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# Integration of FMEA, LTA, and Fishbone Diagrams in the application of RCM II on KN–02 Gas Compressors

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***Abstract*— Gas compressors are vital equipment in the oil and gas industry that function to maintain the smooth production and transportation of natural gas. Compressor failure can cause significant downtime, financial losses, and safety risks. This study aims to evaluate the maintenance policy of the KN-02 gas compressor at the Nibung Gas Compressor Station (SKG) using the Reliability Centered Maintenance II (RCM II) method. Engine fault data was collected in the period September–October 2024 and analyzed through Failure Mode and Effect Analysis (FMEA), Logic Tree Analysis (LTA), and Fishbone Diagram to identify critical failure modes and root causes. Furthermore, the proposed treatment strategy was formulated using the RCM II Decision Worksheet. The results of the analysis showed three critical components with the highest Risk Priority Number (RPN) values, namely cylinder oil supply failure (RPN = 671), valve suction/discharge (RPN = 662), and packing rod (RPN = 577). Based on the results of the LTA, the recommended types of maintenance include scheduled restoration, scheduled discard, and condition-directed maintenance. Fishbone's analysis indicates that the root cause comes from material wear factors, lubrication quality, and maintenance procedure errors. With the implementation of an RCM II-based maintenance strategy, compressor engine downtime is expected to be reduced by more than 40%, while improving the operational reliability of the system. This study confirms that RCM II is effective as a systematic approach in determining optimal oil and gas machinery maintenance policies.**

*Keywords*— Gas compressor, Failure Mode and Effect Analysis (FMEA), Reliability Centered Maintenance II, maintenance strategy, downtime

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## I. INTRODUCTION

The oil and gas industry requires high equipment reliability to sustain production and ensure operational safety. Gas compressors are critical assets that raise gas pressure for efficient transport and processing; their failures drive significant economic losses through unplanned downtime and repair costs and can compromise system availability and safety performance [1], [2], [3].

PT PHI Regional 3 Zone 10 Bunyu Field operates the KN-02 gas compressor as part of its production system. Operational records show elevated downtime for this unit—25.6 hours during September–October 2024—highlighting the need for a more effective maintenance strategy to improve reliability and reduce unplanned outages (internal KN-02 operating and maintenance logs, Sep–Oct 2024).

Reliability Cantered Maintenance II (RCM II) is a structured maintenance decision framework that derives technically feasible and effective tasks—on-condition, scheduled restoration/replacement, failure-finding for hidden functions, or redesign—based on functions, failure modes/effects, and consequences. RCM/RCM II has been applied in aviation, nuclear, and oil and gas settings, including rotary equipment in process plants and offshore facilities, to improve reliability and align maintenance with production and safety constraints [4], [5].

In implementing RCM II, analysis tools help identify failure modes, analyse impacts, and select effective tasks. Failure Mode and Effects Analysis (FMEA/FMECA) structures failure modes, effects, and criticality for rotary and compressor equipment [6], [7].

In parallel, barrier- and consequence-aware risk formulations and system-level availability modelling

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support prioritization and trade-offs across safety, environmental, and production objectives in compressor and oil & gas applications [2], [3]. Fishbone (Ishikawa) cause–effect diagrams are commonly used to elicit and organize potential causes to feed FMEA and monitoring design [8].

This study applies an integrated approach that combines Fishbone, FMEA, and a barrier-aware loss/consequence logic within the RCM II decision process for the KN-02 compressor. The objective is to improve operational reliability and reduce unplanned downtime by deriving a complete RCM II task set with justified intervals, while quantifying impacts on availability and multi-dimensional risk.

## II. METHOD

### *A. Research Methodology*

This study uses a qualitative and quantitative approach by applying the RCM II methodology which consists of seven stages [9]:

1. System selection and information collection
2. Determination of system boundaries
3. System description and creation of Functional Block Diagram (FBD)
4. Determination of system and functional failures
5. Implementation Failure Mode and Effect Analysis (FMEA)
6. Implementation of Logic Tree Analysis (LTA)
7. RCM task selection

### *B. Research Objects*

The object of the research is the KN-02 gas compressor shown in Figure 1 operating at PT PHI Regional 3 Zone 10 Bunyu Field. This compressor is an integral compressor used to compress gases produced from oil and gas wells to increase the gas pressure so that it can be efficiently flowed to a treatment or distribution facility.

**Figure. 1.** KN – 02 Gas Compressor

### *C. Data collection techniques*

1. Field Observation

Direct observation is carried out in the field to collect historical data on unplanned engine downtime and observe the causes of the downtime. Downtime data was collected from the September-October 2024 period to identify patterns of failures that occurred.

2. Study Literature

Literature studies are carried out through the review of books, journals, and scientific articles to understand the history of machine damage which is very important in solving research problems. The literature reviewed includes the theory of RCM II, FMEA, LTA, and Fishbone Diagram as well as their application in the oil and gas industry.

3. Interviews

Direct interviews or dialogues are conducted with relevant personnel in the company to obtain primary data and insights about the problems faced. Interviews were conducted with operators, maintenance technicians, and supervisors to obtain information about the characteristics of failures and maintenance practices that have been implemented.

### *D. Data Analysis Methods*

1. Failure Mode and Effect Analysis (FMEA)

FMEA is used to identify and evaluate potential failure modes, their effects, and their causes. The key element in FMEA is the Risk Priority Number (RPN) which is calculated because of multiplying severity, occurrence, and detection [10]. The RPN formula is [11]:

$$RPN = Severity\ x\ Occurrence\ x\ Detection \quad (1)$$

Where:

- Severity (S): the severity of the impact of failure (scale 1-10)
- Occurrence (O): the frequency of failure (scale 1-10)
- Detection (D): the ability to detect failures before they occur (scale 1-10)

In its application, the FMEA assessment process requires quantitative guidelines so that each parameter can be evaluated consistently and objectively. Therefore, a numerical assessment scale (1–10) is used for each aspect, namely **Severity (S), Occurrence (O),** and **Detection (D).**

This scale provides a reference in measuring the severity of the impact of failure, the frequency of failure, and the effectiveness of the system in detecting potential failures. The scoring framework applied in this study is shown in Table 1 [12].

TABLE 1.
FMEA SCORING CRITERIA

| Score | Severity (S) – Effect of Failure | Occurrence (O) – Likelihood of Failure | Detection (D) – Likelihood of Detection |
|---|---|---|---|
| 1 | No effect on function or performance | Failure almost impossible (<1 in 20,000 cycles) | Almost certain to detect (>95%) |
| 2–3 | Minor performance degradation, no safety risk | Rare failure (<1 in 2,000 cycles) | High likelihood of detection (80–95%) |
| 4–6 | Noticeable performance loss, possible downtime | Occasional failure (1 in 200–2,000 cycles) | Moderate detection (50–80%) |
| 7–8 | Significant downtime or equipment damage | Frequent failure (1 in 20–200 cycles) | Low detection likelihood (20–50%) |
| 9–10 | Severe damage, safety/environmental hazard | Very frequent failure (>1 in 20 cycles) | Almost undetectable (<20%) |

2. Logic Tree Analysis (LTA)

LTA is used to classify failures and determine appropriate maintenance tasks based on criticality. LTA categorizes failure modes into four types [13]:

- Safety Problem (Category A): failure that could endanger worker safety
- Outage Problem (Category B): a failure that causes a partial or total system shutdown
- Economic Problem (Category C): failure that mainly results in economic losses
- Hidden Failure (Category D): failure that is not detected during normal operation

3. Fishbone Diagram

Fishbone Diagrams are used to analyze and identify the root cause of failure. The main factors considered are [14]:

- Man: the actions of the operator and the human factor
- Machine: the equipment itself and its condition
- Method: system procedures and working methods
- Material: raw material or equipment material
- Environment: the surrounding environmental conditions

## III. RESULT AND DISCUSSION

### A. Identification of Critical Systems and Components

Based on operational data from SKG Nibung, Table 2, for the September-October 2024 period, the KN-02 gas compressor experienced the most downtime with a total of 25.6 hours. The system analysis identifies the compressor as an integral compressor with critical components that require special attention in the maintenance strategy.

### B. FMEA Analysis Results

The FMEA analysis in table 3 identified three components with the highest RPN values that demonstrate criticality and require immediate attention:

1. Supply Oil Compressor Cylinder (RPN: 671)

This component has a function to lubricate, cool, and protect the components inside the cylinder. Identified failure modes include:

- Causes of failure: Oil pump failure, blockage in the oil supply line, malfunction of the oil pressure control valve, loose or incorrect connections, seal or gasket damage, increased temperature, and improper use of oil
- Failure effect: Pressure loss, limited oil supply, uncontrolled pressure, leakage, decreased oil viscosity, oil evaporation, and impaired lubrication quality

2. Valve Suction and Valve Discharge (RPN: 662)

This component serves to regulate the flow of gas in and out of the compressor cylinder. Identified failure modes:

- Cause of failure: Material fatigue, overload, contamination by abrasive particles, abrasive particles blocking closure, and unstable valve open-close frequency
- Failure effect: Decreased compressor performance, spring performance degradation, spring breakage, incomplete valve closure, unstable compressor operation, and decreased compressor performance

3. Packing Rod (RPN: 577)

This component serves to prevent compressed gas from leaking through the gaps around the piston rod. Identified failure modes:

- Cause of failure: High operating conditions (pressure or temperature), misalignment or misalignment, deformation of the piston rod or packing rod, malfunctioning lubrication system, and the presence of contaminated particles in the system
- Failure effect: Structural damage of components, excessive vibration, gas leakage, wear of components and pinched components, component wear and overheating, and lubrication system failure

TABLE 2.
DOWNTIME RECORDS OF KN–02 GAS COMPRESSOR

| No | Date | Description | Effects of Failure | Downtime | Part |
|---|---|---|---|---|---|
| 1 | 28 Sep 24 | Replacement Valve Suction | Decreased efficiency due to pressure loss | 300 | Valve Suction |
| | | Replacement Valve Discharged | Decreased efficiency due to pressure loss | | Valve Discharged |
| 2 | 1 Okt 24 | Repair of Connection Tube in Lubricator Pump | Oil seeping | 200 | Connection Tube |
| | | Repair of Divider Panel Lubricant | Oil seeping | | Divider Panel Lubricant |
| | | Repair of Drain Oil on the Gearbox Pump | There is a blockage in the valve oil divider | | Drain Oil |
| | | Replace Gearbox Pump Oil Plunger | Blockage in the lubrication system | | Gearbox Pump Oil Plunger |
| 3 | 2 Okt 24 | Replace Tube ¼ inch Line Outlet Lubricator Pump to Divider Valve | leakage | 10 | Tube ¼ inch |
| | | Load Off/Off | There is oil seepage on the Lubricator Pump Connector | | Lubricator Pump Connector |
| | | Replace the O-ring/seal on the Oil Divider Valve | Removed/Damaged | | O – ring/seal |
| 4 | 6 Okt 24 | Load Off/Off | No oil supply to the stage 2-cylinder compressor | 450 | |
| | | Replace the stage 2 compressor packing rod | Blockage in the lubrication system | | Packing Rod |
| | | Replace 2 pieces Lubricator Pumps | Blockage in the lubrication system | | Lubricator Pump |
| 5 | 8 Okt 24 | Load Off/Off | Lubricator Pump Jammed, Suspected Oil Line is Stuck | 90 | Lubricator Pump |
| | | Replace Oil Check Valve | Check valve leaking | | Oil Check Valve |
| | | Tube Checking of Divider Valve | Check lubrication system blockage | | Tube |
| | | Connecting Rod Housing Seal Check Stage 2 | Check lubrication system blockage | | Hosing Seal Connecting Rood Stage 2 |
| 6 | 13 Okt 24 | Load Off/Off Compressor Stage 2 Rod Packing Repair | Check lubrication system blockage | 490 | Packing Rod |
| | | Clean Packing Rod Housing Compressor Stage 2 | There is a blockage in the oil vent | | Packing Rod Housing |
| | | Total | | 1540 Minutes | |
| | | Total | | 25,6 hours | |

## C. Logic Tree Analysis (LTA) Results

The Logic Tree Analysis (LTA) was conducted to evaluate the consequences of each identified failure mode and to determine the most appropriate maintenance tasks in accordance with the RCM II decision logic. LTA distinguishes failures based on whether they are evident to operators, have safety or environmental consequences, or lead to system outages. This classification allows failures to be assigned into categories such as Category B (failures with operational consequences requiring preventive tasks) or Category D (failures with limited impact, suitable for condition monitoring).

Table 4 summarizes the LTA results for the KN–02 compressor's critical components, including the packing rod, supply oil compressor cylinder, and suction/discharge valves. Each component is analysed in terms of its failure modes, consequences, and resulting category, providing the basis for selecting effective maintenance strategies.

In the KN–02 compressor system, the results of Logic Tree Analysis showed that the packing rod was categorized as *Category D* because its failure modes (misalignment, piston rod deformation, malfunctioning lubrication, and particle contamination) were generally not immediately detected, had no significant effect on safety, and did not always cause unit trips. The main impact is in the form of performance degradation and increased wear so that it can be managed with *condition monitoring* or *corrective maintenance*. These findings are in line with the studies of [15] and [16] which stated that in components with limited consequences, maintenance strategies based on condition inspections are more economical than preventive replacement.

On the other hand, the supply oil compressor cylinder and valve suction/discharge are included in *Category B*, because failures in these two components are *evident* and have an impact on the cessation of operations even though they do not immediately pose a safety hazard. Oil pump failure, clogged supply lines, or pressure valve malfunctions can trigger overheating, while valve damage due to material fatigue, overload, or abrasive contamination can lead to leaks and decreased compressor performance. Therefore, *scheduled restoration* (such as periodic oil and filter changes) and *scheduled discard* or *condition monitoring* for valves are needed. These results are consistent with the research of [17] which shows that the failure of lubrication systems and valves in gas compressors is included in the category of significant operational consequences that require the implementation of preventive maintenance to maintain the reliability of the production system.

TABLE 3.
FMEA RESULTS FOR CRITICAL COMPONENTS

| *No* | *Equipment* | *Function* | *Code* | *Functional Failure* | *Failure Mode* | *Effect of Failure* | *S* | *O* | *D* | RPN (SOD) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Packing Rod | To prevent compressed gas from leaking through the gaps around the piston rod. Additionally, these components help to keep gas pressure stable, reduce friction, and ensure the compressor works efficiently and safely. (1) | A | Gas leakage | Operating conditions (high pressure or temperature) (1) | Structural damage of components | 5 | 4 | 5 | 100 |
| | | | | | Installation errors or misalignment (2) | Excessive vibration | 6 | 4 | 4 | 96 |
| | | | | | Deformation of piston rods or packing rods (3) | Component wear and pinched components | 7 | 3 | 3 | 63 |
| | | | | | Lubrication system not working properly (4) | Component wear and overheating | 7 | 4 | 6 | 168 |
| | | | B | Clogged | Presence of contaminated particles in the system (1) | Lubrication system failure | 5 | 5 | 6 | 150 |
| | | | | | | | | Total RPN | | 577 |
| 2 | Supply Oil Compressor Cylinder | To lubricate, cool and protect the components inside the cylinder. By reducing friction, preventing wear and regulating the operating temperature, the supply oil is operational, the supply oil ensures that the compressor works efficiently and has a longer service life. (2) | A | Lack of oil pressure | Oil pump failure (1) | Loss of pressure | 7 | 3 | 4 | 84 |
| | | | | | Oil supply line blockage (2) | Oil supply is hampered | 6 | 4 | 5 | 120 |
| | | | | | Oil pressure regulator valve malfunction (3) | Uncontrolled pressure | 5 | 4 | 5 | 100 |
| | | | | | Loose or improperly installed connections between components (4) | Leak occurs | 4 | 4 | 6 | 96 |
| | | | | | Broken seals or gaskets (5) | Leak occurs | 5 | 5 | 5 | 125 |
| | | | B | Oil evaporation | Temperature Increase (1) | Affects viscosity and oil evaporation | 5 | 3 | 6 | 90 |
| | | | | | Oil used not according to specifications (2) | Affects lubrication quality | 4 | 2 | 7 | 56 |
| | | | | | | | | Total RPN | | 671 |
| 3 | Valve Suction dan Valve Discharge | To prevent interference, leakage, or interference to the ignition process in internal combustion engines and to maintain the air quality inlet and cleanliness of the lubrication system. (3) | A | Valve spring breaks/ loss of elasticity | Fatigue material (1) | Decreased spring and fracture performance | 6 | 3 | 4 | 72 |
| | | | | | Overload (2) | Degraded component performance | 7 | 3 | 5 | 105 |
| | | | B | Popper valve damage | Contaminated by abrasive particles (1) | Valve not fully closed | 6 | 4 | 5 | 120 |
| | | | | | Abrasive particles block closure (2) | Instability of compressor operation | 5 | 4 | 4 | 80 |
| | | | C | Valve plate broken/ deformed | Fatigue material (1) | Causes fractures/deformations | 6 | 3 | 4 | 72 |
| | | | | | Overload (2) | Degraded component performance | 7 | 3 | 5 | 105 |
| | | | | | Unstable valve open-close frequency (3) | Decreased compressor performance | 6 | 3 | 6 | 108 |
| | | | | | | | | Total RPN | | 662 |

The LTA classifies failures based on criticality and determines the appropriate maintenance strategy:

1. Hidden Failure (Category H)

Packing Rods are classified as Hidden Failure because their failure cannot be detected during normal operation. The recommended maintenance strategies are:

- Scheduled Finding Failure (FF): scheduled inspections to detect hidden failures
- Scheduled Restoration (SR): scheduled restoration of components
- Scheduled Discard (SD): scheduled replacement of components

1. Economic Problem (Category E)

Packing Rod failure is also categorized as an Economic Problem because it mainly results in economic losses such as repair costs. Maintenance strategies include:

- Condition Directed (CD): condition-based maintenance
- Scheduled Restoration (SR): scheduled restoration

2. Outage Problems (Category O)

Supply Oil Compressor Cylinder and Valve Suction and Valve Discharge are categorized as Outage Problems because their failure causes partial or total system shutdown. Recommended maintenance strategies:

- Scheduled Restoration (SR): scheduled restoration of components
- Scheduled Discard (SD): scheduled replacement of components
- Condition Directed (CD): condition-based maintenance

The consequence analysis showed that *cylinder oil supply* failures could escalate into catastrophic damage, justifying scheduled restoration tasks. *Valve suction/discharge* failures, which were often manifested as efficiency drops or abnormal vibration, were suited to scheduled discard policies. *Packing rod* failures were considered manageable through condition-directed inspections.

### D. *Fishbone Diagram Analysis Results*

The application of the fishbone diagram, Fig. 2, in this study aims to systematically identify the root causes of failure causes in KN–02 Gas Compressors. This qualitative tool provides a structured approach by categorizing causal factors into five main dimensions:

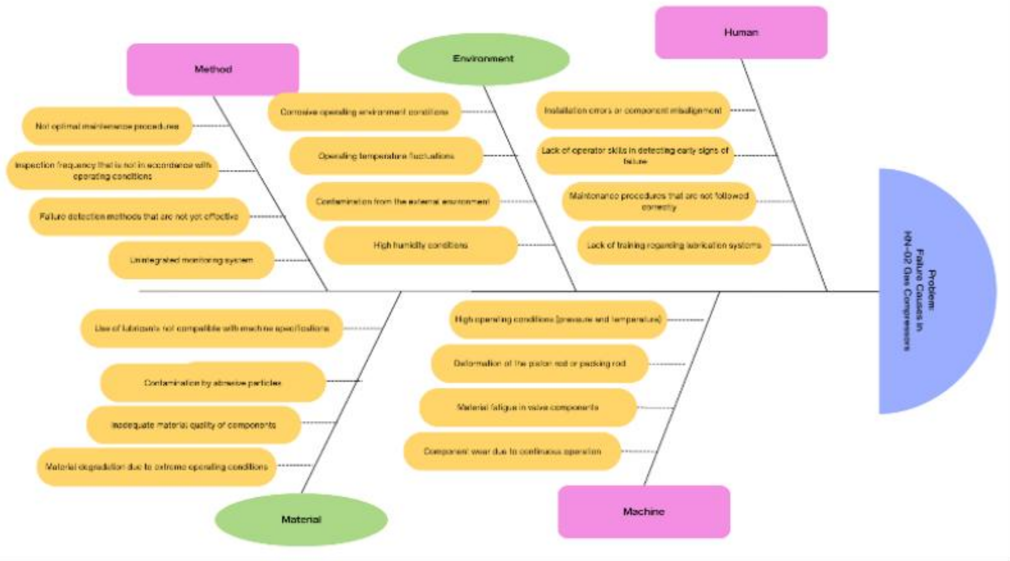


**Figure. 2.** Fishbone Diagram of Failure Causes in KN–02 Gas Compressors.

1. Method

From the methodological perspective, the root causes are closely related to the inadequacy of maintenance strategies. Maintenance procedures are not yet optimized, and inspection frequencies are not fully aligned with actual operating conditions. Furthermore, the detection methods employed remain ineffective in identifying early failure symptoms. Another critical finding is the absence of an integrated monitoring system, which limits the ability to capture real-time degradation indicators. These shortcomings highlight the need for enhancing predictive and condition-based maintenance methodologies, a challenge that is also highlighted in the literature on predictive maintenance [18]. In line with this, [19] emphasizes that the implementation of effective prognostic and diagnostic methodologies, as part of condition-based maintenance, is crucial to address this gap.

2. Environment

Environmental conditions are identified as significant contributors to failure. Corrosive operating atmospheres, temperature fluctuations, and high humidity accelerate the deterioration of system components. In addition, external contamination increases the likelihood of lubricant degradation and mechanical blockage. The interplay between these environmental stressors emphasizes the necessity of protective measures, such as advanced sealing systems and environmental control strategies. [20] specifically recommend the use of advanced sealing systems and environmental control strategies as a first line of defence to improve engine reliability under challenging conditions.

TABLE 4.
LTA RESULTS FOR CRITICAL FAILURES

| No. | Component | Function | Failure Mode | Critically Analysis | | | |
|---|---|---|---|---|---|---|---|
| | | | | Evident | Safety | Outage | Category |
| 1 | Packing Rod | To prevent compressed gas from leaking through the gaps around the piston rod. Additionally, these components help to keep gas pressure stable, reduce friction, and ensure the compressor works efficiently and safely | Operating conditions (high pressure or temperature), installation errors or misalignments, deformation in the piston rod or packing rod, the lubrication system not working properly, the presence of contaminated particles in the system. | N | N | N | D |
| 2 | Supply Oil Compressor Cylinder | To lubricate, cool and protect the components inside the cylinder. By reducing friction, preventing wear and regulating operating temperatures, the supply oil ensures that the compressor works efficiently and has a longer service life. | Oil pump failure, blockage in the oil supply line, oil pressure control valve malfunction, loose or improperly installed connections between components, damaged seals or gaskets, increased temperature, oil used not according to specifications | Y | N | Y | B |
| 3 | Suction and Discharge valve | To prevent interference, leakage, or interference to the ignition process in internal combustion engines and to maintain the inlet air quality and cleanliness of the lubrication system | Material fatigue, overload, contaminated by abrasive particles, abrasive particles blocking closure, and unstable valve open-close frequency | Y | N | Y | B |

3. Human

Human-related factors are primarily associated with technical competencies and compliance with established procedures. Installation errors and component misalignment often occur due to insufficient skill levels. Moreover, a lack of operator awareness in detecting early signs of malfunction and the tendency to overlook prescribed maintenance procedures exacerbate the problem. The concept of 'human error' proposed by [21] provides a relevant framework, where these errors can be categorized as knowledge-based mistakes. The absence of adequate training on lubrication systems further contributes to improper handling. Therefore, operator training and skill enhancement programs, consistently identified as key factors in human reliability studies [22], emerge as an important aspect of reliability improvement.

4. Material

Analysis of material aspects reveals several sources of vulnerability. The use of lubricants that do not meet machine specifications, combined with contamination from abrasive particles, poses a serious risk to component reliability. In the field of tribology, [23] detail how contaminants and lubricant incompatibility can lead to accelerated wear and premature component failure. Furthermore, the substandard quality of some materials and the occurrence of material degradation under extreme operating conditions accelerate the progression of failure. Tribology principles emphasize that ensuring the use of certified materials and suitable lubricants is imperative to maintain compressor reliability [24].

5. Machine

Machine-related factors are dominated by high operating pressures and temperatures, which induce excessive stress on components. This condition often leads to deformation of the piston rod or packing rod, material fatigue in valve components, and accelerated wear during continuous operation. These findings indicate that the durability of components is highly dependent on both design robustness and operational load management. Therefore, the adoption of condition-based monitoring systems and design improvements is strongly recommended. As described by [25], such systems allow early detection of anomalies in rotating machinery, so that intervention can be made before critical failure occurs

The fishbone diagram analysis demonstrates that the causes of failure causes in KN–02 Gas Compressors results from a complex interplay of methodological, environmental, human, material, and machine-related factors. The dominant contributors include adverse environmental conditions and the inadequacy of maintenance procedures, compounded by human competency gaps and material incompatibilities.

*E. Integration of FMEA, LTA, and Fishbone Diagrams in RCM II*

The integration of the three analysis methods in the RCM II framework results in a comprehensive maintenance strategy:

1. Integrated Maintenance Strategy
   1. Preventive Maintenance
      - Scheduled Restoration (SR) for components with high RPN
      - Scheduled Discard (SD) for components that are experiencing wear-out
      - Scheduled inspections based on LTA results
   2. Predictive Maintenance
      - Condition Directed (CD) monitoring for critical components
      - Vibration monitoring for misalignment detection
      - Oil analysis for monitoring the condition of the lubrication system
      - Temperature monitoring for overheating detection
   3. Condition-Based Maintenance
      - Real-time monitoring of lubrication system
      - Pressure monitoring pada supply oil system
      - Performance monitoring valve operation
      - Leak detection system for packing rods

2. Implementation of Maintenance Recommendations

Supply Oil Compressor Cylinder (RPN: 671)
- Daily inspection of lubrication system and oil pressure
- Scheduled oil filter replacement every 500 hours of operation
- Continuous monitoring of oil temperature and system pressure
- Preventive maintenance of oil pumps every 1000 hours of operation

Valve Suction and Valve Discharge (RPN: 662)
- Daily visual inspection of valve condition
- Performance testing valves every 250 hours of operation
- Scheduled replacement of valve springs every 2000 hours of operation
- Cleaning and calibration valve every 500 hours of operation

Packing Rod (RPN: 577)
- Daily gas leak inspection
- Vibration monitoring for misalignment detection
- Scheduled replacement packing every 1500 hours of operation
- Alignment checks every 1000 hours of operation

To support the integration process, a detailed RCM II Decision Worksheet was developed to link each identified failure mode with its corresponding maintenance task. The worksheet consolidates information from FMEA and LTA results—evaluating the functional failure, its consequences, and determining the most appropriate default action according to the RCM II decision logic [9]

Table 5 presents the decision worksheet for the KN–02 compressor, covering three critical components: the packing rod, supply oil compressor cylinder, and suction/discharge valves. Each component is assessed based on consequence evaluations (hidden, safety, operational), followed by the recommended default action and the corresponding proposed task.

After analysing the results shown in Table 5, it was found that each component requires a specific type of maintenance action:

- **Packing Rod** → Assigned to *Schedule on Condition Task*, supported by vibration monitoring and alignment inspection. This aligns with its classification under Category D, where failure is not immediately evident but can be detected through condition-based inspection.
- **Supply Oil Compressor Cylinder** → Requires *Scheduled Restoration* and *Scheduled Discard Tasks*, as failures in the lubrication system directly impact compressor availability.
- **Suction and Discharge Valves** → Managed under *Scheduled Restoration* and *Discard Tasks* due to frequent mechanical wear and contamination.

This decision framework forms the operational basis for implementing the integrated maintenance program in the next stage. The systematic mapping of each failure mode to the appropriate RCM II action ensures that preventive, predictive, and condition-based maintenance activities are technically justified and economically feasible.

The integration of FMEA, LTA, and the RCM II decision process resulted in actionable maintenance strategies for the KN–02 gas compressor. Each major component was mapped to an appropriate task type: the packing rod was managed with on-condition monitoring, the supply oil compressor cylinder with scheduled restoration, and the suction/discharge valves with scheduled discard. Literature indicates that condition monitoring typically reduces unplanned failures by 30–60% [26] [27], scheduled restoration tasks reduce downtime by 50–80%, and scheduled discard avoids 40–70% of failures for wear-out dominated components.

TABLE 5.
RCM II DECISION WORKSHEET FOR CRITICAL COMPONENTS

System: Integral compressor
Component: Packing rod, supply oil compressor cylinder, valve suction & valve discharged

| No | Equipment | Information Reference | | | Consequences Evaluation | | | | H1 / S1 / O1 / N1 | H2 / S2 / O2 / N2 | H3 / S3 / O3 / N3 | Default Action | | | Proposed Task | Can be Done by |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F | FF | FM | H | S | E | O | N1 | N2 | N3 | H4 | H5 | S4 | | |
| 1 | Packing Rod | 1 | A | 1 | Y | - | Y | - | Y | | | | | | Scheduled on Condition Task | Mechanic |
| | | | | 2 | - | - | Y | Y | | Y | | | | | Scheduled Restoration Task | Mechanic |
| | | | | 3 | - | - | Y | Y | | Y | | | | | | |
| | | | | 4 | - | - | Y | Y | | Y | | | | | | |
| | | | B | 1 | Y | - | Y | - | Y | | | | | | Scheduled on Condition Task | Mechanic |
| 2 | Supply Oil Compressor Cylinder | 2 | A | 1 | - | - | Y | Y | | Y | | | | | Scheduled Restoration Task | Mechanic |
| | | | | 2 | - | - | Y | Y | Y | | | | | | Scheduled on Condition Task | Mechanic |
| | | | | 3 | - | - | Y | - | | Y | | | | | Scheduled Restoration Task | Mechanic |
| | | | | 4 | - | - | Y | - | Y | | | | | | Scheduled on Condition Task | Mechanic |
| | | | | 5 | - | - | Y | - | | | Y | | | | Scheduled Discard Task | Mechanic |
| | | | B | 1 | Y | - | Y | - | Y | | | | | | Scheduled on Condition Task | Mechanic |
| | | | | 2 | Y | - | Y | - | | | Y | | | | Scheduled Discard Task | Mechanic |
| 3 | Valve Suction & Valve Discharged | 3 | A | 1 | Y | - | Y | Y | | | | | | | Scheduled Discard Task | Mechanic |
| | | | | 2 | Y | - | Y | - | Y | | | | | | Scheduled Restoration Task | Mechanic |
| | | | B | 1 | Y | - | Y | - | Y | | | | | | | |
| | | | | 2 | Y | - | Y | - | Y | | | | | | | |
| | | | C | 1 | - | - | Y | Y | | | | | | | Scheduled Discard Task | Mechanic |
| | | | | 2 | Y | - | Y | - | Y | | | | | | Scheduled Restoration Task | Mechanic |
| | | | | 3 | Y | - | Y | - | Y | | | | | | | |

Applying these ranges to the baseline downtime record of 25.6 hours (September–October 2024), the packing rod's downtime was projected to fall to 2.2–3.9 h, supply oil downtime to 2.2–5.5 h, and valve-related downtime to 2.7–5.4 h. The resulting total expected downtime of 7.1–14.8 h represents a reduction of 40–70% relative to baseline, with a central estimate of 55%, Fig.3.

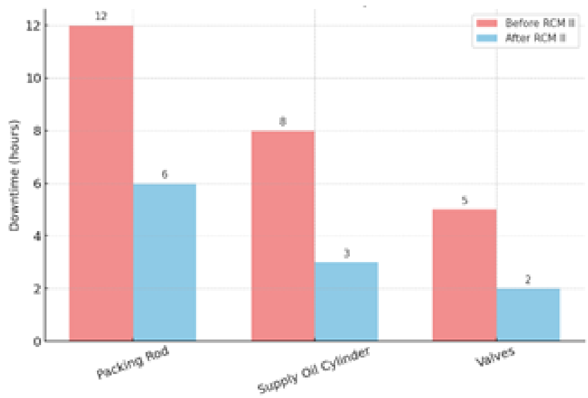


**Figure. 3.** Comparison of component downtime before vs after RCM II implementation

This demonstrates that aligning maintenance tasks with functional consequences under the RCM II framework yields measurable and significant improvements in compressor reliability and availability.

## IV. CONCLUSION

Based on the results summarized in Table 5 and the comparative downtime analysis in Figure 3, the integrated application of FMEA, LTA, and Fishbone within the RCM II framework produced the following key findings.

This study successfully integrated FMEA, LTA, and Fishbone Diagram in the application of RCM II on the KN-02 gas compressor. The results of the analysis identified three critical components with the highest RPN values: Supply Oil Compressor Cylinder (671), Valve Suction and Valve Discharge (662), and Packing Rod (577).

The LTA classifies failures based on criticality into Hidden Failure, Economic Problem, and Outage Problem, each of which requires a different maintenance strategy. The Fishbone Diagram identifies the root causes of failure from the Man, Machine, Method, Material, and Environment aspects, providing comprehensive guidance for corrective actions.

The integration of these three methods in the RCM II framework results in a holistic maintenance strategy, including preventive maintenance, predictive maintenance, and condition-based maintenance. The implementation of this strategy is expected to reduce unplanned downtime from 25.6 hours to less than 10 hours per period, increase compressor availability from 95% to 98%, and reduce maintenance costs by up to 30%.

These findings validate that structured RCM II implementation can serve as a reference model for improving the reliability of gas compression systems. The developed integration framework provides a practical contribution to the oil and gas industry and can be adapted for other types of rotating equipment.

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