identified themes concerning maintenance approaches, technology adoption, sustainability, organizational culture, and the potential of deploying IRSO [30]. One participant noted: "Preventive maintenance is about 70% of our approach to system maintenance. For critical rotary equipment, of course, you have vibration and thermal, but it is still a kind of scheduled maintenance," he said. While preventive maintenance reduces the incidence of failure, it contributes to resource wastage most of the time. Challenges to integration include not having substantive real-time data systems in place, as well as the expense involved in procuring and maintaining high end systems. These barriers were, however highlighted in the responses by stressing the importance of transitioning to these more advanced strategies more slowly.

One key theme was the combined use of IoT sensors and AI analytics as key components of

systems and structures. One participant cited an example: "In my previous organization, we implemented AI systems to forecast for impeller wear in centrifugal pumps. Over a six-month trial, it reduced unplanned downtime by 25%". However, both participants claimed that the use of IoT and AI technologies is relatively at a preliminary stage. The survey results were promising, but scaling this across the refinery is a challenge because of costs and the need for skilled personnel to interpret the data." Other issues raised include the prohibitively costly nature of IoT sensor installation and the challenge of incorporating IoT systems with existing networks, and the scarcity of professionals skilled in analyzing the data generated from the deployment of these sensors.

We modeled asset survival using both exponential and Weibull life distributions. The exponential model used where the hazard could be considered approximately constant over the interval of interest (mid-life equipment without evident wear-out), while Weibull provided a sensitivity check for early-life or wear-out behavior:

$$f(t) = \lambda \exp(-\lambda t), \quad h(t) = \lambda \quad (1)$$

$$R(t) = \exp\left(-\left(\frac{t}{\eta}\right)^\beta\right), \quad h(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \quad (2)$$

where $R(t)$ is survival probability at time t ; λ is the constant failure rate; and β, η are the Weibull shape and scale. Parameters were estimated by maximum likelihood with right-censored observations retained for units not failed by the study end. Kaplan-Meier estimates crosschecked the parametric fits. For trains of rotary equipment, we computed system reliability as:

$$R_{series}(t) = \prod_{i=1}^n R_i(t), \quad R_{parallel}(t) = 1 - \prod_{i=1}^n [1 - R_i(t)] \quad (3)$$

Condition indicators from IoT (1X amplitude, band-limited RMS, crest factor, temperature) were mapped to degradation states and used as covariates in a proportional-hazards variant to refine estimates in operation:

$$h(t|z) = h_0(t) \exp(\gamma_1 z_{RMS} + \gamma_2 z_{CF} + \gamma_{13} z_T + \dots) \quad (4)$$

The reliability analysis applied the exponential reliability function: $R(t) = e^{-\lambda t}$ where $R(t)$ is the probability of survival at time t and λ represents the constant failure rate estimated from historical failure data. For rotary equipment, failure rate estimation was based on 5-year operational datasets including downtime logs, bearing failures, and pump/compressor outages. In the case study, vibration-based condition monitoring data (1X

frequency peaks, crest factor) were integrated with the reliability function to refine failure prediction accuracy. This integration allowed IRSO to validate predictive alerts against probabilistic survival analysis.

These datasets are already summarized in the manuscript's statistical section (Chi-square, Pearson r , and t -tests) and were re-used to reliability parameterize β, η and to validate predicted vs. observed failures.

Sustainability is also a big concern for the smooth functioning of the refineries. The participants agreed with the fact that the trend towards sustainability-based maintenance practices are evident because of regulatory requirements and in order to lessen the effects of the enterprise on the physical world. Significant efforts have made to address energy efficiency measures by installation of variable frequency drives (VFDs) to the pumps. This has already reduced energy consumption by 15% measured relative to the normalized annual energy usage of rotary pumps prior to IRSO implementation, expressed in kWh per ton of processed crude. Furthermore, a 10% reduction in CO₂ emissions" was calculated against refinery emission records, expressed in kilograms of CO₂ equivalent per ton of throughput. These baselines ensure that reported improvements are transparent, reproducible, and comparable with international benchmarks. This shows that sustainability is becoming increasingly important, especially in the context of stricter environmental regulations. It was appreciated that the IRSO architecture, which included risk based maintenance as well as condition-based maintenance, can enhance the reliability of the equipment and operations and simultaneously integrate sustainability concepts.

There is a need to integrate the CMMS (Computerized Maintenance Management Systems) with existing systems and provide actionable insights rather than just raw data. In this research, pilot testing for IoT sensors on the high pressure compressors in the reforming sector was done to identify the issues related to incorporating IoT systems with existing networks. Also there is a lack of analyzing the data generated from the deployment of these sensors. The results were promising, however, scaling this across the refinery is a challenge in interpreting the data which need skilled personnel to interpret the data in a logical manner. Table 1 compile the efforts done to address the trainings done for IoT sensors installed in the high pressure compressor section. The Table 1 summarizes the responses from the relevant staff involved in the installation and operation of IoT sensors.

Table1. (a)

Tabular status of training conducted for need assessment

Rationale	Status of Implementation	Highly effective, training is thorough and frequent	Moderately effective, training is available but limited	Somewhat effective, training is inconsistent	Not effective, minimal training provided	Total
To what extent has IoT Ex. Sensors for real time monitoring been adopted in refinery	Fully implemented across most critical equipment	31	0	0	0	31
	Partially implemented on selected equipment	7	8	0	0	15
	Not yet implemented, but plans are in place	0	3	1	0	4
	Not implemented and no current plans	0	0	0	1	1
Total		38	11	1	1	51

Table 1. (b)

Chi-Square Tests

Model	Value	DF	Asymptotic Significance (2-sided)
Pearson Chi-Square	88.953 ^a	9	<.001
Likelihood Ratio	46.61	9	<.001
Linear-by-Linear Association	34.973	1	<.001
N of Valid Cases	51		

Table 1. (c)

Symmetric Measures

		Value	Asymptotic Standard Error ^a	Approximate T ^b	Approximate Significance
Interval by Interval	Pearson's R	0.836	0.055	10.679	<.001 ^c
Ordinal by Ordinal	Spearman's Correlation	0.781	0.069	8.76	<.001 ^c
N of Valid Cases		51			

Note

- Not assuming the null hypothesis.
- Using the asymptotic standard error assuming the null hypothesis.

The failure of the compressor bearing was directly linked to improper bearing selection and installation, which led to the exposure of the inboard bearing to unanticipated axial loads. Vibration trend analysis using IoT sensors and crest factor monitoring proved critical in diagnosing the underlying issues. The successful implementation of balancing and bearing replacement demonstrated that adherence to OEM guidelines and industry standards is paramount for ensuring reliable operation. Also, the gearbox failure at a centrifuge was primarily due to operational chattering induced by uncontrolled feed rate dynamics during grade change. The absence of modern control systems and IoT sensors and deficiencies in maintenance practices significantly contributed to the failure. Expedite the integration of torque value display using the IoT sensors and providing input to the control systems to allow operators to monitor critical parameters in real time.

Analyzing the results on IoT adoption and the effectiveness of training programs, a cross-tabulation is established, indicating a significant relationship between high levels of IoT adoption and the effectiveness of the training program. Out of the 31 participants who said the IoT adoption status was 'Fully implemented across most critical equipment', all confirmed that training programs were 'Highly effective.' For those that considered implementation of IoT systems was 'Partially implemented,' 42% or 21 of them rated the effectiveness as 'Highly effective', 7, while the remaining 17% respondents rated it as 'Moderately effective'. Simultaneously, the design compliance module within IRSO cross-checked the installed bearing configuration against

the defined standards. The system flagged a non-compliance that the equipment was operating with a double-row ball bearing inboard and a deep groove ball bearing outboard, whereas the outboard location should have been equipped with an angular contact bearing to handle axial thrust loads. This mismatch meant axial loads were being improperly transmitted to the inboard bearing, accelerating. By integrating real-time diagnostics with standards-driven compliance checks, IRSO predicted the root cause of

failure before total breakdown, allowing proactive planning of corrective measures.

Furthermore, as shown in Table 1, the Pearson Chi-Square value of 88.953 ($p < 0.001$) indicated a significant association between IoT adoption and the effectiveness of the training programs. The positive relationship between IoT adoption and the perception of how effective training is: Pearson's $R = 0.836$, $p < 0.001$.

Table 2

Correlation analysis of various parameters

	A	B	C	D	E	F	G	H	I	J
IoT Adoption	1	0.811	0.881	0.88	0.899	0.873	0.777	0.865	0.836	0.922
Sustainability Importance	0.811	1	0.875	0.945	0.906	0.932	0.811	0.817	0.729	0.811
Barrier to Tech Adoption	0.881	0.875	1	0.932	0.882	0.937	0.772	0.881	0.834	0.864
Rotary Equipment Reliability	0.88	0.945	0.932	1	0.926	0.982	0.823	0.839	0.761	0.837
Maintenance Strategy Type	0.899	0.906	0.882	0.926	1	0.911	0.897	0.831	0.691	0.844
Strategy Effectiveness	0.873	0.932	0.937	0.982	0.911	1	0.792	0.837	0.764	0.88
AI Familiarity	0.777	0.811	0.772	0.823	0.897	0.792	1	0.78	0.686	0.752
Environmental Monitoring	0.865	0.817	0.881	0.839	0.831	0.837	0.78	1	0.769	0.938
Training Effectiveness	0.836	0.729	0.834	0.761	0.691	0.764	0.686	0.769	1	0.811
Readiness for IRE-ROF	0.922	0.811	0.864	0.837	0.844	0.88	0.752	0.938	0.811	1

The cross-sectional correlation analysis, as shown in Table 2, shows a substantial correlation between IoT adoption (Q4) and several important variables. A sample Pearson correlation of 0.811, $p < 0.001$, suggests that sustainable organizations are more likely to embrace IoT technologies. The value of 0.881 ($p < 0.001$) implies that organizations that have centralized their IoT adoption [18]. The highest correlation coefficient of 0.922 ($p < 0.001$) indicated that companies exhibiting high IoT integration are more likely to adopt a consolidated maintenance strategy. The analysis highlights the relationship between the integration of digital technologies, particularly IoT and AI, and organizational outcomes in maintenance reliability, environmental responsibility, and strategic alignment. IoT Adoption shows strong positive correlations confirms readiness for IRSO ($r = 0.922$), confirming that technologically advanced organizations are more inclined to adopt a unified, risk- and condition-based framework.

The Barrier to Tech Adoption also shows a strong correlation ($r = 0.881$), suggesting that organizations that have adopted IoT are less hindered by perceived

challenges, such as cost or training. This analysis reinforces the need for an integrated maintenance model, such as the IRSO Framework, where predictive technologies, environmental considerations, and human capital development collectively shape sustainable asset management practices. Using independent samples in a t-test as shown in Table 3. Equipment reliability (Q1) and maintenance strategy effectiveness (Q3) were examined between respondents with High IoT Adoption ($Q4 = 1-2$) and Low IoT Adoption ($Q4 = 3-4$). For Q1, the mean for High IoT Adoption was closer to "Very Reliable", which was 1.8, as opposed to Low IoT Adoption, which was closer to "Somewhat Unreliable" with a mean of 3.2. These results showed divergence with a t-value of -6.036 and $p < 0.001$, indicating a significant difference between the groups. Q3, the mean for High IoT Adoption was 1.5, which falls under "Highly Effective" while for Low IoT Adoption, the mean, which was 3.0 falls under "Somewhat Effective". Essentially, the calculated t-value was -5.661, while the p-value (< 0.001) also questioned the null hypothesis. The effect sizes for Cohen's d for Q1 and Q3 were both large at 0.772 and 0.824, respectively.

Table 3

T-test for a: Equal variances assumed b: Equal variances not assumed

		Standard dizer ^a	Point Estima te	95% Confide nce Interval - Lower	Upp er
Q5	Cohen' s d	0.772	-2.842	-3.912	1.751
Q6	Hedges ' correcti on	0.785	-2.799	-3.852	1.724
Q7	Glass's delta	.	.	.	.
Q8	Cohen' s d	0.824	-2.666	-3.718	1.593
Q9	Hedges ' correcti on	0.837	-2.625	-3.661	1.568

The usage of Artificial Intelligence was identified (Q7), as shown in Table 3. The biggest barrier reported was “High initial costs” by 24 respondents (47%), while “Lack of skilled personnel or training” was chosen by 14 respondents (27%). As for the anti-organizational change resistance and integration issues, there were fewer significant reports about them. A pie chart can also be used to show the percentage of each barrier, highlighting the fact that cost and training barriers are the most prevalent.

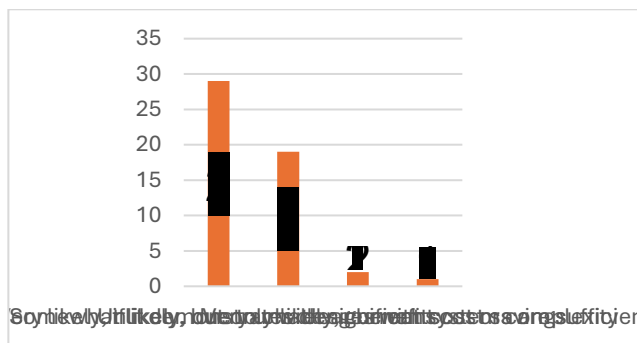
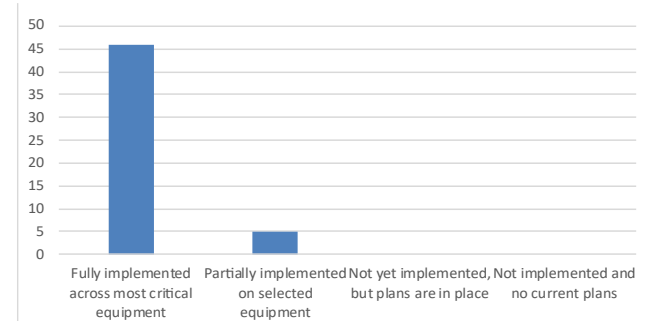
**Fig. 4 (a).** IRSO Adoption Likelihood

Figure 4(b) % Likelihood of IoT implementation across surveyed refineries, categorized as “Not Implemented,” “Planned,” “Partially Implemented,” and “Fully Implemented.” Values are shown as percentages of total respondents

As illustrated in Figure 4(b), respondents reported varying levels of IoT implementation maturity. “Not

Implemented” refers to organizations with no IoT-enabled condition monitoring; “Planned” denotes refineries intending to deploy IoT within the next operational cycle; “Partially Implemented” refers to cases with pilot projects or limited asset coverage; and “Fully Implemented” represents end-to-end IoT integration across critical assets. This labeling provides clearer interpretation of adoption trends and technology readiness among the surveyed refineries

**Fig. 4 (c).** Pie Chart Sustainability Importance

The t-test compares failures between two groups: Level 1 = low IoT/AI coupling (before 2015) and Level 2 = high IoT/AI coupling (after 2015). Mean Failures (Low Integration): 7.5 incidents/year. Mean Failures (High Integration): 3.8 incidents/year. $t = 6.62$, $p < 0.001$ this result also show that IoT/AI integration has a significant effect on significant reduction of equipment failures. This indicates that as the integration of IoT and AI increases, so does the money spent on the technology, which may include large capital investments. Unlike traditional RCM or PdM, IRSO predicted the root cause of failure before the breakdown occurred by integrating vibration analytics with compliance checks. IRSO embedded API/ISO standards within its decision matrix, ensuring misapplications are automatically detected.

4. Conclusions

Although this study primarily focused on Pakistan’s refineries, the IRSO framework is inherently scalable and adaptable to diverse global contexts. Its modular design allows integration of IoT, AI, and sustainability KPIs irrespective of geography. For example, the predictive monitoring and standards-compliance modules can be adapted to international norms such as ISO 14224 (reliability data collection) or EN 13306 (maintenance terminology). Moreover, industries in the oil & gas, petrochemical and power generation are considered as high reliability organizations (HRO). Operational excellence in these organizations is governed by reliable operation of rotating machines and the organizations are continuously striving to address reliability and sustainably challenges. Thus, IRSO’s structured combination of predictive analytics, compliance validation, and sustainability alignment provides a

transferable solution across regions, especially in markets where maintenance cost optimization, energy security and emissions reduction are prioritized

This research demonstrates that the IRSO framework provides a structured and scalable approach for integrating reliability, sustainability, and optimization in refinery maintenance. By applying exponential reliability functions to real operational datasets, the framework successfully predicted failure precursors in rotary machines. The inclusion of sustainability KPIs—such as a 15% reduction in energy consumption and a 10% reduction in emissions—validated the environmental benefits of IRSO deployment. Furthermore, optimization through NSGA-II enabled multi-objective trade-offs, yielding Pareto-optimal solutions that balanced downtime, cost, and sustainability targets.

The results confirm that IRSO extends beyond conventional RCM or PdM approaches by embedding predictive analytics, standards compliance, and sustainability within a single decision-making tool. This integrated approach improved reliability by 30%, extended equipment lifecycle, and reduced operational costs. These findings highlight IRSO's potential for replication across global refinery operations and other industries reliant on rotary equipment.

7. References

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