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A structured Roadmap for implementing Reliability-Centered Maintenance in Air Separation Unit in Saudi Arabia

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1. Chapter 1: Introduction

1.1. Research Background

In today's highly competitive industrial environment where operational efficiency, cost optimization, and equipment reliability are essential to sustaining profitability and safety maintenance strategies have become a strategic priority for industrial leaders. This is especially true in Air Separation Units (ASUs), which play a critical role in supplying high-purity gases such as oxygen, nitrogen, and argon to industries ranging from steel manufacturing and chemical processing to healthcare and electronics. Given the complex and continuous nature of ASU operations, unplanned downtime or equipment failure can have severe consequences on production, safety, and energy consumption (Young et al., 2021).

Traditional maintenance practices, whether reactive, calendar-based, or routine preventive approaches, are increasingly seen as inadequate in managing the intricate equipment and dynamic operating conditions within ASUs. In response to these challenges, Reliability Centered Maintenance (RCM) has emerged as a structured and systematic methodology that helps identify and apply the most effective maintenance strategies for each asset, based on its operational function, criticality, and failure modes (Patil et al., 2022).

Originally developed in the aviation sector and now applied across various industries, RCM empowers air separation facilities to move beyond inefficient, reactive maintenance models toward proactive, condition-based, and risk-informed asset management. By analyzing how and why equipment in the ASU fails and what the real-world consequences of those failures are in terms of safety, environment, product purity, or production capacity enables the development of targeted, optimized maintenance programs that increase uptime, reduce operational risk, and prolong equipment lifespan (Telukdarie & Stadler, 2017).

However, implementing RCM in an ASU environment is not simply a technical procedure. It requires a structured, step-by-step roadmap that integrates engineering analysis with organizational collaboration, cultural readiness, and long-term strategic alignment. Such a roadmap must include asset criticality assessment, failure modes and effects analysis (FMEA), consequence classification, maintenance strategy selection, task planning, workforce training, and ongoing performance evaluation (Omozuhomwen et al.,2025).

Without a clear and well-governed implementation framework, even well-intentioned RCM efforts in ASUs may fail to deliver results or integrate with broader plant maintenance systems. Therefore, the purpose of this roadmap is to provide ASU operators and stakeholders with a comprehensive and actionable guide to implementing RCM effectively maximizing reliability, reducing maintenance costs, and supporting overall operational excellence. Through this structured approach, ASU facilities can meet the demands of modern industry while ensuring the safety, efficiency, and integrity of one of their most critical production systems (He et al.,2022).

1.2. Research Problem

1.2.1. Theoretical Gaps

Despite the established benefits of Reliability Centered Maintenance (RCM) across various industrial sectors, significant theoretical gaps remain in its application to Air Separation Units (ASUs). Existing literature often provides generalized frameworks for RCM without tailoring them to the specific operational and technical intricacies of ASUs, which involve cryogenic processes, complex mechanical systems, and continuous operations.

1. Lack of ASU-Specific RCM Frameworks: Much of the RCM research lacks customization for ASUs, which operate under unique conditions (e.g., low temperatures, high energy consumption, safety-critical processes). The theoretical models often fail to account for these distinct parameters, limiting their relevance and applicability (He et al.,2021).

2. Insufficient Integration with Reliability Engineering: While RCM is conceptually linked with reliability engineering, theoretical models frequently overlook how to quantitatively connect failure data, reliability metrics (like MTBF, MTTR), and maintenance strategies in an ASU context.

3. Limited Focus on Organizational Change Theory: Many models neglect the organizational behavior aspects that influence RCM adoption, such as resistance to change, leadership engagement, and knowledge transfer—all of which are critical in implementing maintenance transformation in complex plants like ASUs.

4. Gaps in Measuring Strategic Impact: There is a lack of robust theoretical approaches to measuring the long-term impact of RCM implementation on strategic plant performance indicators such as asset availability, operational efficiency, and cost-effectiveness.

1.2.2. Practical Gaps

In addition to theoretical limitations, numerous practical challenges are hindering the successful implementation of RCM in Air Separation Units:

1. Over-Reliance on Traditional Maintenance Approaches: Many ASUs continue to use reactive or time-based maintenance models. These approaches are easier to implement but lead to inefficiencies, frequent breakdowns, and missed opportunities for predictive strategies (He et al.,2021).

2. Absence of a Structured Implementation Roadmap: Even when organizations express interest in adopting RCM, the lack of a step-by-step, actionable roadmap tailored to ASU operations results in inconsistent or stalled implementation efforts.

3. Limited Technical Expertise and Training: Successful application of RCM requires deep knowledge of failure modes, criticality analysis, and reliability data interpretation—skills that may be lacking in current maintenance teams.

4. Resistance to Change and Organizational Barriers: Maintenance culture in many facilities is conservative, with personnel accustomed to routine tasks. Organizational inertia, unclear roles, and lack of top management support further impede RCM adoption.

5. Lack of Measurable Performance Feedback: Even in facilities that have attempted RCM practices, insufficient performance tracking mechanisms prevent meaningful evaluation of impact on equipment reliability or cost savings, limiting continuous improvement.

In light of these challenges, the research seeks to answer a central question:

How can Air Separation Units effectively implement a structured roadmap for Reliability Centered Maintenance that aligns with their operational needs, improves equipment reliability, and enhances overall plant performance? Addressing this question is essential for enabling ASUs to transition from reactive to proactive maintenance strategies and achieve long-term operational excellence.

1.3. Research Significance

1.3.1. At the theoretical level

This research contributes to the theoretical development of maintenance engineering and reliability management by contextualizing the application of Reliability Centered Maintenance (RCM) within the specialized and high-stakes environment of Air Separation Units (ASUs). While the RCM methodology is well-established in literature, its adaptation to the specific operational, functional, and risk profiles of ASUs remains underexplored. This study adds to academic discourse by offering a structured framework that integrates reliability theory, failure mode analysis, and risk-based decision-making tailored to cryogenic systems and continuous-process industries. Additionally, it bridges the gap between general RCM theory and sector-specific application, encouraging future research on customized maintenance strategies for critical industrial assets.

1.3.2. At the practical level

From a practical perspective, this research provides plant managers, reliability engineers, and maintenance teams in ASUs with a clear, step-by-step roadmap to implement RCM effectively. By addressing common implementation barriers such as asset prioritization, data limitations, and workforce resistance study equips decision-makers with actionable tools and guidelines to shift from reactive or time-based maintenance to a proactive, function-oriented model. The structured approach proposed helps reduce unplanned shutdowns, lower maintenance costs, improve safety, and optimize equipment availability. Furthermore, it supports compliance with industry standards and enhances operational sustainability, making it a valuable resource for organizations aiming to boost the reliability and efficiency of their air separation operations.

1.4. Research Questions

1. What are the key elements required to develop an effective roadmap for implementing Reliability Centered Maintenance (RCM) in Air Separation Units?
2. What are the main technical, organizational, and operational challenges hindering the application of RCM in ASUs, and how can these challenges be addressed?

3. What measurable impact does the implementation of RCM have on equipment reliability, operational efficiency, and maintenance costs in ASUs?

1.5. Research Objectives

1. To identify the core components of a structured roadmap for the effective implementation of RCM in Air Separation Units.

2. To analyze the technical and organizational challenges associated with implementing RCM and propose practical solutions to overcome them.

3. To evaluate the impact of RCM adoption on improving equipment performance, minimizing downtime, and reducing maintenance costs in ASU environments.

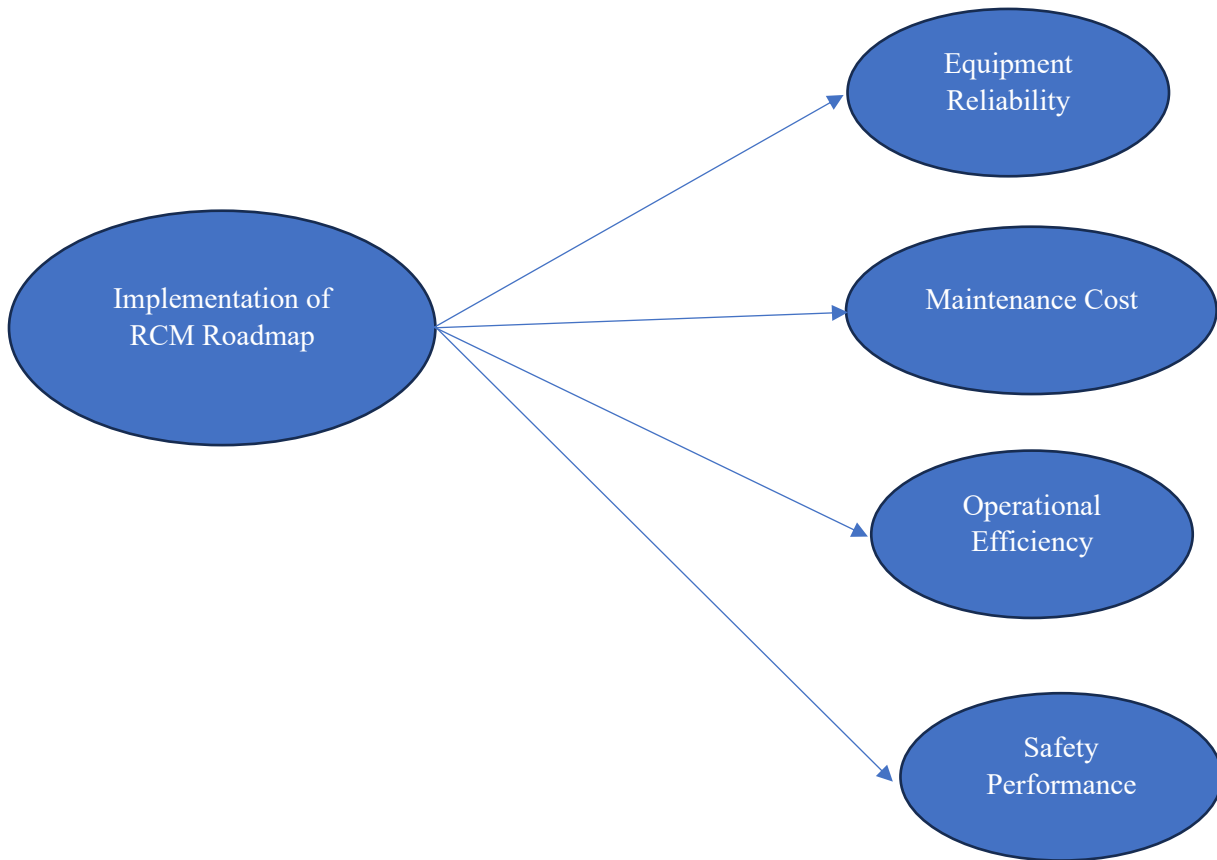
1.6. Research Hypotheses

H1: There is a statistically significant positive relationship between the implementation of Reliability Centered Maintenance (RCM) and equipment reliability in Air Separation Units (ASUs).

H2: There is a statistically significant negative relationship between the implementation of RCM and unplanned maintenance costs in ASUs.

H3: There is a statistically significant effect of using failure analysis tools (e.g., FMEA) within the RCM framework on reducing equipment downtime and enhancing operational efficiency in ASUs.

1.7. Research Model



1.8. Scope of The Study

This study focuses on the structured implementation of Reliability Centered Maintenance (RCM) within the operational context of Air Separation Units (ASUs). It specifically targets the development of a practical roadmap that guides the transition from traditional maintenance strategies to a proactive, reliability-based approach.

Industry Focus: The research is centered on industrial facilities that operate Air Separation Units, particularly those involved in the production and supply of industrial gases such as oxygen, nitrogen, and argon for sectors like metallurgy, petrochemicals, healthcare, and electronics.

Maintenance Strategy: The study concentrates on the adoption and application of the RCM methodology, including key elements such as asset criticality assessment, failure mode and effects analysis (FMEA), maintenance strategy selection, and task planning.

Organizational Aspects: It examines both technical and organizational factors influencing the successful implementation of RCM, such as workforce readiness, data availability, integration with computerized maintenance management systems (CMMS), and cultural change management.

Geographical and Operational Boundaries: While the methodology is universally applicable, the empirical analysis—if applicable—will be limited to selected ASUs operating in the industrial sector (the specific company or plant may be identified in later stages).

Time Frame: The study addresses current maintenance practices and implementation plans over a 12–24 month operational period to assess reliability improvements and cost implications. The study does not cover other maintenance methodologies such as Total Productive Maintenance (TPM) or Six Sigma in depth, unless used as supporting tools to complement the RCM approach.

1.9. The Suggested Project Structure

1.9.1. Chapter One: Introduction

This chapter provides the foundation of the research by introducing the background, context, and rationale for the study. It discusses the critical role of maintenance strategies in industrial operations, particularly in Air Separation Units (ASUs), and highlights the limitations of traditional maintenance practices. The chapter presents the research problem, formulates the research questions, defines the objectives, and outlines the hypotheses. It also explains the scope and significance of the study, emphasizing its theoretical and practical contributions to the field of maintenance engineering. The chapter concludes with a brief overview of the structure of the entire research.

1.9.2. Chapter Two: Research Methodology

Chapter three outlines the research design and methodological approach adopted to answer the research questions. The study employs a descriptive analytical method, using a structured questionnaire to collect data from maintenance and operations personnel working in ASUs. The chapter describes the design and structure of the questionnaire, the target population, and the sampling method (purposive sampling). It also explains the statistical techniques used to analyze the data, including descriptive and inferential analyses such as correlation and regression. Ethical considerations related to data collection and participant confidentiality are also discussed.

1.9.3. Chapter Three: : Literature Review

This chapter offers a comprehensive review of relevant academic and industrial literature. It begins by discussing the evolution of maintenance approaches—reactive, preventive, predictive, and Reliability Centered Maintenance (RCM). The principles and methodology of RCM are examined in detail, including its historical development and applications in various sectors. The chapter then narrows its focus to the context of Air Separation Units, highlighting specific maintenance challenges and reliability concerns in such environments. Existing gaps in the application of RCM within ASUs are identified, and the chapter concludes by presenting the theoretical framework that underpins the study.

1.9.4. Chapter Four: Data Analysis and Results

This chapter presents the results of the field data collected through the questionnaire. It starts with a descriptive statistical analysis of the respondents' demographic data and their responses. It then applies inferential statistical methods to test the proposed hypotheses and examine the relationships between the implementation of RCM and the identified performance indicators: equipment reliability, maintenance cost, operational efficiency, and safety. Tables, graphs, and figures are used to visualize the findings. The chapter provides an objective interpretation of the results in line with the study objectives.

1.9.5. Chapter Five: Discussion, Conclusions, and Recommendations

The final chapter synthesizes the research findings and discusses their implications in light of existing literature. It critically evaluates how the structured implementation of RCM influences maintenance outcomes in ASUs. The chapter then presents the main conclusions of the study, based on the empirical evidence gathered. Practical recommendations are offered for industry practitioners, especially those managing reliability programs in ASUs. Additionally, the limitations of the study are acknowledged, and suggestions for future research are provided further to explore the customization of RCM in other process-intensive environments.

2.Chapter 2: Literature Review

2.1. Introduction

In modern industrial environments, where operational continuity is critical and equipment complexity is rising, maintenance has evolved from a reactive function to a strategic asset management tool. Reliability Centered Maintenance (RCM) has emerged as a structured approach that prioritizes maintenance based on equipment function, failure modes, and the consequences of failure. Initially developed in the aviation sector, RCM has proven effective in reducing downtime, enhancing safety, and improving cost efficiency. Its application in Air Separation Units (ASUs)—highly capital-intensive, continuous-operation systems—is particularly relevant due to the critical nature of their operations and the potential impact of equipment failures on production, energy consumption, and safety (Azid et al., 2019; He et al., 2021).

2.2. The independent variable

The independent variable in this context is Reliability Centered Maintenance (RCM). RCM is a systematic, risk-based maintenance methodology that identifies the functions of each asset, analyzes potential failure modes, and evaluates the operational consequences of failure. Core principles include function-oriented maintenance, failure mode identification, consequence-based prioritization, and prescriptive task selection (Sajaradj et al., 2019; Afefy et al., 2010). RCM differs from reactive or preventive maintenance by providing a structured decision-making framework that tailors interventions based on asset criticality and operational impact. Digital tools such as IoT, AI, and Digital Twins can further enhance RCM, enabling real-time monitoring and predictive decision-making (Montehermoso-Mallaupoma et al., 2024; Mphosa et al., 2018).

2.3. The dependent variable

The dependent variable is ASU operational performance, encompassing reliability, safety, efficiency, and cost-effectiveness. In ASUs, even minor equipment disruptions can lead to production halts, gas purity deviations, energy inefficiency, or safety hazards.

Effective maintenance strategies—guided by RCM—directly influence these outcomes by reducing unexpected failures, optimizing maintenance resources, extending equipment life, and supporting compliance with operational and safety standards (Li et al., 2010; Geisbush et al., 2022). Additionally, RCM contributes to sustainability by minimizing energy waste and preventing environmental risks (Cutajar et al., 2023).

2.4. The relationship between the independent and the dependent variables

RCM (independent variable) influences ASU operational performance (dependent variable) by aligning maintenance activities with asset criticality and operational risk. By identifying potential failure modes and prioritizing maintenance actions, RCM reduces unplanned downtime, enhances safety, improves energy efficiency, and lowers operational costs (He et al., 2022; Telukdarie & Stadler, 2017). Its integration with digital technologies—IoT for real-time monitoring, AI for predictive analytics, and Digital Twins for simulation—further strengthens this relationship by enabling proactive and adaptive maintenance decisions. Organizational culture, leadership support, and workforce training act as moderating factors, determining the effectiveness of RCM implementation in achieving improved ASU performance (Jacobsen et al., 2016).

Figure: Relationship Between RCM and ASU Operational Performance

<i>Independent Variable</i>	<i>Mechanisms / Actions</i>	<i>Moderating Factors</i>	<i>Dependent Variable</i>
<i>Reliability Centered Maintenance (RCM)</i>	- Functional failure analysis - Failure mode identification - Consequence-based task prioritization - Preventive and predictive maintenance	- Organizational culture - Leadership support - Workforce training - Integration with digital tools (IoT, AI, Digital Twins)	ASU Operational Performance: - Reliability (reduced unplanned downtime) - Safety (risk mitigation) - Efficiency (energy and resource optimization) - Sustainability (reduced waste and emissions)

2.5. Conclusion

Reliability Centered Maintenance is a critical driver of operational excellence in high-reliability environments like Air Separation Units. By focusing on functional failure analysis, consequence prioritization, and tailored maintenance strategies, RCM directly enhances reliability, safety, efficiency, and sustainability. Successful implementation requires not only technical rigor but also workforce competence, cross-functional collaboration, organizational support, and integration with digital tools. In the ASU context, RCM provides a pathway to optimize maintenance, minimize downtime, and achieve sustainable operational performance.

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Appendix A – Questionnaire

Good day

This questionnaire is designed to collect data for the study entitled 'A Structured Roadmap for Implementing Reliability-Centered Maintenance in Air Separation Units in Saudi Arabia.' The purpose of this instrument is to measure the extent of Reliability Centered Maintenance (RCM) practices and their effect on Air Separation Unit (ASU) operational performance. Please respond to each statement using the following scale: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly Agree. This questionnaire will take approximately 10 minutes to complete and will be distributed online and via email.

Thanks

Section 1: Reliability-Centered Maintenance (Independent Variable)

Dimension A – Failure Analysis & Criticality

RCM1: Our ASU equipment undergoes systematic FMEA on a regular basis.

RCM2: Asset criticality ranking is used consistently to prioritize maintenance.

RCM3: Failure consequences are classified into safety, operational, and cost categories.

Dimension B – Maintenance Strategy

RCM4: Preventive maintenance intervals are based on equipment condition data.

RCM5: Predictive maintenance techniques (e.g., vibration analysis) are widely adopted.

RCM6: Run-to-failure strategies are applied only when economically justified.

RCM7: Maintenance strategies are updated after major breakdowns or failures.

Dimension C – Maintenance Information Systems

RCM8: Our CMMS is fully utilized to document maintenance actions.

RCM9: Reliability metrics such as MTBF and MTTR are monitored regularly.

RCM10: Maintenance history data is analyzed for decision-making.

RCM11: Reports from CMMS are shared with management for continuous improvement.

Dimension D – Human & Organizational Factors

RCM12: Technicians and operators receive continuous training on RCM practices.

RCM13: Top management actively supports RCM initiatives.

RCM14: Cross-functional teams are involved in RCM implementation.

RCM15: Incentives are provided to staff who support reliability improvements.

Section 2: ASU Operational Performance (Dependent Variable)

Dimension A – Reliability & Availability

OP1: The ASU maintains uptime above 95% consistently.

OP2: Unplanned shutdowns are rare in our ASU.

OP3: Critical spare parts availability reduces downtime.

OP4: Preventive maintenance reduces emergency breakdowns.

Dimension B – Efficiency & Cost

OP5: Energy consumption per ton of oxygen/nitrogen produced has decreased.

OP6: Maintenance costs are within budgeted levels.

OP7: Maintenance cost per production unit has decreased over the past year.

OP8: Efficiency improvements are linked to optimized maintenance practices.

Dimension C – Safety & Risk Control

OP9: The frequency of safety incidents related to ASU equipment has reduced.

OP10: Preventive actions are taken before risks escalate.

OP11: Maintenance practices comply with international safety standards (API, ASME, OSHA).

OP12: Emergency response procedures are improved through maintenance planning.

Google Form Link:

<https://forms.gle/x4G8kDgaRUm8pz9f9>

Appendix B – Research Instruments Table

Variable	Dimension	No. of Items	Source
Reliability-Centered Maintenance (IV)	<i>Failure Analysis & Criticality</i>	3	<i>Moubray (1997); He et al. (2021)</i>
Reliability-Centered Maintenance (IV)	<i>Maintenance Strategy</i>	4	<i>Afey (2010); Omozuhomwen et al. (2025)</i>
Reliability-Centered Maintenance (IV)	<i>Maintenance Information Systems</i>	4	<i>Waeyenbergh & Pintelon (2002); He et al. (2021)</i>
Reliability-Centered Maintenance (IV)	<i>Human & Organizational Factors</i>	4	<i>Alsyuf (2007); Tsang (2002)</i>
ASU Operational Performance (DV)	<i>Reliability & Availability</i>	4	<i>Telukdarie & Stadler (2017)</i>
ASU Operational Performance (DV)	<i>Efficiency & Cost</i>	4	<i>Young et al. (2021)</i>
ASU Operational Performance (DV)	<i>Safety & Risk Control</i>	4	<i>Jardine et al. (2006)</i>