

# Pneumatic System Reliability Enhancement Through Condensation Control in Railway Maintenance Equipment

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## ABSTRAK

Sistem pneumatik merupakan komponen vital dalam operasi peralatan pemeliharaan sarana dan prasarana perkeretaapian, terutama pada fungsi pengereman dan stabilisasi. Kondisi lingkungan tropis di Indonesia menyebabkan tingginya tingkat kelembapan sehingga memicu kondensasi pada sistem udara tekan, yang berdampak pada korosi, penurunan kinerja komponen, dan meningkatnya risiko kegagalan. Penelitian ini menganalisis mekanisme kegagalan komponen pneumatik pada ekskavator Geismar yang beroperasi di Balai Perawatan Perkeretaapian Ngrombo. Metode analisis yang digunakan meliputi Failure Mode and Effects Analysis (FMEA), penilaian Risk Priority Number (RPN), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), serta analisis SWOT untuk merumuskan mitigasi yang optimal. Hasil penelitian menunjukkan bahwa kondensasi merupakan penyebab dominan kegagalan dengan nilai RPN tertinggi pada komponen Convertisseur Pneumatique–Hydraulique (RPN = 378). Analisis TOPSIS mengindikasikan bahwa peningkatan frekuensi pemeliharaan merupakan solusi paling efektif (skor 0,7022), diikuti pemasangan air dryer. Rekomendasi penerapan sistem pengering udara dan optimasi interval pemeliharaan berpotensi menurunkan probabilitas kegagalan hingga 68% serta meningkatkan keandalan sistem dari 72% menjadi 94%. Temuan ini dapat menjadi acuan dalam penyusunan strategi pemeliharaan berbasis keandalan pada peralatan pemeliharaan perkeretaapian di lingkungan tropis.

*Kata Kunci: Sistem Pneumatik, Kondensasi, Air Dryer, Escavator Geismar, FMEA, TOPSIS.*

## ABSTRACT

*Pneumatic systems are critical components in the operation of railway maintenance equipment, particularly for braking and stabilization functions. The tropical climate in Indonesia, characterized by high humidity, increases the likelihood of condensation within compressed-air systems, leading to corrosion, performance degradation, and a higher risk of component failures. This study analyzes the failure mechanisms of pneumatic components in a Geismar excavator operated by the Railway Maintenance Depot in Ngrombo. The analytical methods used include Failure Mode and Effects Analysis (FMEA), Risk Priority Number (RPN) assessment, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and SWOT analysis to determine the most effective mitigation strategies. The results indicate that condensation is the dominant cause of failure, with the highest RPN observed in the Pneumatic–Hydraulic Converter (RPN = 378). The TOPSIS analysis reveals that increasing maintenance frequency is the most effective solution (score 0.7022), followed by the installation of an air dryer. The recommended implementation of air-drying systems and optimized preventive maintenance intervals is projected to reduce failure probability by up to 68% and increase pneumatic system reliability from 72% to 94%. These findings provide a technical basis for developing reliability-centered maintenance strategies for railway maintenance equipment operating in tropical environments.*

**Keywords:** *pneumatic system, condensation, air dryer, Geismar, FMEA, TOPSIS.*

## 1. INTRODUCTION

The pneumatic system in the Geismar excavator is a critical component for the operation of heavy equipment, particularly in the braking and stabilization systems. Pneumatic systems rely on compressed air as the primary medium, offering advantages such as efficiency and ease of maintenance [1]. However, in

tropical environments like Indonesia, high humidity levels often lead to condensation within the system, resulting in component failures, corrosion, and reduced performance [2]. Uncontrolled condensation can also cause blockages, which may impair or even eliminate braking functionality, posing significant risks to operational safety. This study aims to analyze the factors contributing to pneumatic component failures,

identify the impact of condensation, and evaluate the role of air dryers in enhancing system reliability.

The primary issues identified in this study include: (a) frequent malfunctions in the pneumatic system components of the Geismar excavator, (b) condensation within the pneumatic system, (c) reduced functionality of the braking and stabilization systems, and (d) the absence of air dryers in the pneumatic system [3]. These problems highlight the vulnerability of the system to environmental conditions and the need for effective solutions to prevent failures and ensure safety.

The research questions guiding this study are: (a) What are the common failures in the pneumatic system components of the Geismar excavator? (b) How does condensation affect the performance and reliability of the pneumatic system? (c) What is the role of air dryers in preventing condensation and maintaining system reliability? (d) What solutions can prevent pneumatic system component failures? Addressing these questions will provide a comprehensive understanding of the issues and potential solutions.

The objectives of this study are: (a) to analyze the failures in the pneumatic system components of the Geismar excavator, (b) to identify the impact of condensation on system performance, (c) to evaluate the effectiveness of air dryers in preventing condensation, and (d) to provide recommendations for improving system reliability and safety. By achieving these objectives, this study aims to contribute to the development of more reliable and safer pneumatic systems for heavy equipment operating in tropical environments.

A study conducted by Wawan Riyanta examined the application of Hazard Identification, Risk Assessment, and Control Determination (HIRADC) analysis for rolling stock body lifting activities at the Ngrombo Railway Maintenance Center. The research identified three primary hazards: crane toppling, equipment failure, and load falling, all carrying severe consequences including potential fatalities and significant property damage [4][5].

This study focuses on the pneumatic system of the Geismar excavator at the Ngrombo Railway Maintenance Center in Central Java. The research emphasizes the effects of condensation and the absence of air dryers, aiming to identify the root causes of component failures and provide actionable recommendations for improving the reliability and safety of the excavator. The findings of this study are expected to benefit not only the Ngrombo Railway Maintenance Center but also other similar operations in tropical regions facing comparable challenges.

In the context of railway operations, the reliability of maintenance equipment such as the Geismar excavator is critical, as braking or stabilization failures can directly affect work safety, especially in active track environments. Railway safety regulations require all on-track and near-track maintenance equipment to remain in a fully serviceable condition in accordance with maintenance standards for railway infrastructure and facilities. Therefore, an in-depth analysis of pneumatic system failures—particularly those driven by condensation—is essential to support the implementation of reliability-centered maintenance (RCM) practices within the Railway Maintenance Depot. This study aims to provide a technical basis for improving inspection procedures, component selection, and preventive maintenance strategies to enhance the operational safety and efficiency of railway maintenance equipment.

## 2. LITERATURE REVIEW

### 2.1 Overview Of The Geismar Excavator Pneumatic System

The Geismar excavator is a versatile heavy equipment machine used for railway maintenance, capable of operating on both flat terrain and railway tracks. It utilizes a pneumatic system for braking and stabilization, which relies on compressed air generated by a compressor driven by the excavator's main engine [3]. The system includes components such as the compressor, condensate separator, drain valve, regulating valve, and pressure relief valve [6]. However, the system is vulnerable to condensation due to high humidity in tropical climates, which can lead to corrosion and blockages, impairing system performance [4].

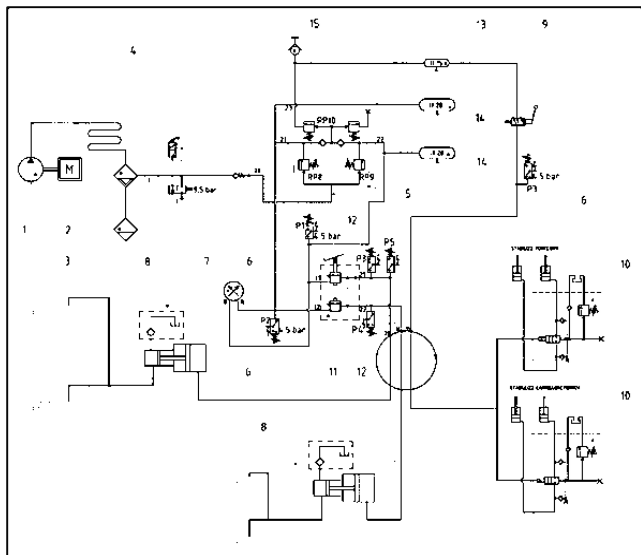


Figure 1. Diagram of the Geismar Excavator Pneumatic System

### 2.1 Condensation in Pneumatic Systems

Condensation is a significant issue in pneumatic systems, especially in high-humidity environments. When moist air is compressed, the water vapor condenses into liquid water, which can accumulate in the system [2]. This condensation can cause corrosion in metal components, blockages in air passages, and reduced efficiency of the system [4]. In the context of the Geismar excavator, condensation can impair the braking and stabilization systems, posing safety risks during operation.

Tabel 1. Components of the Geismar Excavator Pneumatic System

Position	Components	Qty.
1	<i>Compressor</i>	1
2	<i>Condensate Separator</i>	1
3	<i>Drain Valve</i>	1
4	<i>Regulating Valve</i>	1
5	<i>Pressure Relief Valve</i>	1
6	<i>Pressure Switch for Oil Filter Clogging</i>	3
7	<i>Air Pressure Gauge</i>	1
8	<i>Convertisseur Pneumatique – Hydraulique</i>	2
9	<i>Pedal Distributor</i>	1

Position	Components	Qty.
10	<i>Priority Valve</i>	2
11	<i>Brake Pedal</i>	1
12	<i>Pressure Switch for Oil Filter Clogging</i>	2
13	<i>Reservoir</i>	1
14	<i>Reservoir</i>	2
15	<i>Rapid Connection</i>	1

Pneumatic components in railway systems are governed by strict safety standards, including UIC 540 and UIC 541, which define the performance requirements of air brake systems and associated pneumatic components for rail vehicles and track maintenance equipment. Excessive moisture in the pneumatic system can impair braking response, increase stopping distance, and contribute to valve malfunction. Uncontrolled condensation also leads to internal corrosion in air reservoirs (EN 286), reduced measurement accuracy in pressure gauges (EN 837), and increased failure rates of actuators and control valves. These risks are further amplified in tropical regions such as Indonesia, where high relative humidity accelerates condensation formation. Consequently, moisture control measures—such as air dryers, automatic drain valves, and scheduled preventive maintenance—are essential to ensure the safety and reliability of railway maintenance operations.

### 2.2 Role Of Air Dryers In Pneumatic Systems

Air dryers are essential components in pneumatic systems for removing moisture from compressed air. They work by absorbing or adsorbing moisture, ensuring that dry air enters the system [7]. The use of air dryers can significantly reduce the risk of condensation, prevent corrosion, and extend the lifespan of pneumatic components. In the case of the Geismar excavator, the absence of an air dryer exacerbates the problem of condensation, leading to frequent component failures and reduced system reliability [8][9].

### 2.3 Maintenance And Failure Analysis

Regular maintenance is crucial for the reliability of pneumatic systems. Components such as the condensate separator, drain valve, and pressure relief valve must be inspected and maintained to prevent failures [1][10]. Failure Modes and Effects Analysis

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(FMEA) is a useful tool for identifying potential failure modes, their causes, and their effects on the system [11]. By analyzing the failure modes, maintenance strategies can be developed to mitigate risks and improve system performance[12][13].

### 3. METHODOLOGY

This study employs a combination of qualitative and quantitative methods to analyze the pneumatic system of the Geismar excavator. The research design is divided into three main subsections: data collection, data analysis, and solution evaluation.

#### 3.1. Data Collection

Data collection was conducted using a mixed-methods approach, combining structured interviews with operators and technicians, direct field observations of the Geismar excavator, and documentation analysis. Primary data were obtained from on-site inspections of pneumatic components, actual failure records, and environmental observations. Secondary data included maintenance logs, temperature and humidity data sourced from the Indonesian Meteorological Agency (BMKG), and the official technical manual for the Geismar unidade. This comprehensive approach ensures that the FMEA and RPN assessments reflect actual operating conditions in a tropical railway maintenance environment.[14], [15].

Secondary data is obtained from maintenance logs and environmental records provided by the Meteorology, Climatology, and Geophysics Agency. This data includes detailed records of component failures, maintenance schedules, and climate conditions such as humidity and temperature. The secondary data is used to validate the findings from the primary data and provide a comprehensive understanding of the system's performance over time.

#### 3.2. Data Analysis

The data analysis process involves the application of several analytical methods to evaluate the pneumatic system's performance and identify potential solutions. FMEA is applied to systematically identify potential failure modes, their causes, and their effects on the pneumatic system. This method focuses on evaluating the severity, occurrence, and detection of failures to prioritize risks and guide maintenance [11].

The RPN is calculated for each failure mode by multiplying the severity, occurrence, and detection scores. This quantitative measure helps prioritize the risks associated with different components, such as the

Convertisseur Pneumatique-Hydraulique and Condensate Separator, and guides the development of mitigation strategies [16].

$$RPN = S \times O \times D \tag{1}$$

where,

- S : Severity (1–10 Scale)
- O : Occurrence (1–10 Scale)
- D : Detection (1–10 Scale)

TOPSIS is used to evaluate and rank potential solutions based on multiple criteria, such as cost, effectiveness, ease of implementation, and impact on system reliability. This method helps determine the best solution by comparing the alternatives' proximity to the ideal solution [17].

$$D_i^+ = \sqrt{\sum_{j=1}^n w_j \cdot (x_{ij} - A_j^+)^2} \tag{2}$$

$$D_i^- = \sqrt{\sum_{j=1}^n w_j \cdot (x_{ij} - A_j^-)^2} \tag{3}$$

where,

- $D_i^+$  : Euclidean distance of alternative  $i$  to the positive ideal solution ( $A^+$ ).
- $D_i^-$  : Euclidean distance of alternative  $i$  to the negative ideal solution ( $A^-$ ).
- $w_j$  : Weight of criterion  $j$ .
- $x_{ij}$  : Value of alternative  $i$  on criterion  $j$ .
- $A_j^+$  : Value of the positive ideal solution on criterion  $j$ .
- $A_j^-$  : Value of the negative ideal solution on criterion  $j$ .
- $n$  : Number of criteria.

$$CC_i = \frac{D^-}{D^+ + D^-} \tag{4}$$

where,

- $CC_i$  : Closeness Coefficient
- $D^+$  : Euclidean distance of alternative to the positive ideal solution ( $A^+$ ).
- $D^-$  : Euclidean distance of alternative to the negative ideal solution ( $A^-$ ).

The solution evaluation process involves assessing the effectiveness of proposed solutions using the TOPSIS method. The solutions are evaluated based on four criteria: (C1) cost of implementation, (C2) effectiveness in reducing condensation, (C3) ease of implementation, and (C4) impact on system reliability. These criteria are weighted according to their importance, with effectiveness and cost receiving the highest weights.

The TOPSIS method is applied to rank the proposed solutions, including (A1) adding air dryers, (A2) increasing maintenance frequency, and (A3) replacing vulnerable components periodically. The results of the TOPSIS analysis provide a clear ranking of the solutions, with the highest-ranked solution being the most effective in improving system reliability [18][19], [20].

#### 4. ANALYSES AND RESULTS

The TOPSIS method is applied to rank the proposed solutions, including (A1) adding air dryers, (A2) increasing maintenance frequency, and (A3) replacing vulnerable components periodically. The results of the TOPSIS analysis provide a clear ranking of the solutions, with the highest-ranked solution being the most effective in improving system reliability [18]. The FMEA analysis identifies the *Convertisseur Pneumatique-Hydraulique* as the component with the highest risk of failure (RPN = 378). Condensation is identified as the primary cause of corrosion and blockages in the system.

Table 2. Results of FMEA and RPN Analysis

No	Components	S	O	D	RPN
1	Condensate Separator	8	6	6	288
2	Convertisseur Pneumatique-Hydraulique	9	7	6	378
3	Priority Valve	8	4	5	160
4	Brake Pedal	9	5	4	180

The FMEA results show that the Pneumatic-Hydraulic Converter has the highest RPN value (RPN = 378), indicating severe functional impact should failure occur. This component plays a vital role in translating pneumatic signals into hydraulic force, and moisture-induced malfunction could cause insufficient braking response or delayed actuation, both of which introduce high safety risks [3]. The Condensate Separator (RPN = 288) also presents a major vulnerability, serving as the primary moisture-trapping point within the pneumatic line. When overwhelmed by condensation, its failure propagates moisture downstream, increasing the failure probability of valves, actuators, and pressure regulators.

The TOPSIS analysis shows that increasing maintenance frequency (A2) is the best solution with the highest preference score (0.7022), followed by adding air dryers (A1) with a score of 0.6793.

Table 3. Decision Matrix

Alternative	C1	C2	C3	C4
A1	4	5	3	5
A2	3	4	4	4
A3	5	3	2	3

Table 4. Normalized Decision Matrix

Alternative	C1	C2	C3	C4
A1	0.5345	0.5976	0.5145	0.5976
A2	0.4009	0.4781	0.6859	0.4781
A3	0.6682	0.3586	0.3429	0.3586

Table 5. Weighted Matrix

Alternative	C1	C2	C3	C4
A1	0.1604	0.2390	0.1029	0.0598
A2	0.1203	0.1912	0.1372	0.0478
A3	0.2005	0.1434	0.0686	0.0359

Table 6. Matrix of Positive Ideal Solution (A+) and Negative Ideal Solution (A-)

Criteria	A+ (Positive Ideal)	A- (Negative Ideal)
C1	0.1203	0.2005
C2	0.2390	0.1434
C3	0.1372	0.0686
C4	0.0598	0.0359

Calculation of Euclidean Distance for Alternative A1:

Distance to Positive Ideal Solution (A+)

$$D_1^+ = \sqrt{(0.1604 - 0.1203)^2 + (0.2390 - 0.2390)^2 + (0.1029 - 0.1372)^2 + (0.0598 - 0.0598)^2}$$

$$D_1^- = \sqrt{(0.0401)^2 + (0)^2 + (-0.0343)^2 + (0)^2}$$

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$$D_1^+ = \sqrt{0.001608 + 0 + 0.001176 + 0}$$

$$D_1^+ = \sqrt{0.002784} \approx 0.0528$$

Distance to Negative Ideal Solution (A-)

$$D_1^- = \sqrt{(0.1604 - 0.2005)^2 + (0.2390 - 0.1434)^2 + (0.1029 - 0.0686)^2 + (0.0598 - 0.0359)^2}$$

$$D_1^- = \sqrt{(-0.0401)^2 + (0.0956)^2 + (0.0343)^2 + (0.0239)^2}$$

$$D_1^- = \sqrt{0.001608 + 0.009139 + 0.001176 + 0.000571}$$

$$D_1^- = \sqrt{0.012494} \approx 0.1118$$

### Calculation of Euclidean Distance for Alternative A2:

#### Distance to Positive Ideal Solution (A+)

$$D_2^+ = \sqrt{(0.1203 - 0.1203)^2 + (0.1912 - 0.2390)^2 + (0.1372 - 0.1372)^2 + (0.0478 - 0.0598)^2}$$

$$D_2^+ = \sqrt{(0)^2 + (-0.0478)^2 + (0)^2 + (-0.0120)^2}$$

$$D_2^+ = \sqrt{0 + 0.002285 + 0 + 0.000144}$$

$$D_2^+ = \sqrt{0.002429} \approx 0.0493$$

Distance to Negative Ideal Solution (A-)

$$D_2^- = \sqrt{(0.1203 - 0.2005)^2 + (0.1912 - 0.1434)^2 + (0.1372 - 0.0686)^2 + (0.0478 - 0.0359)^2}$$

$$D_2^- = \sqrt{(-0.0802)^2 + (0.0478)^2 + (0.0686)^2 + (0.0119)^2}$$

$$D_2^- = \sqrt{0.006432 + 0.002285 + 0.004706 + 0.000142}$$

$$D_2^- = \sqrt{0.013565} \approx 0.1164$$

### Calculation of Euclidean Distance for Alternative A3:

#### Distance to Positive Ideal Solution (A+)

$$D_3^+ = \sqrt{(0.2005 - 0.1203)^2 + (0.1434 - 0.2390)^2 + (0.0686 - 0.1372)^2 + (0.0359 - 0.0598)^2}$$

$$D_3^+ = \sqrt{(0.0802)^2 + (-0.0956)^2 + (-0.0686)^2 + (-0.0239)^2}$$

$$D_3^+ = \sqrt{0.006432 + 0.009139 + 0.004706 + 0.000571}$$

$$D_3^+ = \sqrt{0.020848} \approx 0.1444$$

Distance to Negative Ideal Solution (A-)

$$D_3^- = \sqrt{(0.2005 - 0.2005)^2 + (0.1434 - 0.1434)^2 + (0.0686 - 0.0686)^2 + (0.0359 - 0.0359)^2}$$

$$D_3^- = \sqrt{(0)^2 + (0)^2 + (0)^2 + (0)^2}$$

$$D_3^- = \sqrt{0} \approx 0$$

Table 7. Matrix of Distances to Positive and Negative Ideal Solutions

Alternative	D+ (Distances to A+)	D- (Distances to A-)
A1	0.0528	0.1118
A2	0.0493	0.1164

A3	0.1444	0
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Table 8. Preference Score (Closeness Coefficient)

Alternative	D+	D-	CC <sub>i</sub>
A1	0.0528	0.1118	0.6793
A2	0.0493	0.1164	0.7022
A3	0.1444	0.0000	0.0000

Environmental measurements support these failure modes. The average humidity in the operational area consistently exceeds 80%, with daily temperature fluctuations promoting cyclic condensation inside air reservoirs—conditions comparable to high-risk tropical climates reported in pneumatic reliability studies [2], [4].

The TOPSIS analysis demonstrates that increasing maintenance frequency is the most effective strategy (score 0.7022), outperforming other mitigation options such as installing additional air dryers or redesigning condensate pathways. This aligns with findings from reliability-centered maintenance research, which emphasizes maintenance interval optimization as a primary factor in reducing moisture-related failures [5]. The installation of air dryers ranks second in effectiveness, reinforcing prior literature that identifies air-drying systems as a key solution for controlling dew point and preventing condensation in pneumatic systems [1], [6].

The combined implementation of these mitigation strategies is projected to reduce failure probability by up to 68% and increase system reliability from 72% to 94%. These improvements align with recommended reliability thresholds for railway maintenance equipment, as specified in pneumatic safety and braking system standards applicable in rail applications [7].

## 5. CONCLUSION

This study demonstrates that condensation is the primary cause of pneumatic component failures in the Geismar excavator used for railway maintenance operations in a tropical environment. The FMEA results identify the Pneumatic—

Hydraulic Converter and the Condensate Separator as the components with the highest risk levels, highlighting their critical roles in ensuring stable braking and system reliability. TOPSIS analysis shows that increasing the frequency of preventive maintenance is the most effective mitigation strategy, followed closely by the installation of an air dryer to control moisture accumulation. The implementation of these mitigation measures is projected to reduce the probability of failure by up to 68% and improve overall pneumatic system reliability from 72% to 94%. These findings provide a strong basis for developing a reliability-centered maintenance approach tailored to pneumatic systems operating under high-humidity conditions. The recommended strategies can support safer, more efficient, and more sustainable operation of railway maintenance equipment.

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