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

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Table of Contents

1. Chapter 1: Introduction	4
1.1. Research Background	5
1.2. Research Problem.....	7
1.2.1. Theoretical Gaps	7
1.2.2. Practical Gaps.....	8
1.3. Research Significance.....	9
1.3.1. At the theoretical level	9
1.3.2. At the practical level	9
1.4. Research Questions	9
1.5. Research Objectives	10
1.6. Research Hypotheses.....	10
1.7. Research Model	11
1.8. Scope of The Study	11
1.9. The Suggested Project Structure.....	12
1.9.1. Chapter One: Introduction	12
1.9.2. Chapter Two: Research Methodology.....	13
1.9.3. Chapter Three: : Literature Review.....	13
1.9.4. Chapter Four: Data Analysis and Results	13
1.9.5. Chapter Five: Discussion, Conclusions, and Recommendations.....	14
2. Chapter 2: Literature Review	15
2.1. Introduction	16
2.2. The independent variable	16
2.3. The dependent variable.....	16
2.4. The relationship between the independent and the dependent variables.....	17
2.5. Conclusion	18
3. Chapter 3: Research Methodology	19
3.1. Introduction	20
3.2. Operational definitions.....	21
3.2.1. Reliability-Centered Maintenance (RCM) – Independent Variable (X).....	21

3.2.2.	ASU Operational Performance – Dependent Variable (Y)	21
3.3.	Research Design (Research Onion).....	22
3.3.1.	Research Philosophy – Positivism.....	22
3.3.2.	Research Approach – Deductive.....	23
3.3.3.	Research Strategy – Survey.....	23
3.3.4.	Research Choice – Quantitative.....	23
3.3.5.	Time Horizon – Cross-Sectional	23
3.3.6.	Data Collection and Analysis Techniques	24
3.4.	Research Population & Sampling Methods	25
3.4.1.	Research Population	25
3.4.2.	Research Sample	26
3.4.3.	Sampling Method & Techniques	26
3.5.	Data Collection Method	27
3.5.1.	The Independent Variable (X): Reliability-Centered Maintenance (RCM).....	27
3.5.2.	The Dependent Variable (Y): ASU Operational Performance (Productivity Levels)...	28
3.6.	Types of Data	28
3.6.1.	Primary Data	28
3.6.2.	Secondary Data.....	29
3.7.	Statistical Analysis Procedures.....	29
3.7.1.	Data Preparation and Coding.....	30
3.7.2.	Descriptive Statistical Analysis	30
3.7.3.	Inferential Statistical Analysis	30
3.7.4.	Transition to Data Analysis.....	31
3.8.	Conclusion	31
	References.....	33
	Appendix A – Questionnaire.....	36
	Appendix B – Research Instruments Table.....	38

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.

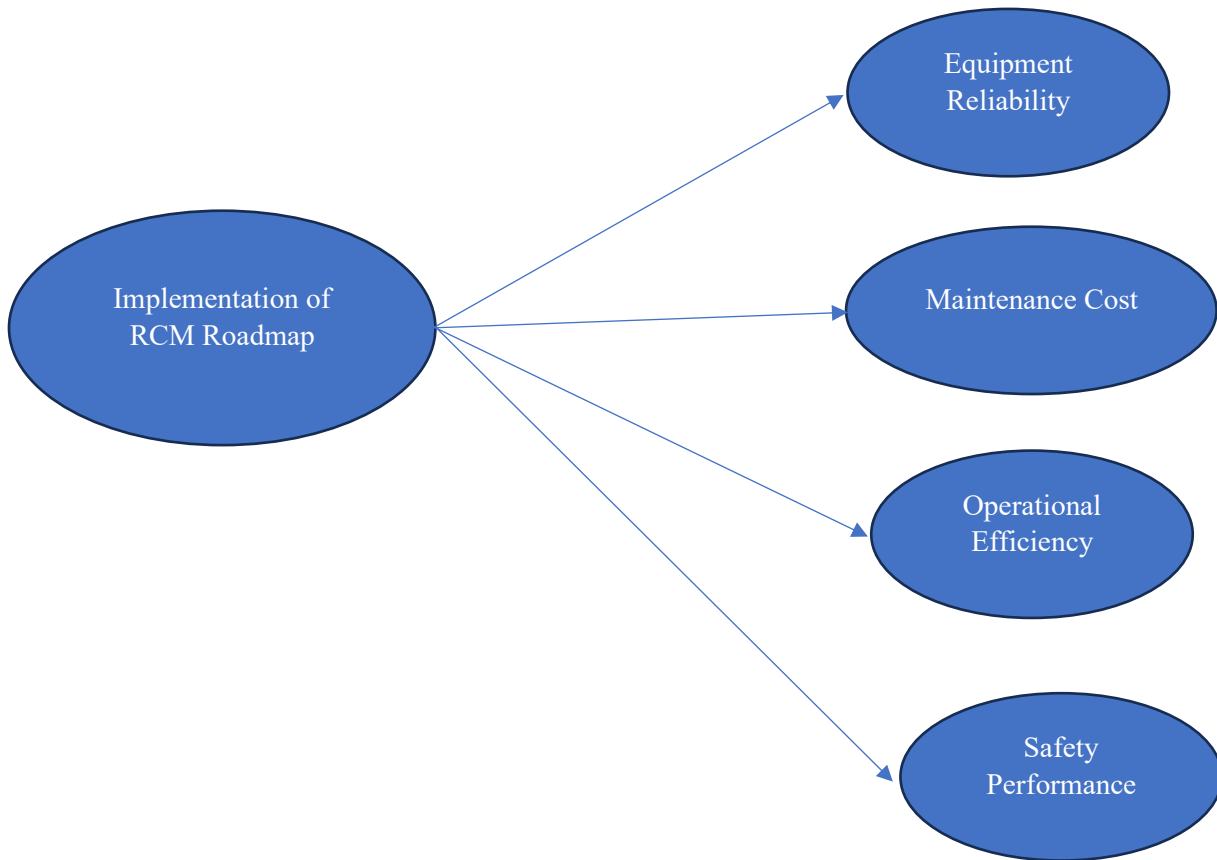
1.6. Research Hypotheses

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.

3. Chapter 3: Research Methodology

3.1. Introduction

The purpose of this chapter is to present the research methodology employed to achieve the objectives of this study, which focuses on developing a structured roadmap for implementing Reliability-Centered Maintenance (RCM) within Air Separation Units (ASUs) in Saudi Arabia. The methodology serves as the foundation for answering the research questions, testing the hypotheses, and ensuring the study's validity, reliability, and reproducibility.

Methodology represents a systematic plan for conducting research through well-defined philosophical assumptions, approaches, and strategies. It allows researchers to justify the selection of research methods and ensure alignment between research objectives, data collection, and analysis procedures. In this study, a quantitative research methodology was adopted to evaluate the relationship between RCM practices—such as failure analysis, maintenance strategies, and organizational factors—and ASU operational performance indicators, including reliability, efficiency, and safety. (Saunders et al., 2019).

The study utilizes a descriptive analytical research design to identify existing RCM practices, assess their level of implementation, and quantify their impact on ASU operational performance. Data are collected through a structured questionnaire targeting maintenance engineers, reliability professionals, and operations managers working in ASU environments. Statistical analysis techniques, including descriptive statistics, correlation, and regression, are applied to examine the relationships among variables and validate the study hypotheses (Patil et al., 2022; Telukdarie & Stadler, 2017).

Overall, this chapter provides a detailed explanation of the operational definitions of variables, research design, population and sampling methods, data collection techniques, data types, and statistical analysis procedures. By following the structured framework of the research onion (Saunders et al., 2019), the methodology ensures the research outcomes are scientifically sound and contribute meaningfully to both theoretical understanding and practical applications of RCM in ASUs.

3.2. Operational definitions

Operational definitions clarify how the study's main variables are measured and observed to ensure that the data collected are consistent, quantifiable, and replicable (Saunders et al., 2019).

3.2.1. Reliability-Centered Maintenance (RCM) – Independent Variable (X)

Reliability-Centered Maintenance (RCM) refers to a systematic and data-driven maintenance methodology used to determine the most effective maintenance strategy for each asset based on its operational function, criticality, and failure modes (Moubray, 1997). For this study, RCM is operationalized through four measurable dimensions:

1. Failure Analysis & Criticality – regular use of Failure Modes and Effects Analysis (FMEA) and asset-criticality ranking to prioritize maintenance activities (He et al., 2021).
2. Maintenance Strategy – implementation of preventive, predictive, and run-to-failure strategies in alignment with equipment condition and cost justification (Afeiy, 2010; Omozuhomwen et al., 2025).
3. Maintenance Information Systems – utilization of Computerized Maintenance Management Systems (CMMS) and reliability indicators such as MTBF and MTTR for decision-making (Waeyenbergh & Pintelon, 2002; He et al., 2021).
4. Human & Organizational Factors – managerial commitment, workforce training, and cross-functional teamwork supporting reliability culture (Alsyoud, 2007; Tsang, 2002).

Responses are measured using a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) across 15 items derived from prior RCM literature.

3.2.2. ASU Operational Performance – Dependent Variable (Y)

ASU Operational Performance represents the measurable outcome of how RCM implementation influences the reliability, efficiency, and safety of Air Separation Units. It

reflects the plant's ability to maintain uptime, minimize costs, and operate safely under continuous production (Telukdarie & Stadler, 2017).

This variable is operationalized through three core dimensions:

1. Reliability & Availability – percentage of uptime, reduction of unplanned shutdowns, and availability of critical spares (He et al., 2022).
2. Efficiency & Cost – optimization of maintenance costs, reduction in energy consumption per production unit, and improved maintenance-to-output ratio (Young et al., 2021).
3. Safety & Risk Control – compliance with international safety standards and prevention of incidents through proactive maintenance (Jardine et al., 2006).

Each dimension is evaluated using 12 items on the same five-point Likert scale, allowing quantitative assessment of ASU performance improvements resulting from RCM implementation.

3.3. Research Design (Research Onion)

The research design provides the overall plan for integrating the different components of the study in a coherent and logical way, ensuring that the research problem is addressed effectively (Saunders et al., 2019). This study adopts the research onion framework, which presents sequential layers that guide the methodological decisions — from philosophical orientation to data collection and analysis techniques. Each layer is selected to ensure that the research questions and hypotheses are answered in a scientifically valid manner.

3.3.1. Research Philosophy – Positivism

The study is grounded in the positivist philosophy, which emphasizes objectivity, empirical evidence, and quantifiable data to test hypotheses and establish cause-and-effect relationships. Positivism assumes that reality is external and can be measured through observable indicators (Collis & Hussey, 2014). This philosophy aligns with the study's goal of statistically analyzing the relationship between RCM implementation and ASU

operational performance through measurable indicators such as reliability, efficiency, and safety.

3.3.2. Research Approach – Deductive

A deductive approach is adopted, whereby hypotheses are developed from existing theories and prior empirical studies on RCM and reliability engineering (Moubray, 1997; He et al., 2021). The deductive process allows the researcher to move from general theoretical concepts to specific observations by testing the formulated hypotheses (H1–H3). This approach ensures logical reasoning and objective validation of the relationship between maintenance strategies and operational outcomes in ASUs.

3.3.3. Research Strategy – Survey

The research strategy employed is a survey, using a structured questionnaire distributed to maintenance engineers, reliability specialists, and operations managers working in Air Separation Units. The survey method is suitable for quantitative research, enabling data collection from a relatively large and diverse population within a defined period. This approach facilitates statistical analysis and comparison of responses across different organizational contexts (Saunders et al., 2019).

3.3.4. Research Choice – Quantitative

This study follows a quantitative research choice, focusing on numerical data and statistical techniques to explain relationships among variables. Quantitative methods allow for objective measurement, reliability testing, and generalization of results, which are essential for validating the RCM implementation framework (Patil et al., 2022). The use of numerical data enhances precision and supports inferential analysis through correlation and regression testing.

3.3.5. Time Horizon – Cross-Sectional

The research adopts a cross-sectional time horizon, as data will be collected once during a specific period from participants across various ASU facilities in Saudi Arabia. This design is appropriate for assessing existing RCM practices and their current impact

on operational performance without requiring long-term observation (Saunders et al., 2019).

3.3.6. Data Collection and Analysis Techniques

Data are collected using a structured questionnaire composed of closed-ended questions and Likert-scale items. This ensures consistency, simplicity, and comparability of responses. After data collection, statistical analyses — including descriptive statistics, correlation, and regression — are conducted to evaluate the hypothesized relationships between the independent and dependent variables (He et al., 2022; Omozuhomwen et al., 2025).

Summary of Research Onion Layers

<i>Layer</i>	<i>Selection for This Study</i>	<i>Justification</i>
<i>Philosophy</i>	Positivist	Supports an objective, evidence-based investigation suitable for quantitative analysis of relationships.
<i>Approach</i>	Deductive	Enables testing of hypotheses derived from established Reliability-Centered Maintenance (RCM) theories.
<i>Strategy</i>	Survey	Facilitates efficient data collection from professionals involved in Air Separation Unit (ASU) operations.
<i>Choice</i>	Quantitative	Ensures statistical validation, reliability, and generalizability of the findings.
<i>Time Horizon</i>	Cross-sectional	Captures a snapshot of current practices and productivity-diversity relationships at a single point in time.
<i>Data Collection & Analysis</i>	Structured Questionnaire	Provides standardized, replicable, and reliable data suitable for statistical analysis.

Figure 3.1: The Research Onion Framework (Adapted from Saunders et al., 2019)

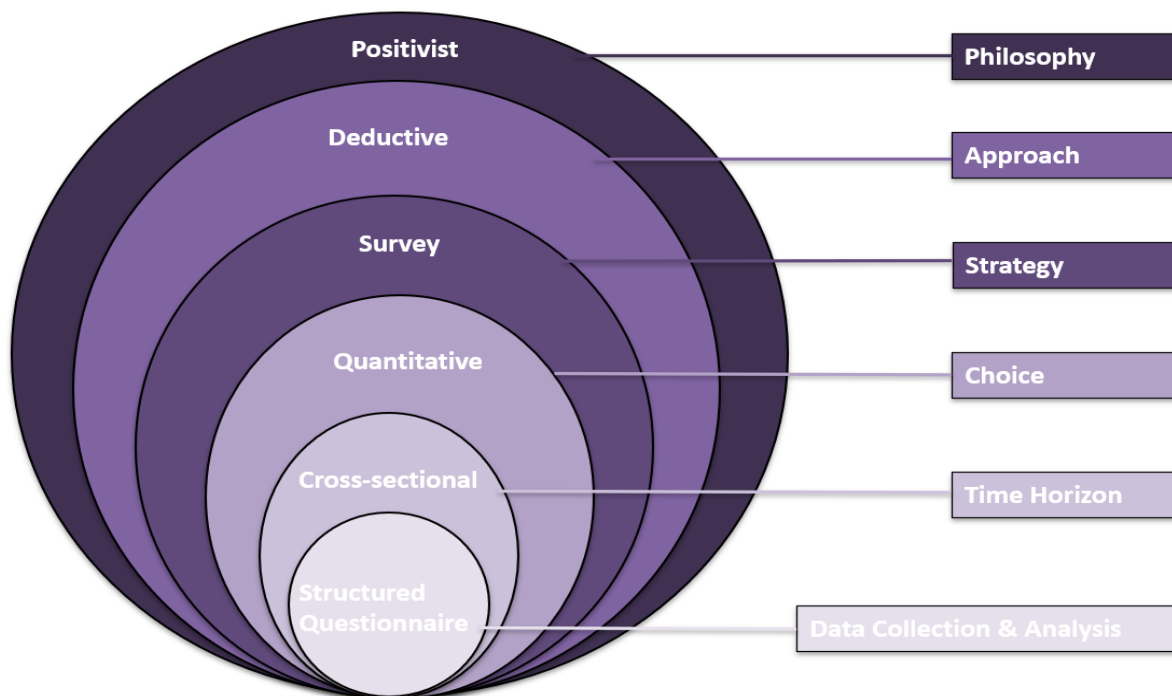


Figure 3.1 illustrates the Research Onion model, which guides the structured selection of research philosophy, approach, strategy, and data collection methods applied in this study

3.4. Research Population & Sampling Methods

3.4.1. Research Population

The research population refers to the total group of individuals or entities that possess the characteristics relevant to the phenomenon being studied (Creswell, 2014). For this study, the population includes employees, supervisors, engineers, and managers working within Air Separation Unit (ASU) operations and maintenance divisions across selected industrial gas plants. These individuals are directly engaged in operational and reliability activities where workplace diversity—in terms of gender, experience, cultural background, and technical specialization—may influence productivity levels. Including a wide range of participants ensures a comprehensive understanding of how workplace diversity affects organizational performance (Sekaran & Bougie, 2019).

3.4.2. Research Sample

Given the large and geographically distributed nature of ASU operations, surveying the entire population is impractical (Saunders et al., 2019).

Therefore, a representative sample is selected to ensure the study remains both feasible and statistically valid. the sample includes approximately 80–120 respondents drawn from operations, maintenance, reliability, and management teams. this sample size supports quantitative analysis using structured questionnaires and provides sufficient data for correlation and regression tests (Cohen et al., 2018).

It also allows findings to be generalized to similar industrial gas environments.

3.4.3. Sampling Method & Techniques

A stratified random sampling method is applied to ensure representation across key organizational levels (Saunders et al., 2019). the population is divided into strata based on job functions—operations, maintenance, reliability, and administration—to guarantee proportional inclusion. within each stratum, simple random sampling is used to select participants, providing every member an equal chance of being included (Creswell & Creswell, 2018). this two-stage sampling technique aligns with the positivist and quantitative research approach and enhances the objectivity, accuracy, and reliability of the collected data. moreover, it fits the cross-sectional design, allowing data collection at a single point in time for comparative analysis across different employee categories (Bryman, 2016).

3.5. Data Collection Method

The data collection process aims to obtain reliable and objective information that enables testing of the study hypotheses (Creswell, 2014).

Because the study adopts a quantitative, positivist, and cross-sectional design, data are gathered through a structured questionnaire divided into two sections:

- Section A – Reliability-Centered Maintenance (RCM): the Independent Variable (X)
- Section B – ASU Operational Performance (Productivity Levels): the Dependent Variable (Y)

Structured questionnaires ensure uniformity of responses, allow statistical comparison, and are widely used in engineering and maintenance management research (Saunders et al., 2019).

3.5.1. The Independent Variable (X): Reliability-Centered Maintenance (RCM)

The independent variable represents the structured maintenance philosophy adopted to enhance reliability and reduce equipment failures. data are collected using five-point Likert-scale items (1 = Strongly Disagree to 5 = Strongly Agree) covering key RCM dimensions such as task efficiency, maintenance reliability, and goal achievement.

Table 3.1 Independent Variable – Reliability-Centered Maintenance (RCM)

<i>Dimension</i>	<i>Indicators / Sample Items</i>	<i>Scale</i>	<i>Source(s)</i>
<i>Task Efficiency</i>	“Tasks are completed on time and meet required standards.”	1–5 Likert	Sekaran & Bougie (2019)
<i>Operational Reliability</i>	“Maintenance practices minimize unplanned equipment downtime.”	1–5 Likert	Bryman (2016)
<i>Output Performance</i>	“Overall output per labor hour has improved during the past year.”	1–5 Likert	Creswell (2014)
<i>Maintenance Response Time</i>	“Corrective maintenance requests are addressed promptly.”	1–5 Likert	Saunders et al. (2019)
<i>Goal Achievement (KPIs)</i>	“Productivity targets and key performance indicators are consistently achieved.”	1–5 Likert	Cohen et al. (2018)

All indicators will be statistically analyzed using descriptive and inferential techniques to evaluate how RCM implementation influences ASU operational performance.

3.5.2. The Dependent Variable (Y): ASU Operational Performance (Productivity Levels)

The dependent variable captures the overall productivity and performance outcomes of Air Separation Unit operations. it reflects how reliability-centered practices contribute to sustained equipment performance, production continuity, and cost efficiency. data are obtained using Likert-scale statements measuring operational reliability, responsiveness, and efficiency.

Table 3.2 Dependent Variable – ASU Operational Performance (Productivity Levels)

<i>Dimension</i>	<i>Indicators / Sample Items</i>	<i>Scale</i>	<i>Source(s)</i>
<i>Equipment Reliability</i>	“The frequency of equipment breakdowns has decreased.”	1–5 Likert	He et al. (2021)
<i>Production Continuity</i>	“Plant uptime and availability meet operational targets.”	1–5 Likert	Creswell & Creswell (2018)
<i>Maintenance Response Time</i>	“Maintenance issues are resolved quickly with minimal production delays.”	1–5 Likert	Sekaran & Bougie (2019)
<i>Energy Efficiency / Cost Performance</i>	“Maintenance practices contribute to reduced operating costs and energy losses.”	1–5 Likert	Cohen et al. (2018)
<i>Overall Output Performance</i>	“ASU production performance has improved due to enhanced maintenance reliability.”	1–5 Likert	Bryman (2016)

The data collected from both sections will provide quantitative evidence on the strength and direction of the relationship between Reliability-Centered Maintenance and ASU operational Performance using correlation and regression analyses.

3.6. Types of Data

This study utilizes both primary and secondary data sources to ensure the validity, reliability, and comprehensiveness of findings (Saunders et al., 2019).

Using a combination of data types strengthens the study’s analytical foundation and enables triangulation between the empirical evidence collected from ASU personnel and the contextual insights drawn from existing literature (Creswell, 2014).

3.6.1. Primary Data

Primary data refer to information gathered directly from respondents for the specific purpose of this study (Sekaran & Bougie, 2019).

In this research, the primary data are obtained through a structured questionnaire distributed to

engineers, technicians, and managers working in Air Separation Unit (ASU) operations and maintenance. the questionnaire includes quantitative Likert-scale items designed to measure the main study variables:

- Reliability-Centered Maintenance (RCM) – the independent variable
- ASU Operational Performance (Productivity Levels) – the dependent variable

The structured format ensures consistency, reliability, and objectivity of responses, allowing for meaningful statistical analysis (Creswell & Creswell, 2018). all responses are coded numerically and analyzed using descriptive and inferential statistical methods such as correlation and regression analysis to determine the relationship between the two variables.

3.6.2. Secondary Data

Secondary data consist of information obtained from previously published or recorded sources for this study, secondary data are used to support the interpretation and validation of primary findings. they include:

- Academic journals and research articles on Reliability-Centered Maintenance (RCM), productivity improvement, and industrial reliability practices (e.g., He et al., 2021; Afefy et al., 2010).
- Textbooks and reference materials on research methodology and maintenance management (e.g., Saunders et al., 2019; Bryman, 2016).
- Company reports and technical documents, where applicable, to provide contextual insights into ASU performance metrics and maintenance trends.

Using secondary data enhances the credibility of the research by allowing comparisons between empirical results and established theoretical frameworks, while also ensuring that the study is grounded in existing knowledge (Cohen et al., 2018).

3.7. Statistical Analysis Procedures

The data collected through the structured questionnaire will be subjected to quantitative statistical analysis to examine the relationship between Reliability-Centered Maintenance (RCM) practices and ASU Operational Performance (Productivity Levels). This process follows a systematic approach involving data preparation, descriptive analysis, and inferential statistical testing, ensuring that findings are valid, reliable, and aligned with the study's positivist philosophy (Saunders et al., 2019).

3.7.1. Data Preparation and Coding

Prior to analysis, all responses from the structured questionnaire are screened, coded, and entered into statistical software such as SPSS or Excel. Each Likert-scale item is assigned a numerical code (1 = Strongly Disagree to 5 = Strongly Agree). data cleaning procedures—such as checking for missing values, outliers, and inconsistent responses—are conducted to ensure accuracy and completeness (Creswell & Creswell, 2018). reliability testing using Cronbach’s Alpha is applied to assess the internal consistency of questionnaire items for both independent and dependent variables.

3.7.2. Descriptive Statistical Analysis

Descriptive statistics provide an overview of the dataset, summarizing respondents’ demographic characteristics and central tendencies of each variable. measures such as mean, standard deviation, and frequency distribution are used to describe how participants perceive the implementation of RCM and its effect on operational performance. these descriptive insights establish a contextual understanding before hypothesis testing (Sekaran & Bougie, 2019).

3.7.3. Inferential Statistical Analysis

Inferential statistics are employed to test the hypotheses and determine the strength and significance of relationships between RCM and ASU operational Performance.

The following analytical procedures will be applied:

<i>Analysis Technique</i>	<i>Purpose / Application</i>	<i>Expected Output</i>
<i>Correlation Analysis (Pearson’s r)</i>	Examines the strength and direction of association between RCM practices and operational performance dimensions.	Correlation coefficients (r) and significance values (p).
<i>Regression Analysis</i>	Determines the predictive effect of RCM on ASU performance and identifies which RCM dimensions significantly influence productivity.	Regression coefficients (β), R^2 values, and p-values.

<i>Reliability Test (Cronbach's Alpha)</i>	Evaluates the internal consistency of questionnaire constructs.	Alpha > 0.70 = acceptable reliability.
<i>ANOVA / t-tests (if applicable)</i>	Compares differences in responses among groups (e.g., departments, job levels).	F-statistics, mean comparison, significance levels.

These statistical tools are appropriate for quantitative, deductive, and cross-sectional research design, enabling hypothesis testing and model validation through objective numerical evidence (Bryman, 2016; Cohen et al., 2018).

3.7.4. Transition to Data Analysis

The outcomes of these statistical analyses will be presented and interpreted in Chapter 4, where both descriptive and inferential results will be discussed to validate the proposed hypotheses and assess the effect of Reliability-Centered Maintenance on ASU operational performance.

3.8. Conclusion

This chapter presented a comprehensive overview of the research methodology employed to examine the relationship between Reliability-Centered Maintenance (RCM) and Air Separation Unit (ASU) Operational Performance (Productivity Levels). It outlined the philosophical foundation, methodological approach, and research design adopted for this quantitative, positivist, and cross-sectional study.

The chapter detailed the research onion framework, justifying each methodological choice — including the positivist philosophy, deductive approach, survey strategy, quantitative data collection, and cross-sectional time horizon — all of which are aligned with the study's objectives and hypotheses.

It further described the target population, sampling methods, and the structured questionnaire used to collect primary data from ASU professionals across operational, maintenance, and managerial roles.

Data collection focused on two key variables: RCM practices (independent variable) and ASU operational performance (dependent variable). Both were measured using standardized Likert-scale instruments, allowing for quantitative analysis through descriptive and inferential statistical procedures, including correlation, regression, and reliability testing. Additionally, the integration of secondary data from scholarly literature supported the contextual grounding and validation of findings.

Overall, this methodological framework ensures that the research is scientifically rigorous, logically structured, and aligned with the objectives of determining how the implementation of RCM influences the operational productivity of ASU facilities. The next chapter, Chapter 4 – Data Analysis and Results, will present the findings derived from the statistical analysis of the collected data and evaluate them in relation to the stated research hypotheses.

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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>Alsyouf (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>