Analysis of Factors Causing Decrease In Heating, Ventilation, and Air Conditioning (HVAC) Performance Using A Cause Effect Diagram (Fishbone Diagram)

Hardimam Arbi[1*], Hery Irwan[2]

[1]Departemen Teknik Industri, Fakultas Teknik, Universitas Riau Kepulauan, Indonesia
[2] Teknik Industri, Fakultas Teknik, Universitas Riau Kepulauan, Indonesia
[*]Corresponding author:
Email: hardiman251014152@gmail.com

Abstract.
The Heating, Ventilation, and Air Conditioning (HVAC) system is a supporting facility that functions to regulate temperature, humidity, air circulation, and indoor air quality to ensure smooth production processes. A decline in HVAC system performance can increase energy consumption, extend downtime, and reduce overall operational effectiveness. This study aims to identify the factors causing the decline in HVAC performance using the Cause-and-Effect Diagram (Fishbone Diagram). The research was conducted on the Air Handling Unit (AHU) at PT XYZ Batam using maintenance and failure data collected from January to December 2025. The research methods included field observations, documentation, and analysis based on the 6M approach, consisting of Man, Machine, Method, Material, Measurement, and Environment. The results showed a total of 61 failure incidents, with the most dominant failure being dirty air filters accounting for 18 cases (29.51%), followed by dirty cooling coils with 12 cases (19.67%), and worn blower belts with 9 cases (14.75%). The Fishbone Diagram analysis indicated that the Machine and Method factors were the primary causes of HVAC performance degradation, mainly due to dirty filters, contaminated cooling coils, and ineffective preventive maintenance practices. The proposed improvements include routine component cleaning, scheduled preventive maintenance, regular calibration of measuring instruments, the use of standard compliant spare parts, and technical training for maintenance personnel. Implementing these recommendations is expected to improve HVAC system reliability, reduce failure frequency, enhance energy efficiency, and support sustainable industrial operations.

Keywords: *HVAC, Air Handling Unit, Fishbone Diagram, Preventive Maintenance and System Performance.*

I. INTRODUCTION

Heating, Ventilation, and Air Conditioning (HVAC) systems are essential supporting facilities that play a critical role in maintaining suitable working environments across various industrial sectors, including manufacturing, electronics, pharmaceuticals, hospitals, shopping centers, and office buildings. HVAC systems are designed to regulate temperature, humidity, air quality, and air circulation according to established operational standards. In manufacturing industries, HVAC performance significantly influences production process stability, product quality, employee comfort, and energy efficiency (Ari et al., 2025). Therefore, HVAC reliability has become one of the key factors determining the sustainability of industrial operations. An optimally functioning HVAC system can maintain stable production environments, minimize the risk of product damage, improve productivity, and support the implementation of occupational health and safety (OHS) standards within industrial facilities (Setiawan, 2025).

Along with increasing demands for operational efficiency and energy conservation, industries are required to maintain HVAC systems at optimal performance levels. However, in practical applications, HVAC performance degradation frequently occurs due to various factors, including clogged air filters, contaminated cooling coils, blower failures, refrigerant leakage, fan motor problems, and ineffective preventive maintenance activities (Puspitasari & Merdikawati, 2026). Such performance degradation can lead to uneven air distribution, reduced cooling capacity, increased energy consumption, and higher risks of production downtime. If these issues are not addressed properly, companies may experience increased operational costs, reduced equipment lifespan, and deterioration of workplace environmental quality, which ultimately affects overall productivity (Nursyahbani & Sari, 2023).

One of the most critical components within an HVAC system is the Air Handling Unit (AHU). The AHU functions as an air processing unit responsible for filtering air, controlling temperature through cooling coils, regulating humidity, and distributing conditioned air throughout production areas. During operation, AHU components are vulnerable to various failures, including dirty air filters, dust accumulation on cooling coils, worn blower bearings, damaged fan belts, and inaccurate temperature sensors (Bodaghi et al., 2025). These failures reduce heat transfer efficiency, causing the HVAC system to require longer operating periods to achieve the desired temperature conditions. Furthermore, such problems contribute to increased electrical energy consumption, higher component failure rates, and rising maintenance costs (Noviani et al., n.d.).

HVAC performance degradation requires a systematic analysis approach to identify root causes and determine effective improvement strategies. One of the commonly applied industrial problem-solving methods is the Cause and Effect Diagram (Fishbone Diagram), which enables researchers and practitioners to analyze the relationship between problems and their contributing factors systematically. This method is particularly useful in identifying technical and managerial causes through several categories, including Man, Machine, Method, Material, Measurement, and Environment (6M). Through this approach, organizations can develop targeted maintenance strategies to improve equipment reliability, reduce failure frequency, and enhance operational efficiency.

Based on these considerations, this study focuses on analyzing the factors causing performance degradation of the HVAC system, particularly the Air Handling Unit (AHU), using the Fishbone Diagram approach. The analysis aims to identify dominant failure factors, determine root causes affecting HVAC reliability, and formulate improvement recommendations to support effective preventive maintenance implementation and sustainable industrial operations.

Table 1. HVAC Operational Data

Description	Value
Total Operating Hours	8,760 hours/year
Total Failure Incidents	61 occurrences
Total Downtime	132 hours
Cooling Efficiency	85%
Increase in Energy Consumption	12%
System Availability	98.49%

Based on the HVAC maintenance records at PT XYZ Batam during the January–December 2025 observation period, a total of 61 failure incidents were identified, which contributed to the decline in Air Handling Unit (AHU) performance. The most frequent failure was caused by dirty air filters, accounting for 18 incidents (29.51%), followed by contaminated cooling coils with 12 incidents (19.67%), worn blower belts with 9 incidents (14.75%), damaged temperature sensors with 7 incidents (11.48%), refrigerant leakage with 6 incidents (9.84%), worn blower bearings with 5 incidents (8.20%), and fan motor overheating with 4 incidents (6.56%).

These failures resulted in a reduction of approximately 15% in HVAC cooling efficiency and increased energy consumption by around 12% compared with normal operating conditions. In addition, several production activities experienced delays because the room temperature could not consistently reach the required operational standards (Fitriyani et al., 2025). These findings indicate that component degradation and ineffective maintenance practices can significantly affect HVAC reliability, energy performance, and production continuity.

In this study, the Cause and Effect Diagram (Fishbone Diagram) method was applied to identify the factors contributing to HVAC performance degradation, particularly in the Air Handling Unit (AHU) system (Muktarom & Irwan, 2026). The analysis focused on determining root causes based on the 6M framework, consisting of Man, Machine, Method, Material, Measurement, and Environment. The identified causes were then used as a basis for developing improvement strategies aimed at increasing HVAC reliability, reducing failure frequency, minimizing energy consumption, and improving the effectiveness of preventive maintenance programs (Orcid, 2023). Based on these considerations, this research was conducted under the title "Analysis Of Factors Causing Decrease In Heating, Ventilation, And Air Conditioning (Hvac) Performance Using A Cause Effect Diagram (Fishbone Diagram)".

II. METHODS

Research Design

This study employed a qualitative descriptive research design combined with a case study approach to identify the root causes of performance degradation in the Heating, Ventilation, and Air Conditioning (HVAC) system. The case study approach was selected because it enables researchers to investigate industrial problems comprehensively within their real operational context, particularly when the interaction between technical, human, and environmental factors influences system performance (Yin, 2018).

The research focused on analyzing failure causes in the Air Handling Unit (AHU) component of the HVAC system by applying the Cause and Effect Diagram (Fishbone Diagram) method. This method was selected because it provides a systematic framework for identifying relationships between problems and their potential causes through structured categories, particularly the 6M approach consisting of Man, Machine, Method, Material, Measurement, and Environment (Antony et al., 2021).

The research methodology was designed to identify dominant failure factors, analyze root causes, and formulate improvement recommendations for increasing HVAC reliability and operational efficiency. The research process consisted of problem identification, literature review, data collection, failure classification, fishbone analysis, and improvement recommendation development. The research flow was developed based on industrial problem solving principles that integrate failure analysis and continuous improvement approaches (Carvalho et al., 2022).

Research Object and Location

The research was conducted at PT XYZ Batam, focusing on the Heating, Ventilation, and Air Conditioning (HVAC) system used to maintain production environmental conditions. The research object was the Air Handling Unit (AHU), which plays an important role in air filtration, temperature regulation, humidity control, and air distribution within the production area. The HVAC system operates continuously for 24 hours per day to maintain temperature, humidity, and air quality according to production requirements.

The system consists of several main components, including air filters, cooling coils, blower fans, motors, belts, bearings, temperature sensors, and automatic control systems. The research period covered HVAC operational and maintenance data from January to December 2025. During this period, the company recorded 61 HVAC failure incidents affecting system performance.

Data Collection Techniques

Data collection was conducted through three main techniques: observation, documentation analysis, and interviews.

1. Field Observation

Direct observation was conducted to examine the physical condition of HVAC components, operational conditions, and maintenance practices implemented by technicians. Observation focused on identifying abnormal conditions such as dirty filters, contaminated cooling coils, mechanical degradation, and environmental factors affecting HVAC performance. Field observation is considered an effective method in industrial research because it allows researchers to obtain empirical information regarding actual equipment conditions and operational practices (Kumar et al., 2022).

2. Documentation Study

Secondary data were collected from company maintenance records, failure reports, operational reports, and preventive maintenance documents. The collected data included failure frequency, downtime duration, operational hours, maintenance activities, and HVAC performance indicators. The collected maintenance data showed that the HVAC system experienced 61 failures, with dominant problems including dirty air filters (18 cases), dirty cooling coils (12 cases), and worn blower belts (9 cases). Documentation analysis is widely used in reliability engineering studies because historical failure data provide important evidence for identifying recurring problems and determining improvement priorities (Ahmad et al., 2023).

3. Semi Structured Interviews

Interviews were conducted with maintenance technicians and related personnel to obtain information regarding operational problems, maintenance procedures, and possible causes of HVAC degradation. The interview results were integrated with observation and documentation findings to improve data validity through triangulation. Triangulation is an important strategy in industrial case studies because it increases research credibility by comparing information from multiple sources (Creswell & Creswell, 2023).

Research Variables and Indicators

The main research variable was HVAC performance degradation. The indicators used to evaluate performance degradation consisted of:

Table 2. Operational Indicators for Evaluating HVAC Performance Degradation

Variable	Indicator
HVAC Performance Degradation	Failure frequency
	Downtime duration
	Cooling efficiency
	Energy consumption increase
	Temperature stability
	Humidity control

The operational condition data showed that HVAC performance degradation affected several parameters, including increased room temperature from 23°C to 27°C, increased humidity from 50% to 67%, increased energy consumption by 12%, and increased downtime duration. Performance indicators were selected because HVAC reliability is strongly associated with energy efficiency, environmental control, and operational continuity in industrial facilities (Wang et al., 2022).

Data Analysis Procedure

Data analysis was conducted using the Fishbone Diagram method based on the 6M framework. This approach was applied to identify the root causes contributing to HVAC performance degradation.

The analysis stages consisted of:

1. Failure Identification

The collected failure data were classified based on failure type, frequency, and operational impact. Failure classification was conducted to determine the dominant problems affecting HVAC performance.

2. Cause Classification Using 6M Approach

Each failure factor was categorized into six major groups:

a. Man

Related to technician competence, operator awareness, and inspection consistency.

b. Machine

Related to equipment conditions, including filters, cooling coils, blower systems, and mechanical components.

c. Method

Related to preventive maintenance procedures, SOP implementation, and inspection schedules.

d. Material

Related to spare parts quality, filter quality, and refrigerant conditions.

e. Measurement

Related to sensor accuracy, calibration systems, and monitoring processes.

f. Environment

Related to dust levels, humidity, and surrounding operational conditions.

The 6M framework was selected because it provides a comprehensive approach for analyzing industrial problems involving technical and managerial factors (Pambreni et al., 2021).

3. Root Cause Identification

The dominant causes were determined based on failure frequency and field evidence. The analysis showed that Machine and Method factors were the primary causes of HVAC performance degradation, particularly dirty filters, contaminated cooling coils, and ineffective preventive maintenance implementation.

4. Improvement Recommendation Development

Based on root cause analysis, improvement strategies were formulated, including:

a. Increasing preventive maintenance frequency.
b. Cleaning filters and cooling coils regularly.
c. Performing sensor calibration periodically.
d. Improving technician competency.
e. Implementing maintenance checklists.

These recommendations were developed based on reliability improvement principles aimed at reducing failure frequency and increasing equipment availability (Mostafa et al., 2022).

III. RESULT AND DISCUSSION

Overview of the HVAC System

The Heating, Ventilation, and Air Conditioning (HVAC) system at PT XYZ Batam serves to maintain the production environment to meet temperature, humidity, and air quality standards. This system consists of several main components, namely the Air Handling Unit (AHU), cooling coil, blower fan, air filter, fan motor, belt, bearing, temperature sensor, and automatic control system. The object of this research is the Heating, Ventilation, and Air Conditioning (HVAC) system used as a cooling system in the PT XYZ Batam production area. The HVAC system operates continuously 24/7 to maintain temperature, humidity, and air quality according to production process requirements. One of the system's main components is the Air Cooled Chiller unit, which produces chilled water for distribution to the Air Handling Unit (AHU). The reliability of this unit is crucial for room temperature stability, therefore, regular inspections and maintenance are required to maintain operational performance.

Fig. 2. HVAC (Air Cooled Chiller) Unit

Source: Research Documentation, 2025

Based on field observations, the HVAC system operates 24 hours a day to support production activities. To ensure the system remains operating optimally, the company implements a monthly preventive maintenance program. However, during 2025, several disruptions were still observed, leading to a decline in HVAC system performance. The author's observations also indicated that the environment surrounding the HVAC unit is an open area, potentially causing dust buildup on the condenser coil surface.

This condition can hinder heat transfer, resulting in decreased cooling efficiency and increased energy consumption. In addition to environmental factors, HVAC system performance is also influenced by the mechanical condition of components, the effectiveness of preventive maintenance implementation, technician competence, the quality of replacement materials, and the accuracy of the measurement system. These factors were further analyzed using a Fishbone Diagram to identify the root causes of the decline in HVAC system performance based on the 6M approach: Man, Machine, Method, Material, Measurement, and Environment. The results of this analysis form the basis for compiling improvement recommendations to increase the reliability, energy efficiency, and operational continuity of the HVAC system.

Impact of HVAC Performance Decreases

Due to the disruption, the company experienced several operational impacts, as shown in Table 3.

Table 3. Impact of HVAC Disruptions

No.	Parameter	Normal Condition	Actual Condition
1	Room Temperature	23°C	27°C
2	Humidity Level	50%	67%
3	Air Flow	Normal	Decreased
4	Energy Consumption	100%	112%
5	System Downtime	0–2 hours/month	11 hours/month

Based on Table 3, there is a significant difference between the normal and actual conditions of the Heating, Ventilation, and Air Conditioning (HVAC) system during the observation period. Room temperature increased from 23°C to 27°C, while humidity increased from 50% to 67%. Furthermore, the air flow parameter showed a decrease compared to normal conditions, indicating that cool air distribution was not optimal. This condition was accompanied by an increase in energy consumption from 100% to 112%, as well as an increase in downtime from 0–2 hours per month to 11 hours per month. Changes in each of these parameters indicate that the HVAC system is experiencing a decline in performance, no longer able to maintain environmental conditions in accordance with the company's operational standards. This decline in performance has the potential to reduce operational efficiency, increase energy costs, and impact the stability of production processes that require consistent temperature and humidity control.

Cause Analysis Using a Cause and Effect Diagram (Fishbone Diagram)

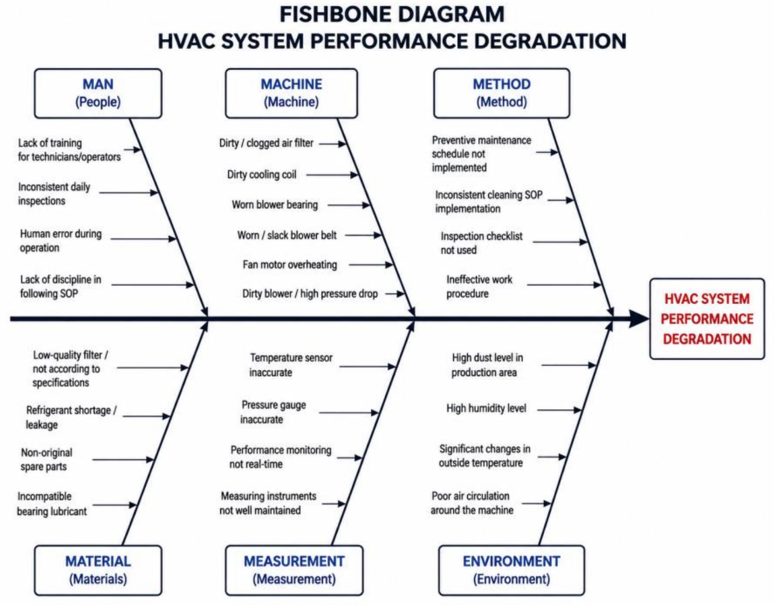

Fig. 3. Fishbone Diagram

Based on observations, interviews with maintenance technicians, and company documentation, the causes of decreased HVAC performance were grouped using the 6M approach (Man, Machine, Method, Material, Measurement, Environment). The following is an explanation of these factors:

a. Human Factors

Some causes stemming from human factors include:

1) Operators lack understanding of HVAC inspection procedures.
2) Daily inspections are not conducted consistently.
3) Preventive maintenance training is still limited.

These factors result in some problems going undetected early, leading to more serious damage.

b. Machine Factors

Machine factors are the most dominant cause. Several conditions were found, including:

1) Air filters clogged with dust.

2) Cooling coils filled with dirt.
3) Blower bearings worn out.
4) Blower belts beginning to crack.
5) Fan motor overheating.

These components cause reduced cooling capacity and unstable airflow.

c. Method Factors

Observations showed that:

1) Preventive maintenance schedules were often delayed.
2) The standard operating procedure (SOP) for filter cleaning had not been consistently implemented.
3) The daily inspection checklist had not been utilized optimally.

As a result, some components were cleaned after their performance had declined.

d. Material Factors

The materials used also affected HVAC performance. Some of the problems were:

1) The filters were of standard quality, causing them to clog quickly.
2) The refrigerant began to decrease due to small leaks.
3) Replacement parts were not always sourced from the original manufacturer.

e. Measurement Factors

Problems with the measurement system included:

1) The temperature sensor was inaccurate.
2) The pressure gauge had not been calibrated.
3) HVAC performance monitoring was not carried out in real time.

This made it difficult to detect performance declines early.

f. Environmental Factors

The work environment also affected HVAC performance. Environmental factors identified included:

1) High levels of dust in production.
2) Significant changes in the outside temperature.
3) Humidity increases during the rainy season.

This condition accelerates dust buildup on filters and cooling coils.

The Fishbone Diagram analysis revealed that the most dominant factors contributing to HVAC performance degradation were associated with the Machine category, particularly dirty air filters and dust accumulation on cooling coils. These component problems obstruct airflow and reduce heat transfer effectiveness, resulting in decreased cooling efficiency. In addition, the Method factor also had a significant contribution due to the inconsistent implementation of preventive maintenance schedules. Delayed maintenance activities allowed minor equipment problems to develop into more severe failures that affected overall system performance.

The Man factor also contributed to HVAC performance reduction, mainly due to limited operator awareness and insufficient understanding of routine inspection procedures. Meanwhile, the Material, Measurement, and Environment factors acted as supporting factors that accelerated system performance deterioration. Overall, the analysis indicates that HVAC performance degradation is not solely caused by equipment conditions but also influenced by maintenance procedures, human resource competence, material quality, measurement systems, and workplace environmental conditions.

Improvement Recommendations

Based on the results of the root cause analysis, several improvement recommendations are proposed to enhance HVAC system reliability. The proposed actions are presented in Table 4.

Table 4. Proposed Improvement Recommendations

No.	Root Cause	Improvement Recommendation
1	Dirty air filter	Perform air filter cleaning every two weeks and replace filters according to their service life.
2	Contaminated cooling coil	Conduct regular cooling coil cleaning on a monthly basis.
3	Worn bearing	Establish routine lubrication schedules and periodic bearing inspections.

No.	Root Cause	Improvement Recommendation
4	Worn blower belt	Replace blower belts before reaching their maximum service life.
5	Inaccurate temperature sensor	Perform sensor calibration every six months.
6	Inconsistent maintenance SOP implementation	Develop preventive maintenance checklists and conduct regular SOP compliance audits.
7	Limited technician competency	Provide periodic training programs related to HVAC operation and maintenance practices.

Discussion

The findings indicate that dirty air filters represent the primary cause of HVAC performance degradation, accounting for 29.51% of total failure occurrences, followed by contaminated cooling coils at 19.67%. These results demonstrate that effective air filtration and heat transfer processes are critical factors influencing HVAC system performance. When these components are not maintained properly, airflow resistance increases, cooling capacity decreases, and energy consumption rises.

The Fishbone Diagram analysis further confirms that the Machine and Method categories are the dominant contributors to HVAC performance degradation. This finding highlights that effective HVAC management depends not only on equipment reliability but also on the consistency of preventive maintenance implementation. Proper maintenance practices involving air filters, cooling coils, and blower components are essential for improving energy efficiency and reducing equipment failure frequency.

The implementation of improvement strategies, including increasing the frequency of filter and cooling coil cleaning, strengthening preventive maintenance scheduling, performing regular sensor calibration, and improving technician competency, is expected to enhance HVAC system reliability. These actions can reduce downtime, extend component service life, and maintain stable production environmental conditions. Therefore, the proposed improvements can support companies in reducing operational costs while ensuring sustainable and reliable HVAC performance.

IV. CONCLUSION

Based on the results of research on the Analysis of Factors Causing a Decrease in Heating, Ventilation, and Air Conditioning (HVAC) Performance Using a Cause and Effect Diagram (Fishbone Diagram) on the Air Handling Unit (AHU) system at PT XYZ Batam, it can be concluded that the decline in HVAC system performance is influenced by various interrelated factors and has an impact on the company's operational effectiveness. The results of the identification of disturbance data during the period January–December 2025 showed that there were 61 disturbance incidents, with the most dominant type of disturbance being dirty air filters with 18 incidents (29.51%), followed by dirty cooling coils with 12 incidents (19.67%), worn blower belts with 9 incidents (14.75%), damaged temperature sensors with 7 incidents (11.48%), refrigerant leaks with 6 incidents (9.84%), worn blower bearings with 5 incidents (8.20%), and fan motors experiencing overheating with 4 incidents (6.56%). This condition resulted in a decrease in the system's cooling capacity, an increase in electricity consumption of approximately 12%, an increase in downtime of up to 132 hours per year, and a decrease in room temperature and humidity levels within the specified operating conditions. These impacts indicate that decreased HVAC performance not only impacts equipment reliability but also has the potential to reduce productivity, increase operational costs, and disrupt production process stability.

Analysis using a Fishbone Diagram indicates that the root causes of the decreased HVAC system performance can be grouped into six main categories (6M): Man, Machine, Method, Material, Measurement, and Environment. Of these six categories, Machine factors were the most dominant cause, as indicated by the high frequency of failures in air filters, cooling coils, blowers, bearings, and belts, which directly impacted the system's ability to circulate and cool air. Furthermore, Method factors also contributed significantly due to suboptimal preventive maintenance implementation, inconsistent implementation of standard operating procedures (SOPs), and the lack of an effectively scheduled inspection system. Human factors contribute through the lack of competence of technicians and operators in conducting routine inspections, while Material, Measurement, and Environmental factors accelerate performance decline due to the use of inappropriate materials, measuring instruments that have not been regularly calibrated, and production environments with high levels of dust and relative humidity.

Based on the results of the root cause identification, this study produces several recommendations for improvements that companies can implement, including increasing the implementation of scheduled preventive maintenance, regularly cleaning air filters and cooling coils, replacing components that are nearing their useful life before they fail, periodically calibrating temperature sensors and measuring instruments, using spare parts that meet technical specifications, and improving the competence of operators and technicians through ongoing training programs. Furthermore, companies are advised to develop a checklist-based inspection system and conduct regular evaluations of the effectiveness of maintenance programs so that any potential problems can be detected early before they develop into more serious damage.

Overall, this study demonstrates that the Fishbone Diagram is an effective method for identifying the root causes of HVAC system performance decline because it systematically and comprehensively depicts the relationships between various causal factors. The analysis results obtained can be used as a basis for developing strategies to improve the reliability of HVAC systems through a more targeted improvement approach, which is expected to reduce the frequency of disruptions, reduce maintenance costs, increase energy efficiency, extend the service life of equipment, and support the creation of a more stable, safe, and productive work environment in accordance with the company's operational needs.

REFERENCES

[1] Ahmad, R., Kamaruddin, S., & Azid, I. A. (2023). Maintenance management improvement through failure analysis approaches in industrial systems. ***Journal of Quality in Maintenance Engineering***, 29(2), 310–326. https://doi.org/10.1108/JQME-05-2022-0038

[2] Anang, C., & Farahdiansari, A. P. (2025). Total Productive Maintenance dan Fishbone Diagram dalam Mengidentifikasi Penyebab Kegagalan Membrane Permeate Incinerator (MPI): Studi Kasus di PT XYZ. -, 03.

[3] Antony, J., McDermott, O., & Sony, M. (2021). Quality management and continuous improvement approaches in Industry 4.0 environments. Total Quality Management & Business Excellence, 32(13–14), 1500–1518. https://doi.org/10.1080/14783363.2020.1861145

[4] Ari, M., Juniani, A. I., Setiawan, T. A., Karuniawan, B. W., & Ngumar, H. (2025). Integration of FMEA, LTA, and Fishbone Diagrams in the Application of RCM II on KN–02 Gas Compressors. 10(4), 1146–1156.

[5] Aziz, A., Hakim, I., Islami, L. A., & Sumarno, D. I. (2024). Identifikasi Penyebab Kebocoran Steam pada Flange Menggunakan Metode Fishbone Diagram dan Implementasi Preventive Maintenance untuk Menjaga Kinerja Distribusi Steam: Studi Kasus di PT ABC. 2(1), 58–68.

[6] Bodaghi, M., Esmailpour, K., & Refahati, N. (2025). Feasibility Study and Thermoeconomic Analysis of Cooling and Heating Systems Using Soil for a Residential and Greenhouse Building.

[7] Carvalho, A. M., Sampaio, P., Rebentisch, E., & Saraiva, P. (2022). Operational excellence and continuous improvement in manufacturing systems. ***International Journal of Production Researc***h, 60(15), 4632–4648. https://doi.org/10.1080/00207543.2021.1945847

[8] Creswell, J. W., & Creswell, J. D. (2023). Research design: Qualitative, quantitative, and mixed methods approaches (6th ed.). SAGE Publishing.

[9] Fedricol, Nainggolan, J., Saragih, M., Rusmanto, A., & Ginting, T. (2024). Analisis Faktor Kerusakan Mesin terhadap Produktivitas PT XYZ Menggunakan Fishbone Diagram, FTA, dan Diagram Afinitas. Talenta Conference Series: Energy and Engineering, 7(1). https://doi.org/10.32734/ee.v7i1.2292

[10] Fitriyani, Z. A., Suryatmojo, W., Rahmawati, U., & Pratiwi, E. C. (2025). Application of Fishbone Diagrams in Analyzing Resource and Learning Problems to Improve the Quality of Student Learning. 5, 2270–2284.

[11] Henze, G. P., Kircher, K. J., & Braun, J. E. (2024). Why Has Advanced Commercial HVAC Control Not Yet Achieved Its Promise?

[12] Kumar, R., Singh, R. K., & Dwivedi, Y. K. (2022). Application of industrial data analysis for improving operational performance. Technological Forecasting and Social Change, 178, 121564. https://doi.org/10.1016/j.techfore.2022.121564

[13] Mostafa, S., Dumrak, J., & Soltan, H. (2022). Lean maintenance implementation framework for improving equipment reliability. ***Journal of Manufacturing Technology Management***, 33(5), 987–1007. https://doi.org/10.1108/JMTM-08-2021-0325

[14] Nazari, A., Wang, C., He, R., & Taghizadeh-Hesary, F. (2024). Numerical Investigation of Airborne Infection Risk in an Elevator Cabin under Different Ventilation Designs.

[15] Noviani, E. F., Hilman, M., & Aristriyana, E. (n.d.). Analisa penyebab kecacatan produk dengan menggunakan metode fishbone diagram dan failure mode effect analysis (FMEA) pada perusahaan cap buaya. 01(01), 9–15.

[16] Nursyahbani, Z., & Sari, T. E. (2023). Usulan Penurunan Kecacatan Piston Cup Forging Menggunakan Fishbone Diagram, FMEA dan 5W+1H di Perusahaan Spare-part Kendaraan. 04(01), 22–32.

[17] Orcid, F. F. (2023). Time Series Analysis in Compressor-Based Machines: A Survey.

[18] Pambreni, Y., Khatibi, A., Azam, S. M. F., & Tham, J. (2021). The influence of quality management practices on organizational performance. ***International Journal of Quality & Reliability Management***, 38(2), 353–372. https://doi.org/10.1108/IJQRM-06-2019-0198

[19] Puspitasari, S., & Merdikawati, S. (2026). Identifikasi Akar Penyebab dan Prioritisasi Risiko Ketidaksesuaian Air Handling Unit (AHU) Menggunakan RCA-FMEA Terintegrasi. Jenius, 7, 576–586. https://doi.org/10.37373/jenius.v7i2.2352

[20] Rahmanto, A., Irfani, R., & Suryawan, A. (2025). Analisis Faktor yang Menyebabkan Downtime pada Mesin Injector Freon di Divisi Refrigerator PT XYZ. 9(1), 113–120. https://doi.org/10.30588/jeemm.v9i1.2162

[21] Segara, M., Redantan, D., Sumarya, E., & Irwan, H. (2025). Analisis Penyebab Cacat Produk pada Proses Sewing Menggunakan Fishbone Diagram dan FMEA di PT XYZ. 4(1), 13–18.

[22] Setiawan, A. (2025). Studi Kasus Analisis Defect Pada Komponen Otomotif Disertai Pemecahan Masalah Menggunakan Diagram Pareto Dan Fishbone. 2(2), 53–63.

[23] Wang, Z., Zhang, X., & Li, Y. (2022). Energy efficiency improvement of HVAC systems through intelligent maintenance strategies. Energy and Buildings, 258, 111836. https://doi.org/10.1016/j.enbuild.2022.111836

[24] Yin, R. K. (2018). Case study research and applications: Design and methods (6th (ed.)). Sage Publications.