ISSN 2622-2035 (Online)
ISSN 2622-2027 (Cetak)

TIBuana

Journal of Applied Industrial Engineering

Industrial Engineering Department
Faculty of Industrial Technology
University of PGRI Adi Buana Surabaya

JURNAL TEKNIK | VOLUME 9 | NOMOR 02 | JULY 2026 | UNIPA PRESS

Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana

Publisher:
Program Studi Teknik Industri Universitas PGRI Adi Buana Surabaya

Publisher Address:
Jalan Dukuh Menanggal XII/4 Surabaya
http://jurnal.unipasby.ac.id/index.php/tibuana
e-mail : jurnaltibuana@unipasby.ac.id

Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
e-ISSN 2622-2035

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Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11137 *e*-ISSN 2622-2035

Application of Failure Mode and Effect Analysis (FMEA) and Fishbone Diagram in the Analysis of Engine Component Failure on Harbour Mobile Crane

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Abstract – **Container loading and unloading port is a port that uses Harbour Mobile Cranes (HMCs) as its main tool in the container loading and unloading process and operates 24 hours. The high work intensity causes the HMC engine components to be susceptible to failure, thus disrupting the smooth operation of operational activities. This study aims to analyze failures of Harbour Mobile Crane (HMC) engine components at a container loading and unloading service company using Failure Modes and Effects Analysis (FMEA) and Fishbone Diagram methods. The FMEA method is used to identify engine component failures and determine the Risk Priority Number (RPN) value, while the fishbone diagram is used to identify the root cause of failure and determine recommendations. The results of the FMEA analysis on 7 engine components show that the highest RPN value is found in the fuel filter component with an RPN value of 105. Furthermore, the component with the highest RPN value is analysed using a fishbone diagram to determine the root cause in terms of people, method, machines, material, measurements, management, environment, and maintenance factors. The results of the fishbone diagram analysis are used as a reference for providing recommendations using the risk control hierarchy, namely elimination, substitution, engineering, administrative control, and personal protective equipment.**

Keywords : **Failure Mode and Effect Analysis, Fishbone Diagram, Harbour Mobile Crane, Risk Priority Number**

I. INTRODUCTION

Ports play a crucial role in economic activity, particularly in the distribution of goods, services, and information. Ports also serve as logistics hubs, integrating various modes of transportation, including sea, land, and air. Consequently, loading and unloading activities are one of the largest drivers of a country's economy. (Ardiansyah et al., 2024).

Container loading and unloading ports play a vital role in driving the economy through the distribution of goods and are an example of a service industry representative of the service industry, with a focus on maritime freight forwarding. As a crucial sector of the national economy, container loading and unloading ports play a significant role in providing satisfactory service and operating professionally and efficiently. To support the effectiveness and efficiency of container loading and unloading operations, ports focus on container loading and unloading services that require the assistance of heavy equipment. Harbour Mobile Crane (HMC) is one such tool that can support loading and unloading activities.

Harbour Mobile Crane (HMC) is heavy equipment, a type of lifting and transporting equipment used in container loading and unloading activities, operating 24/7. HMC plays a crucial role in ensuring the smooth flow of goods, accelerating ship docking times at ports, and improving the overall efficiency and productivity of port operations [2].

Data on Harbour Mobile Crane (HMC) component failures or damage at a container loading and unloading service company from January to December 2024 shows that the highest number of component failures occurred on the Konecranes Gottwald 5506 HMC. There were 137 component failures on the Konecranes Gottwald 5506 HMC. In expert judgment interviews with engineering supervisors, one of the HMC components that frequently failed was the engine. Maintenance and upkeep of the equipment is carried out by the company's engineering division by implementing a maintenance system in the

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11137 *e*-ISSN 2622-2035

form of corrective maintenance and preventive maintenance to prevent failures; however, based on data and field observations, failure or damage to engine components on HMC equipment still occurs frequently. Equipment failure can occur at any time without warning and cause disruption to the production process, posing a risk to workers around it (Fimansyah, 2018).

Based on the above issues, a risk analysis is necessary to prevent and mitigate HMC component failures. This risk analysis aims to mitigate and minimise existing risks, thereby streamlining the production process. [4]. According to Pibisono et al., (2020) Failure Mode and Effect Analysis (FMEA) is a tool that systematically identifies the effects or consequences of system or process failures and reduces or eliminates the likelihood of failure occurring. A method for finding the root cause of a component failure is necessary to identify the root cause of the problem. Fishbone diagrams are one of the root cause analysis methods that have advantages over other methods, namely identifying and organising the causes that arise from a specific effect, and separating the root causes. (Putri et al., 2023).

This study uses a combination of the Failure Mode and Effect Analysis (FMEA) and fishbone diagram methods to analyse the failure risk of Harbour Mobile Crane (HMC) engine components. This combination of the two methods has been applied in a previous study by Cintya Putri et al., (2023) which discussed the failure risk analysis of wet sandblasting machine components using the Failure Mode and Effect Analysis (FMEA) and fishbone diagram methods in the manufacturing industry. In a study by Sufriyani Tanuwijaya dan Sukania (2021)This combination of the two methods was also used to analyse the failure of steel production machines and maintenance management systems in the steel manufacturing industry.

This research focuses on Harbour Mobile Crane (HMC), which is used as an operational aid for loading and unloading containers. Different research locations and objects naturally have different factors that cause problems. These factors include management, work methods and processes, and labour, which can contribute to component failures. It is hoped that the analysis of Harbour Mobile Crane (HMC) engine component failures will reduce the number of HMC failures.

II. THEORY REVIEW

A. *Risk Management*

Risk management is a systematic process for identifying, assessing, and managing risks that can impact a company's objectives by minimising those that could hinder them. The goal of risk management is to help companies identify and mitigate risks, thereby preventing financial losses, reputational damage, and operational disruptions. (Siswanto, 2021). Risks inherent in the workplace must be controlled. Risk control aims to minimise hazards by implementing a risk control hierarchy: elimination, substitution, engineering, administrative controls, and personal protective equipment.

Table 1. Severity Scale

Rank	Impact	Severity Level
10	Failure not preceded by warnings	Dangerous without warning
9	Failure preceded by warnings	Dangerous with a warning
8	Product inoperable	Very High
7	Product operable with significantly reduced performance	High
6	Product operable, but some additional items (secondary functions) are inoperable.	Medium
5	Product operable with slightly reduced performance	Low
4	Customer-aware defect (>75%)	Very Low
3	Customer-aware defect (50%)	Minor
2	Customer-aware defect (<25%)	Very Minor
1	No impact	Nothing

Table 2. Occurrence Scale

Rank	Risk Probability	Description
10	Very High	More than one occurrence per day
9	High	One occurrence every three or four days
8	High	One occurrence per week
7	Quite High	Once a month
6	Medium	Once every 3 months
5	Low	Once every 6 months
4	Very Low	Once a year
3	Rare	Once every 1-3 years
2	Very Rare	Once every 3-6 years
1	Rarely	Once every 6-100 years

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B. Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a tool used to analyse the reliability of a system and the causes of its failure to meet system reliability and safety requirements, design, and process by providing basic information regarding system, design, and process reliability predictions. (Hendra, 2023). The goal is to evaluate the effects of failure modes to determine actions to reduce the risk of component failure. FMEA identifies information from each failure type, the impact of the failure, and the level of failure risk priority (Situngkir et al., 2019). The output of FMEA is the failure mode, the impact of the failure, and the Risk Priority Number (RPN) value of the analysed object. The Risk Priority Number (RPN) is obtained from the multiplication of severity, occurrence, and detection. The higher the RPN value, the more critical the problem is and requires further action.

Table 3. Detection Scale

Rank	Detection Probability	Detection Level
10	The controller cannot detect the failure	Almost Impossible
9	It is improbable that the controller will detect a potential failure	Very Rarely
8	The controller will rarely detect a potential failure	Rarely
7	The controller has a very low probability of detecting a failure	Very Low
6	The controller has a low probability of detecting a failure	Low
5	The controller's probability of detecting a failure is moderate	Medium
4	The controller's probability of detecting a failure is somewhat high	Quiet High
3	The controller's probability of detecting failure is high	High
2	The controller's probability of detecting failure is very high	Very High
1	Failure in the process cannot occur because it has been prevented through the Solution design.	Almost Certain

Table 1 explains the severity scale from 1 to 10, the higher the value is more dangerous. Table 2 explains the occurrence scale from 1 to 10, the higher the value has more frequent the occurrence. Table 3 explains the detection scale from 1 to 10, the higher the value has more detectable the failure.

C. Fishbone Diagram

A fishbone diagram is a visual tool used to graphically and structurally depict the causes or factors related to a particular problem or issue. This diagram was invented by Kaoru Ishikawa, a Japanese quality management expert, and is often used in various fields, including manufacturing, business, and other fields, as an analysis and improvement tool. [11]. The basic principle of a fishbone diagram is to illustrate the relationship between the problem that occurs and all its causal factors. The shape of the diagram resembles a fishbone, with a centre line depicting the problem or issue whose causes will be identified. In identifying using a fishbone diagram, there are several main factors involved in finding the cause of a problem. According to Pušnik et al., (2019these main factors are people or manpower, methods, machines, materials, measurements, environment, management, and maintenance.

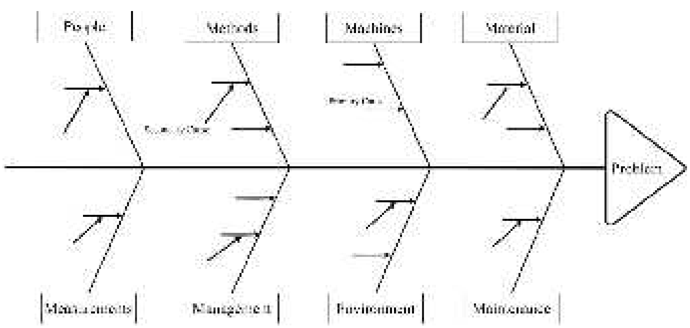

Figure 1. Fishbone Diagram.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11137 *e*-ISSN 2622-2035

III. METHODS

This research uses a qualitative descriptive approach with the aim of systematically, factually, and accurately describing the data in the field. The initial step in this research is to conduct initial observations, including literature studies related to the object being studied, field studies, and problem identification. Furthermore, to support future research, data collection is carried out. The data collected are primary data in the form of interviews with expert judgment and field observations. Meanwhile, secondary data includes data on HMC Type 5506 engine components, failure data, organisational data, and tool manuals. After the data is collected, the next stage is data processing and analysis. Data processing and analysis in this study include determining expert judgment, identifying objects using the Failure Mode and Effect Analysis (FMEA) method, identifying root causes using Fishbone Diagrams, and providing recommendations using the risk control hierarchy.

III. RESULTS AND DISCUSSION

A. *Failure Mode and Effect Analysis (FMEA)*

Failure Mode and Effect Analysis (FMEA) is an analytical method used to analyse failure modes, effects, and causes of failure in Harbour Mobile Crane (HMC) engine components. Table 4, the FMEA worksheet, presents an analysis of failures, impacts, causes, and control measures based on failure prevention based on the severity, occurrence, and detection criteria in Tables 1, 2, and 3. The FMEA was conducted using expert judgment, conducted by an HMC equipment supervisor familiar with each HMC component, as well as by an HSSE supervisor and HSSE manager familiar with hazard identification and risk management techniques within the company.

Table 4 shows the results of the FMEA analysis on seven HMC 5506 engine components: the auxiliary power supply, battery, fuel injector pump, fuel filter, radiator, temperature sensor, and water separator, with a total of 10 failure modes. From the results of the FMEA analysis, the Risk Priority Number (RPN) value can be determined for each component of the HMC type 5506 engine, which is obtained from calculations in the form of multiplying the severity value, the frequency value of a failure mode (occurrence), and the value of how effectively the existing system or control can detect the failure mode (detection).

The FMEA analysis of the HMC 5506 engine component showed the highest RPN value for the fuel filter component, with a clogged fuel filter failure mode. The Risk Priority Number (RPN) calculation is based on the multiplication of severity x occurrence x detection. Severity is scored as 5 (low) because a dirty/clogged fuel filter can slightly reduce HMC performance; occurrence is scored as 7 (moderately high) because the incident occurs once a month; and detection is scored as 3 (high) because a clogged fuel filter is highly detectable by controllers and mechanics. Based on the multiplication of severity × occurrence × detection, the total RPN for the fuel filter subcomponent with a dirty/clogged fuel filter failure mode is 105.

The component with the highest RPN value will be further identified for its root cause using a fishbone diagram, with the failure mode as the effect or head of the fish. The analysis using a fishbone diagram aims to identify the root cause of subcomponent failure from the perspective of people, methods, machines, materials, management, maintenance, measurement, and the environment, and facilitates the determination of recommendations for future implementation.

B. *Fishbone Diagram*

Figure 2 below shows a fishbone diagram of a fuel filter component failure, with the failure mode being a clogged fuel filter. The root cause analysis of the fuel filter component failure is reviewed from the perspectives of people, method, machine, material, measurements, management, environment, and maintenance.

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DOI: https://doi.org/10.36456/tibuana.9.02.11137 *e*-ISSN 2622-2035

Table 4. Failure Mode and Effect Analysis of HMC Engine Components
Failure Mode and Effect Analysis Worksheet

System: Harbour Mobile Crane 5506 Date: May
Subsystem: Engine Years: 2025

NO	Component	Potential Failure Mode	Potential Effect of Failure	Severity (S)	Potential Cause of Failure	Occurrence(O)	Current Control Detection	Detection (D)	RPN
1	Aux Power Supply	Aux power supply drop	HMC cannot start	7	The Auxiliary Power Supply cable is broken or corroded	2	Perform an inspection on the cable and plug connections	3	42
2	Accu	Accu drop	The engine cannot start	6	Battery usage period is up (age factor)	5	Replace the battery unit according to the validity period	3	90
		Clamp broken	The battery cannot supply electricity to the engine	4	Broken or corroded battery clamp	5	Perform clamp replacement and physical visual inspection of the battery	2	40
		Out of water	The battery cannot store the maximum amount of electricity	4	The battery water check was not carried out	5	Conduct regular inspections and filling	2	40
3	Fuel Injector Pump	Weak pump pressure	Fuel supply to the engine is not optimal	5	The fuel injector pump is broken	4	Replace the fuel pump according to specifications	3	60
4	Fuel Filter	Fuel filter clogged	The engine stalls and has no power	5	Dirty fuel and filter checks were not performed	7	Perform corrective maintenance on the fuel filter	3	105
5	Radiator	Out of water	Engine is overheated	5	The radiator water check was not carried out	6	Carry out routine filling periodically	2	60
		Leaking	Engine cooling is not optimal	4	The radiator is hit by an impact or iron particles	3	Visual check and engine temperature indicator	2	24
6	Sensor Temperature	Abnormal	The engine overheats due to a temperature indicator failure	4	The age factor of the temperature sensor is outdated	5	Replacing the temperature sensor unit and checking the sensor cable	3	60
7	Water Separator	Water is fresh to low	Water filtration from fuel is disrupted	5	Frequency too low	6	Replacing the water separator unit according to specifications	3	90

The following is a description of the causes that contribute to clogged fuel filters, reviewed from the aspects of people, method, machine, material, management, measurements, maintenance, and environment in Figure 3.

1. People
   Negligence in routine maintenance can easily lead to fuel filter clogging. Failure to maintain this component regularly can have serious consequences and disrupt the fuel supply to the engine.
2. Methods
   Incorrect fuel filter replacement can reduce the filter's capacity and hinder engine performance. These errors can include using a fuel filter that doesn't meet specifications and failing to maintain cleanliness during replacement. This occurs due to a lack of understanding of standard operating procedures (SOPs) by mechanics.
3. Machines
   Fuel filter blockages can be caused by other supporting components failing to function optimally, such as a damaged fuel pump, a

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11137 *e*-ISSN 2622-2035

suboptimal injection system, or a rusty fuel tank. If other supporting components aren't working optimally, the fuel filter is more likely to become clogged, as it has to work harder.

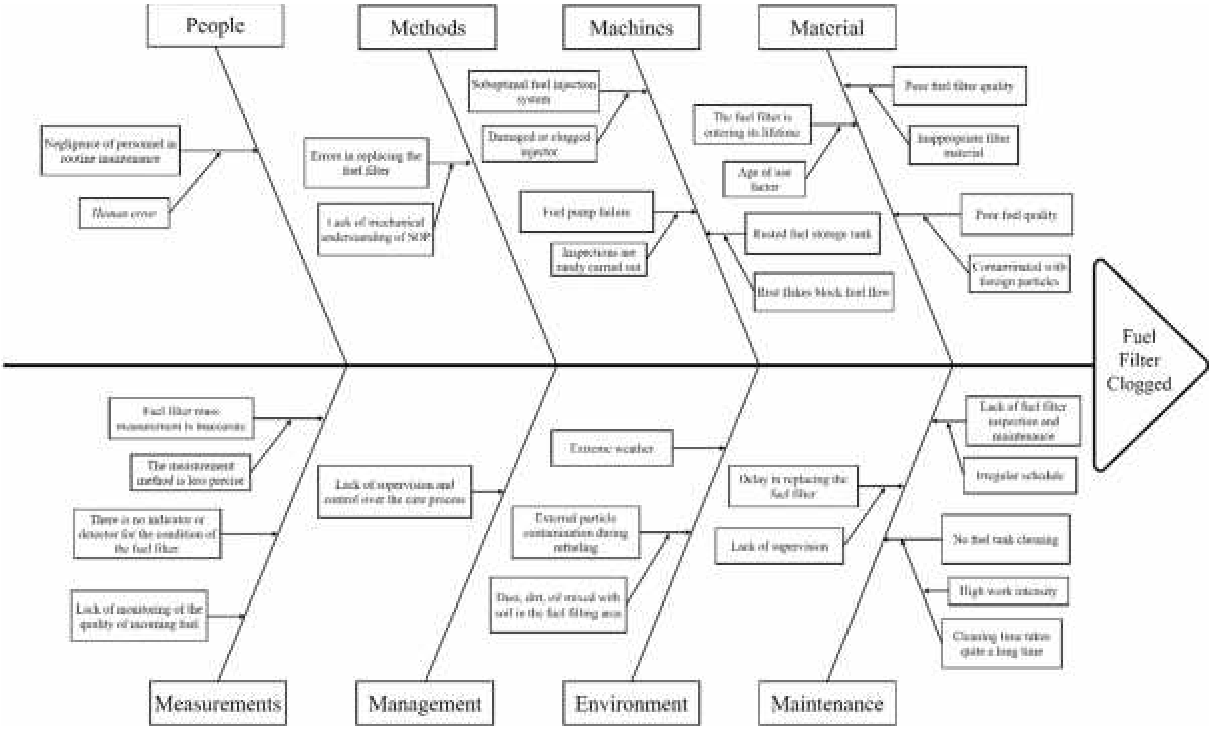

Figure 2. Fishbone Diagram of a Clogged Fuel Filter

4. Material
   A fuel filter that's reaching its lifespan is of poor quality and uses poor fuel quality will accelerate fuel filter clogging. The presence of clogging particles from poor fuel and the fuel filter's inability to filter properly contribute to this.
5. Management
   Lack of oversight and control over the maintenance process. Component maintenance is crucial to prevent future problems. However, sometimes this maintenance process is not carried out properly or even infrequently. A lack of oversight and control by management is one of the causes of this.
6. Measurements
   The lack of a fuel filter condition indicator and minimal fuel quality monitoring can lead to clogged filters. Fuel filter condition can only be detected visually. Therefore, measuring the service life must be determined from the time the component is installed.
7. Maintenance
   Delayed replacement, lack of inspection and maintenance, and failure to clean the tank can all lead to clogged fuel filters. This is because the fuel filter's performance has deteriorated due to numerous blockages and not being replaced promptly.
8. Environment
   A clogged fuel filter can be caused by extreme weather conditions and external particle contamination during refueling. These particles become airborne and enter the fuel tank, clogging the filter.

C. Recommendation

Recommendations for controlling clogged fuel filter failures are based on the underlying cause of the failure. Recommendations are based on a risk control hierarchy: elimination, substitution, engineering, administrative controls, and personal protective equipment.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11137 *e*-ISSN 2622-2035

The following are recommendations for handling clogged fuel filters.

1. Elimination – This control cannot be done because the fuel filter is an important component for filtering fuel before it is distributed to the HMC engine.
2. Substitution – Replace the dirty fuel filter with a new one that meets the specifications of the diesel engine used, replace the damaged injector and fuel pump with a new one that meets the tool standards.
3. Engineering Control – Provides filter material in the fuel tank filler hole that can filter dirt mixed with the fuel that is entered, provides fuel filter protection to prevent foreign particles from entering, protects against extreme weather that causes dirt deposits on the fuel filter, and provides an anti-rust coating on the fuel tank.
4. Administration – Conducting toolbox meetings regularly, creating routine inspection schedules and adjusting the number of inspection officers, filling fuel by paying attention to the cleanliness of the surrounding environment, marking the fuel filter and recording the replacement time to estimate its service life, paying attention to the quality of the fuel before filling it into the tank, cleaning the fuel tank to prevent rust debris from entering the fuel flow, storing fuel stocks in a clean place and avoiding oil and dirt, maintaining the cleanliness of the fuel filling and storage area, and conducting daily supervision at the HMC equipment maintenance location.
5. Personal Protective Equipment (PPE) – In the existing basic failure causes, the use of PPE is not necessary because it does not cause injury to humans.

IV. CONCLUSION

Based on the results of the analysis and discussion carried out in this study, the following conclusions can be drawn:

1. The results of the calculation of the RPN value on 7 engine components of the Harbour Mobile Crane (HMC) type 5506 using the Failure Mode and Effect Analysis (FMEA) method showed that the highest RPN value was found in the fuel filter component with a value of 105, and the failure mode of the fuel filter was clogged.
2. The results identifying the causes of risk for components with the highest RPN values for the Harbour Mobile Crane (HMC) type 5506 using the Fishbone Diagram method revealed eight factors that influence fuel filter clogging. These factors include:
   a. People – Negligence of officers in routine maintenance.
   b. Methods – Fuel filter replacement error.
   c. Machines – Suboptimal injection system, fuel pump damage, and rusty fuel tank.
   d. Material – The fuel filter is entering its lifetime, and the quality of the fuel filter and fuel is poor.
   e. Management – Lack of supervision and control over the care process.
   f. Measurements – Inaccurate service life measurements, no indicators, and minimal monitoring of fuel quality.
   g. Maintenance – Delay in replacing the fuel filter, lack of inspection and maintenance, and failure to clean the fuel tank.
   h. Environment – Extreme weather and external particle contaminants.
3. Controls to reduce the occurrence of Harbour Mobile Crane (HMC) engine component failures were obtained from the results of the analysis using a fishbone diagram. The basic causes that influence the occurrence of failures were controlled based on the hierarchy of risk control, namely elimination, substitution, engineering, administrative control, and personal protective equipment. Recommendations that can be given to clogged fuel filters include conducting regular toolbox meetings to ensure understanding and compliance with SOPs, replacing damaged or expired component units, and conducting supervision in the equipment maintenance area.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 *e*-ISSN 2622-2035

Integrated ABC–VED–AHP Framework for Prioritizing Returned Materials in Electricity Transmission Warehouse Management

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***Abstract*—Returned materials in electricity transmission warehouses represent ex-operational assets that may still contain economic value and operational utility. However, their accumulation can reduce warehouse efficiency, increase storage burden, and delay asset recovery decisions. In PT PLN (Persero) transmission warehouses, warehouse capacity utilization reached an average of 93.29%, exceeding the recommended operational threshold, with several warehouses experiencing overcapacity conditions. Existing classification practices remain administrative and do not provide a systematic basis for determining whether materials should be retained, repaired, reused, transferred, or disposed of. This study proposes an integrated multi-criteria decision framework for prioritizing returned materials by combining ABC analysis, VED analysis, physical condition assessment, reuse potential evaluation, and the Analytic Hierarchy Process (AHP). The framework was applied to 580 returned material items with a total replacement value of IDR 256,057,003,073. The AHP results show that operational criticality is the most influential criterion with a weight of 0.5342, followed by physical condition, economic value, and reuse potential. The consistency ratio was 0.0455, indicating consistent expert judgment. The final prioritization classified 397 items as high priority, 116 items as medium priority, and 67 items as low priority. The proposed framework supports more objective, transparent, and data-driven decision-making in returned material management and contributes to warehouse space optimization, dead stock reduction, and asset recovery improvement in electricity infrastructure systems.**

Keywords : **AHP, electricity transmission warehouse, returned material, VED analysis.**

I. NTRODUCTION

Inventory management is a critical component of supply chain and logistics systems because it directly affects service level, operational reliability, and total logistics cost [5], [12]. In electricity infrastructure companies, inventory management becomes more complex because the warehouse not only manages new materials, but also returned materials originating from operational activities, maintenance work, and project replacement activities. Returned materials are ex-operational materials or equipment that have been dismantled from field operations and returned to the warehouse for further evaluation regarding their feasibility for reuse, repair, storage, transfer, or asset disposal.

In electricity transmission systems, returned materials may include current transformers, circuit breakers, lightning arresters, disconnecting switches, conductors, and other transmission equipment. These materials often still contain economic value and may remain operationally important, depending on their physical condition, technical feasibility, and future demand. Therefore, returned material management is closely related to reverse logistics, asset recovery, and warehouse capacity optimization.

The accumulation of returned materials has become a significant issue in PT PLN (Persero) transmission warehouses based on internal warehouse capacity records [9], [10]. Based on warehouse capacity data, the average utilization level of transmission warehouses reached 93.29%, exceeding the recommended operational threshold. Several warehouses even experienced overcapacity, indicating that storage space has been heavily occupied by returned materials and inactive assets. A large proportion of these materials are categorized as non-moving or dead stock items, which have remained in storage for long periods without clear handling decisions.

This condition creates several managerial problems. First, warehouse space becomes increasingly limited for materials that are

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 *e*-ISSN 2622-2035

operationally needed. Second, companies incur storage and handling costs for materials whose future use is uncertain. Third, valuable materials may not be reused in a timely manner because they are mixed with damaged or obsolete materials. Fourth, decisions regarding retain, repair, reuse, transfer, or disposal remain highly dependent on administrative status and subjective assessment rather than an integrated prioritization framework.

Current returned material classification practices generally rely on administrative categories such as standby, damaged, repair, warranty, or disposal proposal. Although these categories describe the process status of materials, they do not adequately represent economic value, operational criticality, physical condition, and reuse potential simultaneously. As a result, materials with low economic value but high operational criticality may receive insufficient attention, while materials with poor physical condition may continue occupying warehouse space despite having limited practical value.

Several inventory classification methods have been widely used in previous studies. ABC analysis classifies inventory based on economic value and is useful for identifying high-value items that require managerial attention. VED analysis classifies materials based on operational criticality, particularly the consequences of material unavailability. Meanwhile, the Analytic Hierarchy Process (AHP) provides a systematic multi-criteria decision-making approach by assigning relative weights to different criteria. However, previous studies have mostly focused on active inventory or spare parts, while limited attention has been given to returned materials and dead stock in electricity infrastructure warehouses.

This study addresses this gap by developing an integrated ABC–VED–AHP framework for prioritizing returned materials in electricity transmission warehouse management. The proposed framework combines economic value, operational criticality, physical condition, and reuse potential into a single composite priority score. The output of the framework is a priority classification that supports managerial strategies for retention, repair, transfer, or disposal decisions.

The main contributions of this study are threefold. First, this study develops a returned material prioritization framework specifically designed for electricity transmission warehouses, where most materials are non-moving and conventional movement-based classifications such as FSN are less relevant. Second, this study integrates economic value, operational criticality, physical condition, and reuse potential into a single multi-criteria decision framework using AHP. Third, the proposed framework translates classification results into practical managerial strategies, thereby supporting warehouse optimization and asset recovery in electricity infrastructure systems.

Although this study uses PT PLN (Persero) as a case study, the proposed framework is designed to be applicable to other infrastructure-based organizations that manage returned materials, spare parts, and non-moving assets. Therefore, the contribution of this study is not limited to a company-specific solution but also provides a structured prioritization approach for returned material management in utility and infrastructure warehouse systems.

II. LITERATURE REVIEW

A. *Inventory Management and Reverse Logistics*

Inventory management aims to ensure material availability while minimizing total inventory-related costs. In infrastructure-based industries, inventory management is not limited to new materials but also includes returned materials from maintenance and replacement activities. Returned materials require different treatment because their condition, value, and usability are uncertain.

Reverse logistics refers to the process of moving materials from the point of use back to the organization for reuse, repair, remanufacturing, recycling, or disposal [1], [6], [12]. In the context of electricity transmission, returned materials represent reverse logistics flows because equipment removed from the field is returned to the warehouse for technical and economic evaluation. Effective reverse logistics can improve asset utilization, reduce waste, support circular economy principles, and contribute to more sustainable inventory management [2].

B. *ABC Analysis*

ABC analysis is an inventory classification method based on the Pareto principle and is widely used for inventory grouping based on economic value [7], [8], [11]. It classifies materials into three categories according to their contribution to total inventory value. Category A represents high-value materials that require strict control, Category B

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 *e*-ISSN 2622-2035

represents medium-value materials, and Category C represents low-value materials. The economic value of each material can be calculated using replacement cost and quantity.

Although ABC analysis is useful for identifying economically important materials, it has limitations because it only considers financial value. In electricity infrastructure systems, some low-value materials may still be operationally critical. Therefore, ABC analysis should be complemented with an operational criticality assessment.

C. VED Analysis

VED analysis classifies materials based on their operational criticality and is commonly used to identify items whose unavailability may affect operational continuity [3], [4]. Vital materials are items whose unavailability may cause severe operational disruption, system failure, or safety risk. Essential materials are important for maintaining system performance, although temporary unavailability may still be tolerated. Desirable materials have relatively minor operational impact and are easier to substitute.

VED analysis is particularly relevant for electricity transmission systems because operational reliability is a key performance requirement. Materials with high criticality should not be evaluated only from their economic value, but also from their impact on system continuity and maintenance readiness.

D. Analytic Hierarchy Process

The Analytic Hierarchy Process is a multi-criteria decision-making method used to determine the relative importance of criteria through pairwise comparisons [13], [14], [15]. AHP decomposes a complex decision problem into a hierarchical structure consisting of goals, criteria, and alternatives. Pairwise comparisons are conducted using Saaty's scale, and the consistency of expert judgments is evaluated using the consistency ratio.

AHP is suitable for returned material prioritization because the decision involves both quantitative and qualitative criteria. Economic value can be measured from replacement cost, while operational criticality, physical condition, and reuse potential require expert judgment and structured assessment.

E. Research Gap

Previous studies have applied ABC analysis, VED analysis, and AHP in inventory classification and spare parts management. However, most studies focus on active inventory systems where demand movement and consumption patterns are available. In returned material warehouses, many items are non-moving or dead stock, making movement-based classification less relevant.

Furthermore, limited studies have integrated economic value, operational criticality, physical condition, and reuse potential into a single framework for returned material management in electricity infrastructure systems. Unlike previous studies that mainly focus on demand movement or economic value, this study addresses returned materials whose future usability is uncertain. Therefore, this study proposes an integrated ABC–VED–AHP framework by incorporating physical condition and reuse potential as additional criteria for returned material prioritization.

III. RESEARCH METHODOLOGY

F. Research Design

This study uses a case-based quantitative and qualitative approach. Quantitative data are used to evaluate economic value and warehouse utilization, while qualitative assessments are used to evaluate operational criticality, physical condition, and reuse potential. The research framework consists of data collection, ABC classification, VED classification, physical condition assessment, reuse potential assessment, AHP weighting, composite scoring, priority categorization, and managerial strategy formulation.

G. Data Collection

The data used in this study consists of secondary and primary data. Secondary data are obtained from the warehouse inventory database and include material identification, material type, warehouse location, quantity, replacement cost, administrative status, and warehouse capacity utilization. Primary data are obtained through physical inspection and expert assessment.

Physical inspection is conducted to evaluate the condition of returned materials based on structural condition, component completeness, corrosion or degradation level, and technical documentation availability. Expert assessment is conducted to evaluate operational criticality and reuse potential. Experts are selected from logistics, maintenance, and transmission operation functions because they have direct knowledge of material usage,

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 e-ISSN 2622-2035

operational risk, and warehouse handling practices.

H. ABC Classification

ABC classification is used to categorize returned materials based on economic value. The economic value of each material is calculated as:

$$EV_i = RC_i \times Q_i \quad (1)$$

Where:
EV_i is the economic value of material (i),
RC_i is the replacement cost of material (i),
Q_i is the quantity of material (i).

Materials are sorted in descending order based on economic value, and cumulative value percentages are calculated. Category A consists of materials contributing the highest cumulative value, Category B consists of medium-value materials, and Category C consists of low-value materials.

For composite scoring, ABC categories are converted into numerical scores as follows:

Table 1. ABC Category Score

ABC Category	Interpretation	Score
A	High economic value	3
B	Medium economic value	2
C	Low economic value	1

I. VED Classification

VED classification is used to evaluate the operational criticality of each material. The classification is based on the potential impact of material unavailability on electricity transmission reliability, maintenance execution, and operational safety.

Table 2. VED Category Score

VED Category	Interpretation	Score
Vital	Severe operational impact if unavailable	3
Essential	Important but temporary unavailability can be tolerated	2
Desirable	Minor operational impact	1

J. Physical Condition Assessment

Physical condition assessment evaluates the technical feasibility of returned materials for reuse or repair. Four sub-criteria are used: structural condition, component completeness, corrosion or degradation level, and technical documentation availability. Each sub-criterion is assessed using a Likert scale and combined into a physical condition score.

Table 3. Physical Condition Assessment Criteria

Sub-criterion	Weight	Assessment Focus
Structural condition	40%	Cracks, deformation, broken parts, physical integrity
Component completeness	30%	Availability of main parts and accessories
Corrosion/degradation	20%	Rust, oxidation, insulation aging, surface degradation
Technical documentation	10%	Nameplate, manual, maintenance record, traceability

The physical condition score is then converted into a 1–3 scale for consistency with other criteria:

Table 4. Physical Condition Score Conversion

Physical Condition	Initial Score	Converted Score
Good / Very good	4–5	3
Fair	3	2
Poor / Very poor	1–2	1

K. Reuse Potential Assessment

Reuse potential measures the feasibility and usefulness of returned materials for future operational use. It is evaluated based on repairability, demand frequency, and market availability.

Table 5. Reuse Potential Assessment Criteria

Sub-criterion	Description	High Score Condition
Repairability	Technical and economic feasibility of repair	Repair cost is relatively low compared to replacement cost
Demand frequency	Historical or expected need for the material	Material is frequently needed for maintenance or replacement
Market availability	Ease of procuring new material	Material is difficult to procure, obsolete, imported, or has a long lead time.

The reuse potential score is converted into three categories: high reuse potential = 3, medium reuse potential = 2, and low reuse potential = 1.

L. AHP Weighting

AHP is used to determine the relative importance of four criteria: economic value, operational criticality, physical condition, and reuse potential. Experts perform pairwise comparisons using Saaty's 1–9 scale. The pairwise comparison matrix is normalized to obtain priority weights. Consistency is evaluated using the consistency ratio (CR). The expert judgment is considered acceptable if CR ≤ 0.10. In this study, the consistency test produced λmax = 4.1229, CI = 0.0410, and CR = 0.0455. Since the CR value is below 0.10, the pairwise comparison

Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 *e*-ISSN 2622-2035

results are considered consistent and acceptable for further analysis.

The criteria used in AHP are:

1. Economic Value (ABC)
2. Operational Criticality (VED)
3. Physical Condition
4. Reused Potential

M. Composite Priority Score

The final priority score is calculated by multiplying each criterion score by its AHP weight:

$$P_i = (W_1 \times E_i) + (W_2 \times O_i) + (W_3 \times P_i) + (W_4 \times R_i) \quad (2)$$

Where:
PS_i is the priority score of material (i),
EV_i is the economic value score,
OC_i is the operational criticality score,
PC_i is the physical condition score,
RP_i is the reuse potential score,
W_1, W_2, W_3, W_4 are AHP weights.

The final score is classified into three priority categories:

Table 6. Final Priority Classification and Handling Strategy

Priority Category	Interpretation	General Strategy
High Priority	High value, high criticality, good condition, or high reuse potential	Retain, repair, strategic stock, or transfer to other units
Medium Priority	Moderate value or moderate operational importance	Selective repair, controlled storage, or further evaluation
Low Priority	Low value, low criticality, poor condition, or low reuse potential	Disposal, scrap, or liquidation

III. RESULTS AND DISCUSSION

A. Warehouse Utilization Condition

The warehouse utilization data indicates that returned materials have significantly occupied the electricity transmission warehouse capacity. The average warehouse utilization reached 93.29%, exceeding the recommended operational threshold. One warehouse experienced overcapacity above 100%, while several others operated close to full capacity. This condition shows that returned material accumulation has become a structural warehouse management issue rather than a temporary storage problem.

Table 7. Warehouse Utilization of Transmission Implementation Units

Warehouse Area	Total Area (m²)	Used Area (m²)	Utilization (%)	Dominant Content
UPT Cikupa	4,804	5,451	113.5	Returned/inactive assets
UPT Cilegon	5,484	5,351	97.6	Returned/inactive assets
UPT Durkos	1,000	500	50.0	Returned and spare materials
UPT Pulogadung	8,670	8,218	94.8	Returned/inactive assets
UPT Cawang	5,253	4,754	90.5	Returned/inactive assets
UPT Gandul	6,404	5,220	81.5	Returned and spare materials
Average	**31,615**	**29,494**	**93.29**	**Non-moving materials**

The high utilization level indicates that warehouse space is being consumed by materials whose future use is uncertain. Without a prioritization framework, valuable and critical materials may not be distinguished from low-value and non-critical materials. Therefore, a structured classification system is needed to support handling decisions.

B. ABC Classification Result

ABC analysis was conducted on 580 returned material items with a total replacement value of IDR 256,057,003,073. The classification results show that 8 items were categorized as A, 457 items as B, and 115 items as C. Category A consists of a small number of materials with very high replacement value, mainly power transformers and other high-value transmission equipment. Although the number of Category A items is relatively small, these materials represent a significant portion of total asset value and therefore require strict managerial control.

Table 8. ABC Classification Results

ABC Category	Number of Items	Percentage of Items	Interpretation
A	8	1.38%	High economic value
B	457	78.79%	Medium economic value
C	115	19.83%	Low economic value
Total	**580**	**100.00%**	

The dominance of Category B indicates that most returned materials have moderate economic

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 *e*-ISSN 2622-2035

value. This condition implies that warehouse decisions cannot rely only on high-value materials because a large number of medium-value materials also contribute to storage burden and asset recovery potential. Category C materials, although economically lower, still need to be evaluated together with operational criticality before disposal decisions are made.

C. VED Classification Result

VED analysis was used to evaluate the operational criticality of returned materials. The results show that 408 items were classified as Vital, 108 items as Essential, and 64 items as Desirable. This result indicates that most returned materials are operationally important for electricity transmission reliability, even though they are currently stored as returned or inactive materials.

Table 9. VED Classification Results

VED Category	Number of Items	Percentage of Items	Interpretation
Vital	408	70.34%	Severe operational impact if unavailable
Essential	108	18.62%	Important for operational support
Desirable	64	11.03%	Lower operational impact
Total	**580**	**100.00%**	

The high proportion of Vital materials confirms that returned materials should not be treated merely as obsolete or inactive assets. Some returned materials may still play an important role as backup equipment, emergency replacement materials, or candidates for repair and reuse. Therefore, operational criticality must be included in returned material handling decisions.

D. Integrated ABC-VED Matrix

The combination of ABC and VED produces a 3×3 classification matrix. This matrix provides an initial prioritization map by combining economic value and operational criticality.

Table 10. ABC–VED Matrix and Recommended Strategy

Category	Interpretation	Recommended Strategy
A–V	High value and vital	Top priority: retain, inspect, repair if feasible, strategic stock
A–E	High value and essential	High priority: retain with strict control, repair selectively
A–D	High value but desirable	Review for transfer, sale, or value recovery
B–V	Medium value and vital	High priority: retain as strategic backup
B–E	Medium value and essential	Medium priority: selective repair and controlled storage
B–D	Medium value but desirable	Low priority: evaluate for disposal if the condition is poor
C–V	Low value but vital	Medium priority: retain minimum stock due to operational importance
C–E	Low value and essential	Low priority: retain a limited quantity or replace if damaged
C–D	Low value and desirable	Disposal priority: scrap or remove from the warehouse

The ABC–VED matrix helps identify materials that should be prioritized for retention and repair, as well as materials that should be considered for disposal. The integrated ABC–VED results show that the largest group is B–V with 360 items, followed by B–E with 97 items, C–D with 64 items, C–V with 40 items, C–E with 11 items, and A–V with 8 items.

Table 11. Integrated ABC–VED Classification Results

ABC–VED Category	Number of Items	Percentage of Items	Main Interpretation
A–V	8	1.38%	High value and vital
B–V	360	62.07%	Medium value and vital
B–E	97	16.72%	Medium value and essential
C–V	40	6.90%	Low value but vital
C–E	11	1.90%	Low value and essential
C–D	64	11.03%	Low value and desirable
Total	**580**	**100.00%**	

The dominance of B–V materials indicates that most returned materials have medium economic value but high operational criticality. This finding strengthens the need for a multi-criteria approach because many materials that are not classified as high-value assets may still be critical for system reliability. However, the ABC–VED matrix does not fully capture physical condition and reuse potential. Therefore, AHP-based composite scoring is needed to generate a more comprehensive priority classification.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 *e*-ISSN 2622-2035

E. AHP-Based Criteria Weighting

AHP is used to determine the relative importance of economic value, operational criticality, physical condition, and reuse potential. In electricity transmission warehouse management, operational criticality is expected to receive a high weight because system reliability is a primary concern. Economic value is also important because returned materials represent company assets. Physical condition and reuse potential are needed to determine whether materials are technically and economically feasible to retain or repair.

Based on the AHP calculation, operational criticality obtained the highest weight, followed by physical condition, economic value, and reuse potential. This result indicates that returned material handling should prioritize operational continuity while still considering physical feasibility, asset value, and reuse potential. The consistency ratio was checked to ensure that expert judgments were logically consistent.

Table 12. AHP Criteria Weight Results

Criterion	Weight	Rank
Operational Criticality (VED)	0.5342	1
Physical Condition	0.2286	2
Economic Value (ABC)	0.1646	3
Reuse Potential	0.0727	4

The consistency test produced $\lambda max = 4.1229$, CI = 0.0410, and CR = 0.0455. Since CR < 0.10, the expert judgment is considered consistent. This result indicates that returned material handling decisions in electricity transmission warehouses are primarily driven by operational reliability considerations, while economic value, physical feasibility, and reuse potential serve as supporting criteria.

F. Composite Priority Classification

The composite priority score integrates economic value, operational criticality, physical condition, and reuse potential into a single score. The results show that 397 items were classified as High Priority, 116 items as Medium Priority, and 67 items as Low Priority.

Table 13. Final Priority Classification Results

Priority Category	Number of Items	Percentage of Items	Recommended Strategy
High Priority	397	68.45%	Retain
Medium Priority	116	20.00%	Repair & Reuse
Low Priority	67	11.55%	Disposal
Total	**580**	**100.00%**	

The high proportion of High Priority materials indicates that many returned materials should not be immediately disposed of because they still have operational importance, economic value, acceptable physical condition, or high reuse potential. These materials should be retained as strategic stock or evaluated for transfer to other units that require them. Medium Priority materials should be evaluated for repair and reuse because their condition or reuse potential may still justify recovery actions. Low-priority materials should be prioritized for disposal, scrap, or liquidation because they provide limited operational and economic benefit while continuing to occupy warehouse space.

The physical condition assessment shows that 32 items were categorized as Very Good, 24 items as Good, 412 items as Fair, and 112 items as Poor. This result indicates that most returned materials are not in a completely damaged condition but require further technical evaluation before reuse. Reuse potential assessment shows that 408 items have High reuse potential, 75 items have medium reuse potential, and 97 items have Low reuse potential. These findings support the need for differentiated handling strategies rather than uniform disposal treatment.

The ten highest-priority materials are shown in Table 15. The highest scores are dominated by power transformers and current transformers because these materials have high operational criticality, high economic value, and relatively good physical condition. These materials should be retained as strategic assets and evaluated for reuse or transfer to units that require them.

Table 14/ Physical Condition and Reuse Potential Assessment Results

Assessment Aspect	Category	Number of Items	Percentage of Items
Physical condition	Very Good	32	5.52%
Physical condition	Good	24	4.14%
Physical condition	Fair	412	71.03%
Physical condition	Poor	112	19.31%
Reuse potential	High	408	70.34%
Reuse potential	Medium	75	12.93%
Reuse potential	Low	97	16.72%

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 *e*-ISSN 2622-2035

Table 15
Top Ten Highest-Priority Returned Materials

Rank	Material ID	Material Type	Location	ABC VED	Physical Condition	Reuse Potential	Priority Score	Strategy
1	12345	TRF PWR	GI 150KV Cawang Lama	A–V	Good	High	3.0000	Retain
2	GJBA-01	TRF PWR	Gudang Terbuka Jatirangon	A–V	Good	High	3.0000	Retain
3	GJBA-02	TRF PWR	Gudang Terbuka Jatirangon	A–V	Good	High	3.0000	Retain
4	GJAA-01	TRF PWR	Gudang Terbuka Jatirangon	A–V	Good	High	3.0000	Retain
5	LSI-001	TRF PWR	Gudang Semi Tertutup Balaraja	A–V	Good	High	3.0000	Retain
6	GJAA-29	TRF PWR	Gudang Terbuka Jatirangon	A–V	Good	High	3.0000	Retain
7	GBP-002A	CT	Gudang Tertutup BSD	B–V	Very Good	High	2.8354	Retain
8	GBP-002B	CT	Gudang Tertutup BSD	B–V	Very Good	High	2.8354	Retain
9	GBP-002C	CT	Gudang Tertutup BSD	B–V	Very Good	High	2.8354	Retain
10	GBP-003A	CT	Gudang Tertutup BSD	B–V	Very Good	High	2.8354	Retain

G. Managerial Implication

The proposed framework provides several managerial implications. First, it supports objective decision-making by replacing purely administrative classification with multi-criteria scoring. Second, it helps warehouse managers identify which materials should be retained, repaired, transferred, or disposed of. Third, it supports warehouse capacity optimization by accelerating disposal decisions for low-priority materials. Fourth, it improves asset recovery by identifying high-value materials with reuse potential. Fifth, the framework can be integrated into digital warehouse systems to support automatic scoring and dashboard-based monitoring.

The framework is also aligned with the Material Return and Warehouse Inventory program because it provides a structured basis for evaluating returned materials. By integrating the framework into warehouse information systems, companies can improve traceability, reduce dead stock accumulation, and support faster managerial decisions.

IV. CONCLUSION

This study proposes an integrated ABC–VED–AHP framework for prioritizing returned materials in the management of electricity transmission warehouses. The framework combines economic value, operational criticality, physical condition, and reuse potential to generate a composite priority score. ABC analysis identifies materials with high economic value, while VED analysis evaluates operational criticality. Physical condition assessment and reuse potential evaluation provide additional technical and practical considerations. AHP is used to determine the relative importance of the criteria and ensure a systematic decision-making process.

The proposed framework classifies returned materials into high, medium, and low priority categories. High-priority materials should be retained, repaired, or transferred for operational reuse. Medium-priority materials require selective repair and further evaluation. Low-priority materials should be considered for disposal, scrap, or liquidation to reduce warehouse burden. The framework supports more objective, transparent, and data-driven returned-material management and contributes to warehouse space optimization, dead stock reduction, and improved asset recovery.

Compared with previous inventory classification studies, this research contributes by integrating economic value, operational criticality, physical condition, and reuse potential into a single prioritization framework for returned materials, particularly for non-moving and dead stock items in infrastructure warehouse systems.

Future research may apply the framework to a larger dataset, incorporate actual cost-benefit analysis, and integrate the model into warehouse information systems for real-time decision support. Further studies may also compare AHP with other multi-criteria decision-making methods, such as TOPSIS, PROMETHEE, or ANP, to evaluate the robustness of returned material prioritization results.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11512 *e*-ISSN 2622-2035

Acknowledgment

The authors would like to express gratitude to PT PLN (Persero), UIT JBB, and all experts involved in the assessment and validation process of returned material prioritization data. Their support and technical insights greatly contributed to the completion of this research.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11584 *e*-ISSN 2622-2035

Production Process Quality Improvement In Ice Cream Manufacturing Using Integrated Pareto Chart and 5M1E Fishbone Diagram

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***Abstract*— The research object is the ice cream production process at PT Sejuk Abadi Nusantara, using production and quality-control records from January to June 2024. Of the 29,530 produced units, 630 were defective, representing a defect rate of 2.13%. Pareto analysis indicated four vital few defects that accounted for 79.21% of total defects: non-uniform texture, excessive moisture content, uneven color, and non-standard portion size. A 5M1E Fishbone Diagram and 5-Why verification showed that dominant root causes were associated with machine, method, measurement, and human factors, especially freezer-temperature sensor drift, worn freezer gaskets, inconsistent hardening time, weak mixing standard operating procedures, and insufficient operator training. A corrective and preventive action plan was proposed, covering sensor calibration, freezer maintenance, hardening standardization, visual work instructions, operator training, moisture testing, environmental monitoring, and monthly calibration. The proposed actions are projected to reduce total defects from 630 to 222 units per semester, or 64.8%. The study demonstrates how integrated Pareto-Fishbone analysis can transform quality-control records into operational process-improvement decisions for frozen-food manufacturing.**

Keywords* : *Pareto Chart;* 5M1E*; Fishbone Diagram; Quality Improvement

I. INTRODUCTION

Ice cream manufacturing is a frozen-food production system in which product quality is determined by the interaction among formulation, pasteurization, homogenization, aging, dynamic freezing, hardening, packaging, and cold-chain storage. Defects such as non-uniform texture, excessive moisture content, uneven color, and non-standard portion size do not only represent final-product nonconformities; they also indicate variation in machine condition, production methods, measurement systems, operator behavior, and processing environment. For this reason, quality improvement in ice cream manufacturing requires an integrated analytical framework that can translate quality records into production-process decisions. [1] [2] [3].

The initial manuscript identified 630 defective units from 29,530 production units at PT Sejuk Abadi Nusantara during January-June 2024. The overall defect rate was 2.13%, exceeding the company's tolerance of 1.5%. Four defects dominated the problem: non-uniform texture, excessive moisture content, uneven color, and non-standard portion size. These defects are important because they influence sensory acceptance, regulatory compliance, processing losses, rework cost, and customer trust in frozen dairy products. [4] [5] [2] [6].

Although Pareto charts and Fishbone Diagrams are widely used in quality-improvement studies, many applied manuscripts stop at identifying dominant defects and proposing corrective actions. Such studies often do not test whether the process is statistically stable, do not express defects in correct DPMU and DPMO terminology, do not quantify the economic impact of poor quality, and do not demonstrate at least one implementable improvement. This creates a research gap in applied production-process studies: the need to integrate defect prioritization, SPC stability analysis, CoQ evaluation, root-cause verification, and initial corrective-action implementation within one coherent improvement model. [7] [8] [9] [10].

Second, the Cost of Quality analysis is added to estimate the economic implications of

Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11584 *e*-ISSN 2622-2035

defects and improvements. Third, the SPC analysis is strengthened by showing the p-chart calculation logic, control limits, interpretation of stable-but-incapable performance, and the difference between statistical control and target compliance. Fourth, a minimum real improvement is formulated as an implementable pilot action: hardening-control checklist, daily temperature verification, capacity limit, and operator briefing. Fifth, the research gap is explicitly presented. Sixth, DPMU and DPMO terminology is corrected so that defects per million units and defects per million opportunities are not mixed [7] [8] [9] [11] [12]

Table 1. Alignment of The Manuscript with Tibuana Scope and Applied Production-Process Contribution

Tibuana Scope	Alignment in this article	Evidence In The Manuscript
Application of industrial process	Supporting scope	The study describes ice cream production stages, including homogenization, aging, freezing, hardening, packaging, and cold storage, as the operational context.
Applied methods of the production process	Main scope	The study integrates Pareto Chart, p-chart SPC, CoQ, 5M1E Fishbone Diagram, 5-Why verification, DPMU/DPMO calculation, and CAPA to improve production-defect performance.
Applied management of the production process	Supporting scope	The study translates root causes into PIC, target time, success indicators, implementation checklist, monitoring indicators, and cost implications.

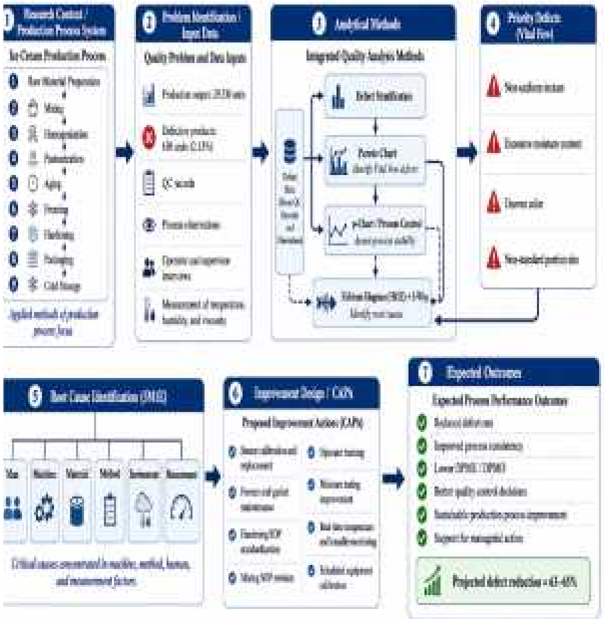


Figure 1. Conceptual Framework for The Applied Methods of Production Process Scope

Table 2. Research Gap and Contribution of the Study

Prior Tendency in Quality Improvement Studies	Identified Gap	Contribution of This Study
Pareto and Fishbone are commonly used to rank defects and list possible causes.	Corrective actions are often proposed without economic justification.	CoQ is added to estimate prevention, appraisal, internal failure, external failure, projected savings, and payback logic.
SPC is sometimes presented as a chart only.	The difference between statistical stability and target compliance is not fully explained.	The p-chart is strengthened with p-bar, UCL, LCL, monthly proportions, and interpretation of a stable but not yet capable process.
DPMU and DPMO are frequently used interchangeably.	Misinterpretation occurs when production units and quality opportunities are not separated.	DPMU is defined as defects per million units produced, while DPMO is based on eight CTQ opportunities per unit.
Corrective action plans are frequently conceptual.	There is limited evidence of initial implementation feasibility.	A minimum real improvement is specified through a hardening checklist, PT-100 verification, batch-capacity control, and operator briefing.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11584 *e*-ISSN 2622-2035

II. RESEARCH METHODOLOGY

2.1. Research Objects and Locations

This study uses a descriptive quantitative case-study approach at PT Sejuk Abadi Nusantara, a medium-scale ice cream manufacturer located in Semarang Regency, Central Java, Indonesia. The company produces ice cream cones, bars, cups, and sandwiches, with a production capacity of approximately 30,000 units per semester. Field observation was conducted in the production line, raw material storage, hardening freezer area, packaging area, and cold storage. [1] [6] [2] [3].

The research object is the quality performance of the ice cream production process, especially defects related to texture, moisture content, color, portion size, packaging, aroma, inclusion distribution, and labeling. This object is suitable for applied industrial engineering research because it converts quality-control records into production-method improvements. [13] [14] [15].

2.2. Data Types and Sources

The study used secondary and primary data. Secondary data included daily production reports from January to June 2024, daily QC inspection sheets, defect-type records, preventive-maintenance documents, and production SOPs. Primary data were obtained through direct observation, structured interviews with production and QC personnel, and direct measurement of process parameters such as freezer temperature, room humidity, mix viscosity, hardening time, and batch load. Twelve key informants were involved: one production manager, one QC manager, three supervisors, five senior operators, and two machine technicians [8] [16] [2] [3]. The combination of production records, direct observation, and interviews is intended to reduce single-source bias and strengthen root-cause verification [1] [3] [16].

2.3. Analysis Method

The analysis was conducted in seven stages. First, defect data were classified into eight CTQ categories based on company inspection criteria. Second, Pareto analysis was conducted by sorting defect frequencies and calculating cumulative percentages.

% Cumulative_i = Σ(f_j, j=1 to i) / Σ(f_j, j=1 to n) x 100% …(1)

Third, SPC analysis was conducted using a p-chart because the quality characteristic was the proportion of defective units.

p_i = d_i / n_i … (2)

p-bar = Σ d_i / Σ n_i … (3)

UCL_i = p-bar + 3√[p-bar(1-p-bar)/n_i] … (4)

LCL_i = max{0, p-bar - 3√[p-bar(1-p-bar)/n_i]} … (5)

Fourth, DPMU and DPMO were calculated with corrected denominators. Fifth, the cost of Quality was calculated to estimate economic losses and the feasibility of improvement actions. Sixth, the two dominant defects were analyzed using a 5M1E Fishbone Diagram and verified by 5-Why questioning. Seventh, corrective and preventive actions were designed, and a minimum improvement was translated into an initial implementation protocol [17] [11].

DPMU = (number of defects/number of produced units) × 1,000,000 … (6)

DPMO = (number of defects / [number of produced units × number of CTQ opportunities]) × 1,000,000 … (7)

In this study, each unit has eight CTQ opportunities. Therefore, DPMO is lower than DPMU because the denominator includes all quality opportunities rather than the produced units only. [10] [14].

Similar integrated quality-tool approaches have been applied in Tibuana studies on packaging defects, wet mix products, ceramic products, sugar packaging, and production-process performance improvement. [17] [18] [19] [20].

Defect rate, DPMU, and DPMO were used as quantitative indicators. Defect rate was computed by dividing defective units by total production units. DPMU was computed as defects per one million produced units. DPMO was computed by dividing the number of defects by total opportunities, where each unit had eight CTQ opportunities, and multiplying the result by one million. This distinction is important because DPMU and DPMO represent different denominators in process-capability interpretation. [13] [14] [15].

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11584 *e*-ISSN 2622-2035

2.4. Data Validity

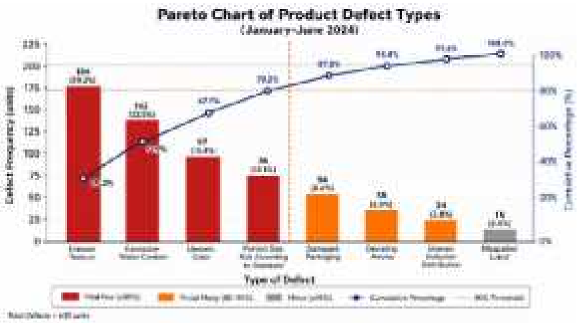
Data validity was maintained through triangulation among QC records, production reports, direct observation, maintenance/ calibration documents, and confirmation from production and QC personnel. Monthly defect records were checked for consistency with total production, and root causes were not accepted as final unless supported by observation, document evidence, process measurement, or informant confirmation. [8] [16] [2] [3].

The classification of defect types was discussed with the QC manager to maintain consistency with company inspection criteria. Root causes identified in Fishbone Diagram sessions were not accepted as final until they were supported by observations, document evidence, process measurements, or confirmation from key informants. This triangulation logic is consistent with applied process-improvement studies in which measurement accuracy and source verification are essential before corrective actions are proposed. [7] [3] [16].

III. RESULTS AND DISCUSSION

3.1. Product Defect Data Profile

During January-June 2024, the company produced 29,530 units and identified 630 defective units. The aggregate defect rate was 2.13%, exceeding the internal tolerance of 1.5%. The four highest defect categories contributed 79.21% of total defects, indicating that improvement should focus on the vital few problems rather than spreading resources across all defect types equally [17] [20] [1].



This prioritization is aligned with applied quality-control studies that use defect data to guide production-process improvement. [17] [21] [18].

Table 3. Distribution of Ice Cream Product Defects, January – June 2024

No.	Type of Defect	Frequency (units)	Percentage (%)	Cumulative (%)	Category
1.	Non-Uniform Texture	184	29.21	29.21	Vital Few
2.	Excessive Moisture Content	142	22.54	51.75	Vital Few
3.	Uneven Color	97	15.40	67.14	Vital Few
4.	Non-Standard Portion Size	76	12.06	79.21	Vital Few
5.	Damaged Packaging	54	8.57	87.78	Trivial Many
6.	Deviating Aroma	38	6.03	93.81	Trivial Many
7.	Uneven Inclusion Distribution	24	3.81	97.62	Trivial Many
8.	Misapplied Label	15	2.38	100.00	Trivial Many
	Total	630	100.00		-

3.2. Pareto Chart Analysis

The Pareto result confirms that non-uniform texture and excessive moisture content are the two most critical defects. These defects are directly connected to homogenization consistency, freezing behavior, hardening temperature, cold-chain stability, and the reliability of measurement instruments. From a production-process perspective, the Pareto result is not merely a ranking of defects; it is a decision tool for selecting process parameters that require immediate control. [1] [22].

Recent ice cream process studies confirm that process conditions influence crystallization, overrun, structural properties, and product stability. [1] [6] [22] [23]. Thus, the Pareto result is not only a statistical priority but also a process-engineering priority.

Figure 2. Pareto Chart of Ice Cream Product Defects

3.3. SPC Analysis Using p-Chart

The SPC analysis uses a p-chart because the measured quality characteristic is the proportion of defective units per month. The central line is p-bar = 630 / 29,530 = 0.02133 or 2.13%. Because monthly sample sizes differ, the upper and lower control limits were calculated separately for each month. Figure 3 presents a monthly recap whose total defects are consistent with the total of 630 units. [8] [10].

p-ISSN 2622-2027
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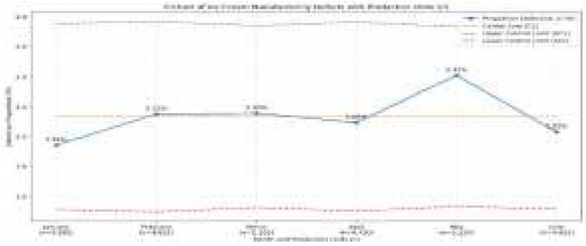

Figure 3. Monthly p-Chart Calculation for Aggregate Defect Rate

All monthly defect proportions are below their respective UCL and above LCL; therefore, the process is statistically in control. However, being statistically in control does not mean that the process is acceptable. The center line of 2.13% remains higher than the company tolerance of 1.5%. This means that the process is stable but not capable of meeting the internal quality target. The dominant causes are common causes embedded in the production system, including weak standardization, freezer-condition variation, calibration gaps, and inconsistent hardening practices. Consequently, the correct managerial response is system-level improvement rather than short-term inspection sorting. [8] [10].

3.4. DPMU and DPMO Terminology

DPMU measures defects per one million produced units. Based on 630 defects and 29,530 produced units, DPMU = 21,334. DPMO measures defects per one million quality opportunities. Because this study uses eight CTQ opportunities per unit, DPMO = 2,667. Thus, a value around 21,334 should be interpreted as DPMU, not DPMO. [10] [14].

Table 4. Quality Indicator Interpretation

Indicator	Formula	Before Improvement	Interpretation
Defect Rate	Defects/production units × 100%	2.13%	Aggregate proportion of defective output.
DPMU	Defects/production units × 1,000,000	21,334	Defects per one million produced units.
DPMO	Defects / (production units × 8 CTQ) × 1,000,000	2,667	Defects per one million quality opportunities.

3.5. Fishbone Diagram — Non-Uniform Texture Defects

Non-uniform texture was the highest defect category, with 184 units or 29.21% of all defects. The Fishbone Diagram in Figure 3 and the root-cause summary in Table 3 indicate that machine, method, human, and measurement factors were the dominant contributors. The most critical machine-related causes were homogenizer wear and freezer temperature sensor drift. A homogenizer operating beyond its service life may reduce pressure consistency and weaken fat-globule dispersion, while freezer sensor drift can prevent accurate control of freezing temperature. Method-related causes included a mixing SOP that did not specify rpm, mixing duration, target viscosity, or acceptance limits. Such weak operational detail can generate inter-operator variation and inconsistent product texture. These findings support the use of method-based industrial engineering tools to translate product defects into controllable process parameters. [17] [6] [13] [16].

Non-uniform texture was the highest defect category, with 184 units or 29.21% of total defects. The 5M1E analysis indicates that machine, method, human, and measurement factors were dominant. Machine-related causes included homogenizer wear, freezer-temperature sensor drift, and calibration inconsistency. Method-related causes included a mixing SOP that did not specify rpm, duration, mixing sequence, target viscosity, or acceptance limit. Human-related causes included different operator interpretations of viscosity and process endpoints. Measurement-related causes included irregular calibration of the viscometer and temperature reference instrument. [16] [1] [6] [4] [22].

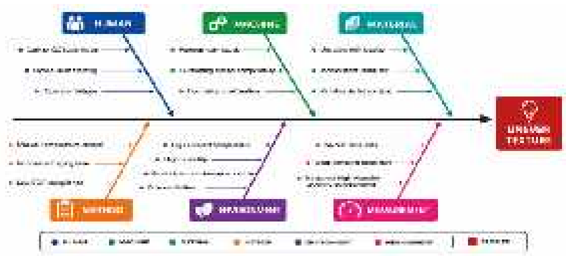

Figure 4. Fishbone Diagram for Non-Uniform Texture Defects

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11584 *e*-ISSN 2622-2035

Table 5. Root-Cause Analysis For Non-Uniform Texture Defects

5M1E Category	Main Symptom	Root-Cause Interpretation	Risk Level
Man	Operators interpret viscosity data inconsistently; fatigue occurs across shifts.	Training, supervision, and quality interpretation are not standardized.	High
Machine	Homogenizer wear, freezer sensor drift, and calibration inconsistency.	Homogenization pressure and actual freezing temperature deviate from the target.	Very High
Material	Variation in milk fat and stabilizer dose.	Incoming inspection does not fully control fat content, total solids, and stabilizer ratio.	High
Method	Mixing SOP lacks rpm, time, sequence, and viscosity limits.	Work instructions are too general and allow inter-operator variation.	High
Measurement	The viscometer and temperature reference are not calibrated routinely.	QC decisions may be based on inaccurate or delayed data.	High
Environment	Room temperature and humidity are not monitored in real time.	Ambient conditions affect mix viscosity and freezing load.	Medium

3.6. Fishbone Diagram — Excessive Moisture Defect

Excessive moisture content accounted for 142 units or 22.54% of total defects. This defect was more strongly linked to hardening and cold-chain control. The dominant root causes were worn freezer gaskets, PT-100 sensor deviation, irregular defrost cycle, hardening-capacity overload, variable hardening time, and insufficient moisture-testing frequency. If the actual hardening temperature is higher than the displayed set point, ice crystallization becomes less controlled, and the product becomes vulnerable to softening, moisture migration, and texture instability [1] [6] [23] [4] [2] [3].

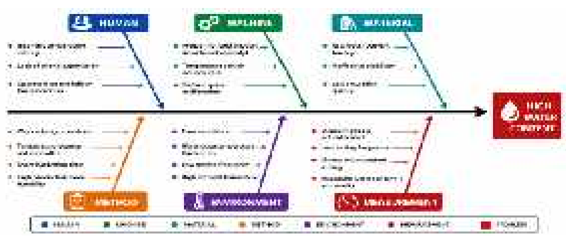

Figure 5. Fishbone Diagram for Excessive Moisture Defects

Table 6. Root-Cause Analysis for Excessive Moisture Defects

5M1E Category	Main Symptom	Root Cause Interpretation	Risk Level
Man	Default hardening setting used without actual-temperature verification	Operators do not have a batch checklist for hardening control	Very high
Machine	Worn gasket; PT-100 sensor deviation; defrost instability	The freezer cannot maintain the actual hardening temperature at the required level	Very High
Material	High water content and low stabilizer effectiveness	Incoming inspection does not consistently test moisture and total solids	High
Method	Hardening time varies; batch load exceeds capacity	The production schedule is not synchronized with the hardening capacity	Very High
Measurement	The moisture test is manual, and the sampling frequency is low	Moisture deviation is detected late and cannot prevent batch defects	High
Environment	Packing-room humidity is high; cold-storage temperature fluctuates	Transfer and storage conditions increase softening risk	High

3.7. Cost of Quality Analysis

The CoQ categories used in this study are prevention cost, appraisal cost, internal failure cost, and external failure cost. Because detailed accounting data were not fully separated in the original QC record, the cost values below are presented as a managerial estimate based on production interviews and standard-cost assumptions. The table should be updated with the company's actual accounting record before final submission if audited cost data are available. [11].

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Table 7. Cost of Quality Used in the Analysis

Cost Category	Cost Component	Assumption Used in Calculation	Estimated Value (IDR)
Prevention	SOP revision, operator briefing, checklist design, calibration schedule preparation	One-time preparation and training support	2,500,000
Prevention	Freezer gasket repair and hardening-capacity marking	Initial corrective maintenance	1,800,000
Appraisal	Moisture analyzer usage, thermometer cross-check, and additional batch inspection	Additional inspection resources per semester	2,000,000
Appraisal	Monthly calibration and verification records	Routine measuring-system control per semester	2,400,000
Internal Failure	Rework, disposal, additional labor, and extra freezing energy	Average IDR 30,000 per defective unit	630 × 30,000 = 18,900,000
External Failure	Complaint reserve, replacement, goodwill loss allowance	Average IDR 5,000 per defective unit	630 × 5,000 = 3,150,000

Table 8. Before-After Cost of Quality Projection

Indicator	Before Improvement	Projected After Improvement	Change
Defective units per semester	630	222	-408 units
Estimated failure cost (IDR 35,000/defect)	22,050,000	7,770,000	Saving 14,280,000
Prevention and appraisal investment	-	8,700,000	Implementation cost
Net first-semester economic benefit	-	-	5,580,000
Estimated payback period	-	-	3.7 months

The CoQ analysis shows that the proposed improvement is economically meaningful because the projected reduction of 408 defects may reduce failure cost by approximately IDR 14.28 million per semester. After considering the prevention and appraisal investment of IDR 8.70 million, the first-semester net benefit is estimated at IDR 5.58 million, with an approximate payback period of 3.7 months. This economic interpretation strengthens the managerial relevance of the quality-improvement program. [11].

3.8. Minimum Real Improvement Implementation

To move beyond a purely proposed CAPA, this study includes one real improvement that can be implemented immediately at the hardening stage. The selected action is a hardening-control improvement package because excessive moisture is the second-largest defect and because the root causes are operationally controllable. The package consists of four elements: (1) actual-temperature verification using a calibrated PT-100 reference before each production batch; (2) a hardening checklist covering batch load, target temperature, hardening duration, and operator sign-off; (3) a maximum batch-capacity limit to prevent freezer overload; and (4) a 15-minute operator briefing before each shift for one implementation week [7] [16] [14] [2] [3].

Table 9. Real Improvement Implementation Matrix

Implementation Item	Operational Action	Responsible Unit	Evidence to Collect	Success Indicator
Temperature Verification	Compare the freezer display with the calibrated PT-100 reference before batch loading.	Engineering and QC	Daily verification sheet	Deviation within ±0.5°C
Hardening Checklist	Record batch load, start time, end time, target temperature, and operator sign-off.	Production supervisor	Completed the checklist per batch	Checklist compliance ≥95%.
Capacity Limit	Mark the maximum rack/batch load and prohibit overloading during peak demand.	Production and warehouse	Batch loading record	No batch exceeds the defined capacity.
Operator Briefing	Brief operators on hardening target, moisture risk, and reporting rule.	Supervisor and HRD	Attendance and post-briefing note	100% of operators briefed.

The implementation does not require large capital expenditure and can be audited using simple production records. For final empirical validation, the company should collect at least four weeks of post-implementation data and compare moisture-related defect proportions before and after implementation using the same p-chart logic. In this article, the minimum real improvement functions as an initial

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11584 *e*-ISSN 2622-2035

implementation bridge between root-cause analysis and full CAPA deployment [8] [9] [10] [16] [14].

3.9. Corrective and Preventive Action Plan and Impact Projection

Table 10. Corrective and Preventive Action Plan Based on 5M1E Root Causes

No.	Root Cause	Corrective/ Preventive Action	PIC	Target	Success Indicator
1.	The freezer temperature sensor is inaccurate	Install/verify the digital PT-100 sensor and conduct initial calibration	Engineering & QC	2 weeks	Temperature stable within ±0.5°C
2.	Freezer gasket or panel leakage	Repair the gasket/panel and include hardening the freezer in preventive maintenance	Maintenance	1 week	No cold-air leakage detected
3.	Hardening time is inconsistent	Define standard hardening time, temperature, and batch-capacity limit	Production & QC	1 week	Hardening compliance ≥95%
4.	Mixing SOP is too general	Revise the visual SOP with rpm, sequence, duration, and viscosity target	QC & Production	2 weeks	Viscosity variation reduced by≥30%
5.	Operator technical capability is uneven	Train operators in ice cream process control and measuring instruments	HRD & Supervisor	1 month	100% of operators pass the post-test
6.	Moisture testing is manual and infrequent	Use a moisture analyzer and inspect every batch	QC	2 weeks	Moisture data available per batch
7.	Temperature and humidity are not monitored in real time	Install data loggers in production, packing, and cold-storage areas	Engineering	3 weeks	RH ≤65%; cold storage stable
8.	Calibration is not routine	Create a monthly calibration schedule for critical instruments	QC & Maintenance	1 month	100% of critical instruments are calibrated

Table 11. Projected Defect Reduction After CAPA Implementation

Defect Type	Before CAPA (units)	Projected After CAPA (units)	Reduction (units)	Reduction (%)
Non-uniform texture	184	62	122	66.3
Excessive moisture content	142	47	95	66.9
Uneven color	97	38	59	60.8
Non-standard portion size	76	28	48	63.2
Damaged packaging	54	24	30	55.6
Deviating aroma	38	16	22	57.9
Uneven inclusion distribution	24	9	15	62.5
Misapplied label	15	6	9	60.0
Total	630	222	408	64.8

Table 12. Quality Indicator Comparison Before and After Projected Improvement

Indicator	Before Improvement	After Improvement	Interpretation
Defect Rate	2.13%	0.75%	Defect proportion moves below the internal tolerance of 1.5%.
DPMU	21,334	7,518	Defects per one million production units.
DPMO (8 CTQ Opportunities)	2,667	940	Defects per one million quality opportunities.
Failure Cost	IDR 22.05 million	IDR 7.77 million	Estimated failure-cost saving of IDR 14.28 million per semester.
Total Reduction	-	64.8%	Expected effect of integrated machine, method, measurement, and human improvements.

The projected implementation of all eight actions would reduce total defects from 630 to 222 units per semester, equivalent to a 64.8% reduction. DPMU would decrease from approximately 21,334 to 7,518, while DPMO, based on eight CTQ opportunities, would decrease from approximately 2,667 to 940. The analysis indicates that technical-mechanical improvements should be implemented first because sensor accuracy, freezer integrity, and hardening standardization directly affect the two dominant defects [7] [8] [9] [10] [16] [14] [11].

p-ISSN 2622-2027
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IV. CONCLUSION

Based on 29,530 produced units and 630 defective units, the aggregate defect rate was 2.13%, exceeding the company's tolerance of 1.5%. Pareto analysis identified four vital few defects that accounted for 79.21% of total defects: non-uniform texture, excessive moisture content, uneven color, and non-standard portion size. Fishbone analysis showed that the dominant root causes were related to machine, method, measurement, and human factors, especially freezer-temperature sensor drift, worn freezer gaskets, inconsistent hardening time, weak mixing SOP, irregular calibration, and insufficient operator training.

The SPC analysis indicates that the monthly defect proportions were statistically in control but not capable of meeting the internal target, because the center line remained above 1.5%. This interpretation changes the improvement focus from short-term sorting to system-level standardization, calibration, preventive maintenance, and process monitoring. The corrected terminology also clarifies that 21,334 is DPMU, while DPMO is 2,667 when eight CTQ opportunities are considered.

The addition of Cost of Quality analysis shows that poor quality creates measurable economic losses through rework, scrap, additional labor, additional freezing energy, and complaint reserves. The projected CAPA can reduce defects from 630 to 222 units per semester, decrease defect rate from 2.13% to 0.75%, reduce DPMU from 21,334 to 7,518, reduce DPMO from 2,667 to 940, and generate estimated failure-cost savings of IDR 14.28 million per semester before improvement investment. A minimum real improvement was specified through hardening-control checklist, PT-100 verification, batch-capacity limitation, and operator briefing. Future research should validate the projected reduction using post-implementation data, integrate FMEA for RPN-based prioritization, and develop IoT-based real-time monitoring of temperature, humidity, viscosity, and hardening time.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11149 *e*-ISSN 2622-2035

Engineering Design and Ergonomic Evaluation of an Assistive Device for Manual Material Handling

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***Abstract* — Manual material handling (MMH) remains a major contributor to work-related musculoskeletal disorders in manufacturing environments. This study proposes and evaluates an assistive device for box panel handling aimed at reducing ergonomic risk during lifting and transport operations at PT. XYZ. A case-study approach was employed using multiple ergonomic assessment methods, including the Nordic Body Map (NBM), Rapid Entire Body Assessment (REBA), the Revised NIOSH Lifting Equation (RNLE), and the Snook Tables. Baseline results indicated dominant lower-back (77%) and upper-back (71%) complaints, a high-risk REBA score of 12, low recommended weight limits (4.46–4.91 kg), and excessive lifting indices (5.50–6.05) for a maximum load of 37 kg. The Snook analysis yielded a maximum acceptable weight of 13.0 kg with a load-to-MAW ratio of 1.38. A trolley-based assistive device integrating lifting and transfer support was then designed to minimize trunk flexion and eliminate manual carrying during transport. Post-intervention evaluation showed substantial improvements, with the REBA score reduced to 1, lifting indices below unity, and the load-to-MAW ratio approaching zero. These results demonstrate that engineering controls in the form of practical assistive devices can effectively reduce ergonomic risk and improve manual material handling safety in industrial settings.**

***Keywords:* Assistive Device, Ergonomic Risk Assessment, Manual Material Handling, Revised NIOSH Lifting Equation.**

I. INTRODUCTION

Manual material handling (MMH) remains a major contributor to work-related musculoskeletal disorders (WMSDs) in manufacturing and logistics operations [1]-[6]. Repetitive lifting, carrying, and load transport impose cumulative biomechanical demands—particularly on the trunk and shoulder regions—leading to fatigue and chronic musculoskeletal symptoms [7], [8]. Empirical studies also report that manual handling–dominant work frequently exhibits elevated discomfort and postural risk when assessed using standardized symptom screening and observational posture methods [9].

PT. XYZ, a medium-scale manufacturer of electrical panel components, currently relies on manual lifting and transportation of box panels weighing 18–37 kg over a 22.5 m route, repeated up to 70 cycles per day. Baseline screening using a Nordic Body Map (NBM) approach indicated substantial discomfort concentrated in the lower back [10]. Postural assessment using Rapid Entire Body Assessment (REBA) produced a score of 12, indicating a high-risk posture requiring prompt corrective action [11]. Biomechanical evaluation using the Revised NIOSH Lifting Equation (RNLE) reported lifting index values exceeding the recommended safe threshold (LI > 1.0), suggesting elevated low-back injury risk under the observed task conditions [12], [13]. Furthermore, psychophysical evaluation using the Snook and Ciriello Tables estimated a maximum acceptable weight (MAW) of approximately 12–13 kg for comparable handling conditions, which is far below the current load demands [14]. Collectively, these results confirm a clear mismatch between task requirements and human capability in the existing process.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11149 *e*-ISSN 2622-2035

Occupational safety and health (OSH) frameworks emphasize that risk reduction is most effective when hazards are controlled at the source, prioritizing engineering controls over administrative measures and personal protective equipment [15]-[17]. Applied OHS studies further show that combining ergonomic identification with structured risk assessment supports more practical and defensible workplace improvements [18], [19].

However, many medium-scale industries still face barriers to adopting engineered solutions due to cost constraints and limited technical resources, and ergonomic risk identification often fails to translate into implementable device concepts [20]. Therefore, this study develops a practical material handling aid as an engineering control to reduce physical workload and ergonomic risk during box panel transfer at PT. XYZ. The contribution lies in linking quantitative ergonomic diagnosis to an actionable technical redesign and evaluating improvement using standard ergonomic indicators.

II. METHODS

This study employed an applied industrial engineering case-study approach to reduce ergonomic risks associated with manual material handling (MMH) of box panels at PT. XYZ. The methodology integrates baseline ergonomic risk assessment with a rational engineering design process based on Nigel Cross to generate, evaluate, and finalize a practical material handling aid.

A. Study Setting, Participants, and Task Observation

PT. XYZ is a medium-scale manufacturer of electrical panel components. The MMH process under study involves repetitive lifting, transporting, and placing box panels from the packing area to the truck loading point. The company employs 35 workers, all of whom are users involved in the box panel handling process. Field observations were conducted on representative task cycles covering (i) lifting at the origin point, (ii) transport along the packing-to-truck route, and (iii) placement at the destination.

Work measurement captured parameters required for ergonomic analysis and design requirement definition, including load weight range, box panel dimensions, horizontal and vertical load locations, vertical travel distance, asymmetry conditions, coupling quality, handling frequency/duration, carrying distance, route width/length, and truck bed height.

B. Baseline Ergonomic Risk Assessment Methods

Four complementary ergonomic assessment methods were applied to quantify baseline risk and justify the need for engineering redesign.

1) *Musculoskeletal symptom assessment*
A Nordic Body Map (NBM)-based instrument was used to identify the distribution and severity of musculoskeletal discomfort among workers performing MMH tasks [12].
2) *Postural risk assessment*
Rapid Entire Body Assessment (REBA) was applied to evaluate whole-body postural loading during lifting and transfer activities and to determine the urgency of corrective actions [11].
3) *Biomechanical lifting analysis*
The Revised NIOSH Lifting Equation (RNLE) was used to compute the Recommended Weight Limit (RWL) and Lifting Index (LI) for the observed lifting task [9], [10]. To improve replicability and reduce manual calculation error, RWL and LI were computed using the ErgoPlus RNLE Calculator by entering task parameters (horizontal/vertical locations, vertical travel distance, asymmetry angle, coupling quality, frequency, and task duration) to obtain RNLE multipliers and final RWL/LI outputs [21].
4) *Psychophysical evaluation*
The Snook and Ciriello Tables were used to estimate Maximum Acceptable Weight (MAW) under comparable manual handling conditions [8]. In this study, MAW and the external load-to-MAW ratio were obtained using the NexGen Ergonomics (ErgoIntelligent MMH) web-based tool implementing Snook-table-based psychophysical models [22].

C. Needs Identification

Needs identification was performed to ensure traceability from shop-floor constraints and user expectations to measurable engineering requirements. System needs were derived from

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11149 *e*-ISSN 2622-2035

workplace measurements and workflow constraints (e.g., box panel weight and dimension range, route constraints, and truck interface height). User needs were collected using an open-ended questionnaire administered to all 35 workers. The responses were compiled and thematically grouped into five dominant criteria that emerged repeatedly: comfort and usability, safety and health, effectiveness, versatility and durability, and efficiency. This needs-to-requirements structuring aligns with work-system design principles that integrate technical constraints with human-centered considerations [23], [24].

The grouped user needs were then translated into quantitative performance specifications (e.g., minimum load capacity, platform/table sizing, stability during transport, route compatibility, and ergonomic handle interface). These specifications served as the formal design requirements input for the rational design process.

D. Assistive Device Design Method

The proposed material handling aid was developed using the rational design method presented by Nigel Cross, applied in six stages to ensure a transparent progression from needs to final design output [25]:

1) *Clarifying objectives*
Design objectives were organized hierarchically with the primary objective of reducing MMH ergonomic risk, supported by safety, usability, durability, layout compatibility, and efficiency objectives.
2) *Function Analysis*
A black-box model defined the transformation from operator input to controlled product transfer, and a transparent-box decomposition translated the overall goal into sub-functions, including load support, controlled movement, stabilization during transport, safe placement at the destination, and operator–device interaction.
3) *Performance Specification*
Performance specifications were derived by integrating ergonomic diagnosis, system constraints (box geometry, route dimensions, truck bed height), and grouped user needs. Key targets included reducing postural risk, decreasing biomechanical lifting risk, ensuring adequate stability, and meeting efficiency expectations.
4) *Determining Technical Characteristics*
The technical characteristics of the material handling aid were derived using Quality Function Deployment (QFD). User needs (voice of users) were listed on the “WHATs” side, and engineering characteristics were defined as “HOWs”. The relationship matrix was used to translate each need into measurable technical directions (e.g., frame strength, stability, mobility, interface ergonomics, platform geometry, and maintainability). Importance weights for the WHATs were obtained from the questionnaire responses of the 35 workers, and the resulting weighted priorities were used to identify the critical engineering characteristics that should be emphasized in concept generation and selection.
5) *Generating alternatives*
Alternative solution principles were generated for each sub-function and combined to form feasible concepts.
6) *Evaluating alternatives*
Concept selection was performed using a weighted objectives method as recommended in systematic engineering design practice [25], [26]. Criterion weights were derived from normalized mean importance ratings obtained from the 35-user questionnaire. Each concept was scored against each criterion, and a total weighted score was computed to identify the best overall concept.
To support rational concept evaluation, the relative importance of evaluation criteria was determined before concept selection. A pairwise comparison using the zero–one method was applied to the representative user-need criteria. Each criterion was compared against the others based on perceived importance derived from brainstorming sessions and questionnaire responses involving 35 operators and supervisors. The resulting scores were normalized to obtain criterion weights, which were subsequently used in the weighted objectives method for concept evaluation

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11149 *e*-ISSN 2622-2035

7) Improving details

The selected concept was refined through dimensioning, material/component selection, and simplification for manufacturability and maintenance, resulting in a finalized design configuration for implementation.

E. Assistive Device Design Method

The effectiveness of the proposed device was evaluated by comparing baseline vs. redesigned conditions using the same ergonomic indicators: (i) REBA score, (ii) RNLE outputs (RWL and LI), and (iii) Snook-based MAW ratio. Improvement was indicated by reduced postural and biomechanical risk levels and improved psychophysical feasibility, consistent with OSH frameworks emphasizing engineering controls to mitigate risk at the source [15]–[17].

III. RESULT AND DISCUSSION

A. Results of Ergonomic Risk Assessment

1. Musculoskeletal symptoms

The Nordic Body Map screening indicates substantial musculoskeletal complaints after operators perform the MMH task. In particular, the lower back is the dominant complaint region, followed by back discomfort, confirming that the task imposes a high physical burden on the trunk region. The baseline complaint proportions can be referenced from the NBM results reported in the case study documentation.

As shown in Table 1, the highest prevalence of discomfort was reported in the lower back (77%), upper back (71%), and back region (63%), indicating that the MMH task primarily imposes excessive loading on the trunk and spinal regions.

Table 1. Nordic Body Map Questionnaire Summary

No	Complaint	Total	Percentage
1	Lower back pain	27	77%
2	Upper back pain	25	71%
3	Back pain	22	63%
4	Pain in the upper neck	19	54%
5	Pain in the upper right arm	16	46%
6	Shoulder pain	11	31%
7	Pain in the right knee	10	29%
8	Pain in the left knee	10	29%
9	Pain in the right arm	10	29%
10	Pain in the left arm	9	26%
11	Pain in the lower right leg	8	23%
12	Pain in the left wrist	8	23%
13	Pain in the wrist	8	23%
14	Pain in the upper left arm	7	20%
15	Pain in the left ankle	5	14%
16	Pain in the right ankle	5	14%
17	Pain in the left calf	4	11%
18	Pain in the right calf	4	11%
19	Pain in the lower neck	3	9%

2. *Psychophysical Evaluation*

Psychophysical evaluation using the Snook Tables for the transport route from packing to the truck shows that the Maximum Acceptable Weight (MAW) is approximately 18 kg at 0.5 lifts/min, while the observed task requires handling loads beyond that level. The baseline external load-to-MAW ratio is 1.47 (> 1), indicating that the task is hazardous and requires improvement.

Figure 1 presents the Snook Table (psychophysical) evaluation of the packing-to-truck carrying task. The Maximum Acceptable Weight (MAW) is 18.0 kg, and the external load-to-MAW ratio is 1.47 (>1), indicating a high-risk task requiring ergonomic intervention. The output was generated using NexGen Ergonomics software based on the Snook and Ciriello psychophysical guidelines.

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DOI: https://doi.org/10.36456/tibuana.9.02.11149 *e*-ISSN 2622-2035

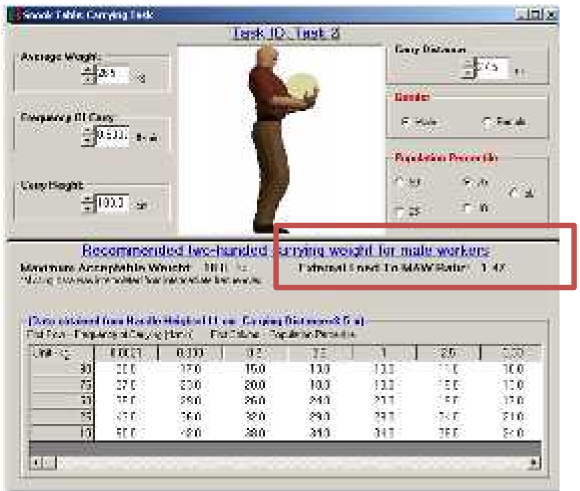

Figure 1. Snook Table Analysis for the Packing-to-Truck Carrying Task

3. Biomechanical Lifting Analysis

The results of the RNLE analysis for the baseline lifting task are presented in Figure 2. The calculated Recommended Weight Limit (RWL) values are 4.46 kg at the origin and 4.91 kg at the destination, which are substantially lower than the actual handled loads.

Figure 2. RNLE results for the baseline lifting task

For the maximum observed load of 37 kg, the corresponding Lifting Index (LI) values reach 6.05 (origin) and 5.50 (destination), indicating a very high-risk lifting condition (LI > 1). These findings confirm that the existing lifting task exceeds acceptable biomechanical limits and requires immediate ergonomic intervention.

4. Postural Risk Assessment

Postural assessment using REBA indicates a high-risk posture during baseline lifting. As shown in Fig. 3, the documented lifting posture involves pronounced trunk flexion and upper-limb deviation, which is reflected in the REBA assessment presented in Fig. 4. The resulting REBA score of 12 corresponds to a high/sustained risk category and requires prompt corrective action.

Figure 3. Baseline lifting posture

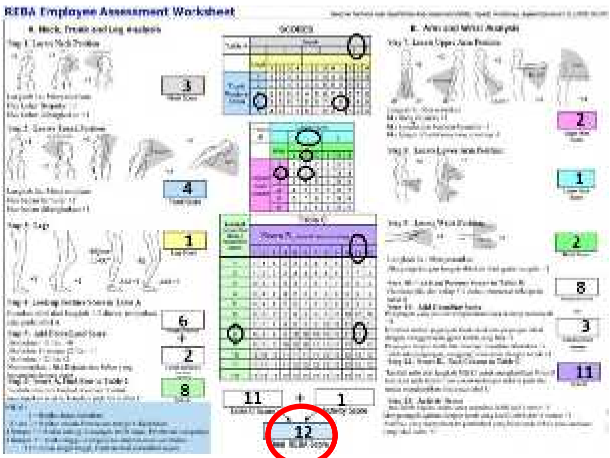

Figure 4. Baseline REBA assessment output

B. Result of Needs Identification

System needs derived from shop-floor observation and measurement indicate that the material handling solution must accommodate box panels weighing up to 37 kg and having maximum dimensions of approximately 80 cm × 60 cm. The device must be operable along the existing transport route (≈15 m length, ≈2 m width), interface safely with the truck bed height (≈145

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DOI: https://doi.org/10.36456/tibuana.9.02.11149 e-ISSN 2622-2035

cm), and maintain stability during pushing and placement to prevent load shifting.

User needs were collected from all 35 workers involved in the handling process through an open-ended questionnaire and follow-up discussion. Responses were summarized and grouped using thematic analysis, resulting in five dominant need categories: comfort and usability, safety and health, effectiveness, versatility and durability, and efficiency. These categories were subsequently used to formulate representative user needs that guided the development of design specifications and concept evaluation.

The representative user needs are summarized as follows: (i) easy and comfortable operation, (ii) avoidance of awkward postures, (iii) safe handling without injury risk, (iv) reduced musculoskeletal load, (v) ability to handle heavy loads, (vi) smooth transport during transfer, (vii) usability for different materials, (viii) suitability for long-term use, (ix) low operating effort, and (x) minimal maintenance.

C. *Results of the Design Process*

1) *Clarifying Objectives*

Based on the identified system and user needs, design objectives were structured into an objectives table. The primary objective was to reduce ergonomic risk during lifting and transport, supported by secondary objectives related to safety, usability, durability, layout compatibility, and efficiency. This structure ensured traceability from stakeholder expectations to design targets, as shown in Table 2**.**

2) *Establishing Functions*

Function analysis was conducted using a black-box and transparent-box approach. The black-box (Fig. 5) model defines the transformation from operator input into the controlled transfer of box panels to the truck in a safe, healthy, and comfortable manner. The transparent-box (Fig. 6) decomposition further specifies sub-functions, including load support, pushing/pulling during transport, stabilization, safe placement at the destination, and operator–device interaction.

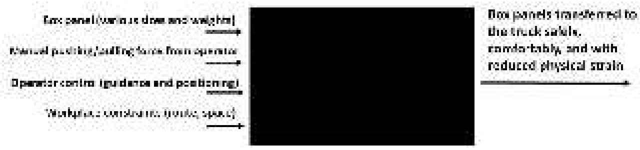

Figure 5. Black Box

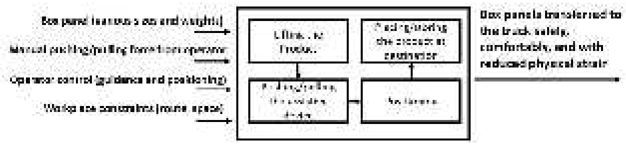

Figure 6. Transparent Box

Table 2. Translation of Objective by Representative User Needs into Engineering Design Specifications

Objective Representative by User Need	Engineering Specification	Objective Category	Supporting Reference
Easy to operate; not complicated; reduces physical effort during handling	Ergonomic interface, handle design, and user–device interaction	Comfort & usability	[11], [12], [13]
Avoid awkward postures (bending/reaching)	Working height alignment and transfer mechanism design		[11], [9], [10]
Prevent box panels from slipping/falling.	Stability system, load securing mechanism, and posture risk reduction	Safety & health	[19], [15]–[17]
Reduce injury risk (especially low back)	Reduction of manual lifting demand through mechanical assistance		[9], [10], [11]
Must carry heavy box panels safely	Structural strength and load-supporting system	Effectiveness	[8], [25]
Reduce transport time and improve flow.	Mobility system and controlled pushing/pulling mechanism		[25], [26]
Usable for other products/materials	Adaptable platform and modular support features	Versatility & durability	[25], [26]
Durable for long-term daily use	Material selection and robust structural design		[25], [26]
Preferably non-electric and low maintenance	Simple mechanical system with low energy requirement	Efficiency	[25], [18], [20]
Must work within existing layout; no fixed rails	Maintenance-friendly design and component simplicity		(measured on-site)

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DOI: https://doi.org/10.36456/tibuana.9.02.11149 *e*-ISSN 2622-2035

3) *Performance Specification*

By integrating ergonomic assessment results, system constraints, and grouped user needs, a set of performance specifications was derived. Key requirements include sufficient load capacity (>37 kg), compatibility with box panel dimensions, stable transport without load shifting, ergonomic handle height for standing operation, and non-powered operation with minimal maintenance. These specifications are summarized in Table 3 and served as the basis for concept generation and evaluation.

Table 3. Performance Specification

No.	Aspect	Observed Condition	Performance Specification
1	Product load	> 37 kg	The box panel support system and frame shall be capable of supporting loads up to 37 kg.
2	Truck bed height	145 cm	The height of the product support/transfer point shall not be lower than 145 cm to enable direct placement on the truck.
3	Box panel length	80 cm	The length of the product support platform shall not be less than 80 cm.
4	Box panel width	60 cm	The width of the product support platform shall not be less than 60 cm.
5	Production floor condition	Limited space	The solution shall operate without installing fixed rails on the production floor.
6	Transport route constraint	-	The device shall be operable along the exit route with an approximate length of 15 m and a width of 2 m.

4) *Determining Technical Characteristics*

Quality Function Deployment (QFD) was applied to translate representative user needs into engineering design priorities. The analysis shows that safety- and load-related needs dominate the importance ranking, followed by usability and efficiency considerations.

The most critical technical characteristics identified from the QFD analysis include structural strength and load support, stability and load securing, mobility for pushing/pulling transport, ergonomic interface and working height alignment, and simplicity for low maintenance.

These characteristics represent the main design drivers and were used to guide the subsequent concept generation and concept selection stages.

5) *Generating alternatives*

Based on the prioritized technical characteristics identified through the QFD analysis, alternative design concepts were generated using a morphological approach. Three feasible concepts (Concept A, Concept B, and Concept C) were developed to represent different combinations of load support, mobility, stabilization, and transfer mechanisms. Concept A emphasizes higher mechanization, Concept B represents a fully manual but bulkier structure, and Concept C adopts a simple non-powered assistive solution. The complete morphological chart is omitted for brevity, and only the resulting concepts are carried forward for evaluation.

6) *Evaluating alternatives*

Concept evaluation was conducted using a weighted objectives method to compare the generated alternatives in a structured manner. Evaluation criteria were derived from representative user needs and QFD results, covering comfort and usability, safety and health, effectiveness, versatility and durability, and efficiency. Criterion weights were obtained from aggregated questionnaire responses of 35 users.

Three alternatives (Concept A, Concept B, and Concept C) were evaluated using the same criteria and weighting scheme. The evaluation results are summarized in Table 5, showing that Concept C achieved the highest total weighted score. Concept C provides a balanced solution that satisfies key ergonomic and operational requirements while maintaining simplicity and low maintenance, making it the most suitable option for further development.

Table 4. Pairwise Comparison (Zero–One Method) for Determining Criterion Weights

Criteria	C 1	C 2	C 3	C 4	C 5	Total	Weights
C1 Comfort & usability	–	0	0	1	0	1	0,1
C2 Safety & health	1	–	1	1	1	4	0,4
C3 Effectiveness	1	0	–	1	1	3	0,3
C4 Versatility & durability	0	0	0	–	1	1	0,1
C5 Efficiency	1	0	0	0	–	1	0,1
Total	2	4	3	1	0	**10**	**1**

Criterion weights were determined using a zero–one pairwise comparison method. Each evaluation criterion was compared against the others based on relative importance as perceived by system users and supervisors. The resulting scores were normalized to obtain criterion weights, which

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DOI: https://doi.org/10.36456/tibuana.9.02.11149 *e*-ISSN 2622-2035

were then used in the weighted objectives evaluation of design alternatives.

Table 5. Concept Evaluation Using the Weighted Objectives Method

No	Evaluation Criterion	Weight	Concept A	Concept B	Concept C
1	Comfort and usability	0,1	4	2	4
2	Safety and health	0,4	4	4	4
3	Effectiveness	0,	4	3	4
4	Versatility and durability	0,1	4	3	3
5	Efficiency (low effort & maintenance)	0,1	1	4	4
	Total	**1**	**3,7**	**3,4**	**3,9**

Table 5 presents the evaluation results of the three design alternatives using the weighted objectives method. Criterion weights were derived from aggregated questionnaire responses of 35 operators, reflecting the relative importance of each user-need category. Concept C achieved the highest total weighted score, indicating superior overall performance across ergonomic, safety, effectiveness, and efficiency criteria. Therefore, Concept C was selected for further development and final design.

7) *Improving details*

After Concept C was selected through the weighted objectives evaluation, the design was refined into a detailed configuration by specifying the main components, dimensions, and interface features. The final design focuses on providing stable load support, ergonomic operation, and smooth transport while remaining compatible with the existing layout constraints. The finalized configuration of the assistive device is illustrated in Fig. 5, showing the overall structure, lifting table, handle, and mobility system.

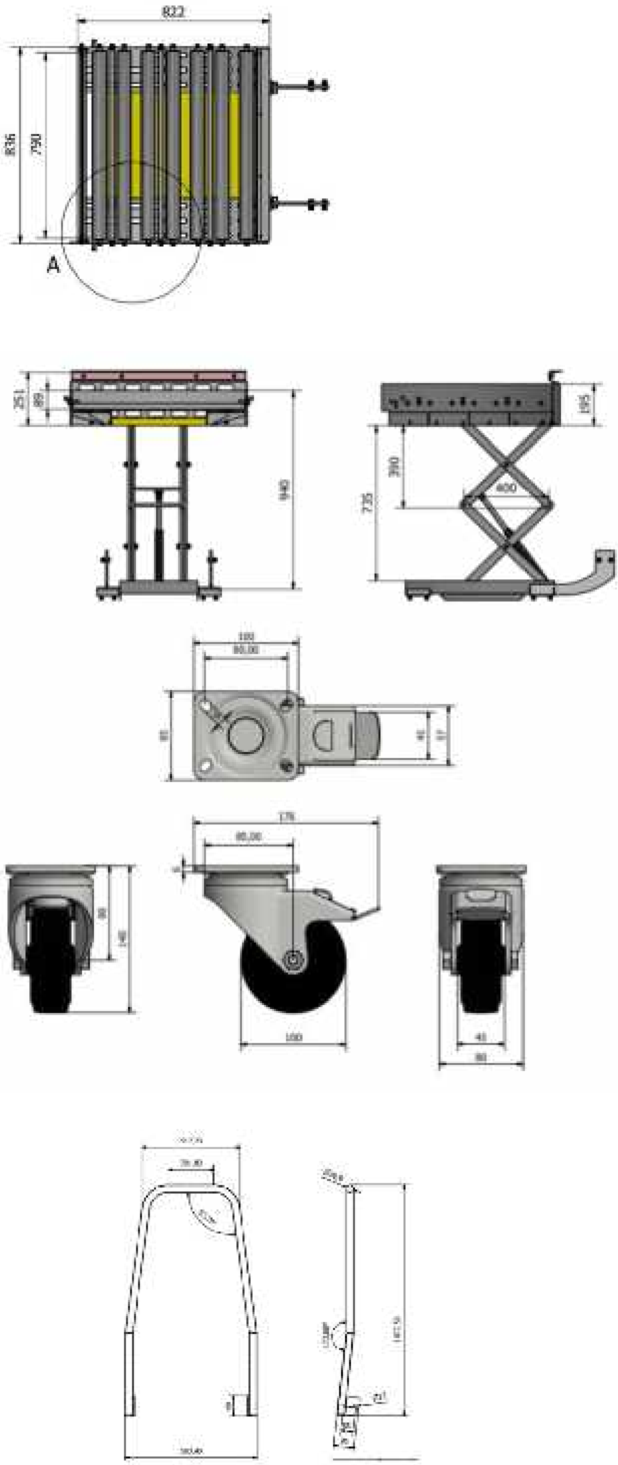

Figure 5. Final Configuration

Dimensioning was performed to ensure consistency with the identified system requirements and performance specifications. The main frame height was set to enable direct transfer to the truck bed, while the platform dimensions were defined to accommodate the maximum box panel size during transport. Handle height and grip dimensions were specified to support comfortable

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11149 *e*-ISSN 2622-2035

pushing and pulling during operation, and wheel diameter was selected to ensure stable movement along the transport route. The detailed dimensions of the main components are summarized in Table 6.

Table 6. Final Dimensions Used in the Assistive Device Design (cm)

Component	P	L	T	D	Remarks
Main frame (lifting cart frame)	95	75	145	–	Adjusted to the selected alternative
Box panel support table/platform	82	83	20	–	Adjusted to the selected alternative
Handle grip (handgrip)	51,77	–	102,75	2,68	Adjusted to the selected alternative
Wheel/caster	–	–	–	10	Adjusted to the selected alternative

The frame height was set to support transfer at the destination point, while the platform dimensions were defined to provide stable support for the box panels during transport. The handle grip dimensions were specified to improve operator comfort and control during pushing/pulling, and wheel diameter was selected to support stable movement along the transport route.

D. *Evaluation of Ergonomic Improvement*

Ergonomic improvement was evaluated by comparing baseline manual handling conditions with the proposed assistive device (Concept C) using three complementary indicators described in the methods: postural risk (REBA), biomechanical lifting demand (RNLE: RWL and LI), and psychophysical feasibility (Snook and Ciriello MAW). Baseline results indicate a high-risk posture (REBA = 12) and an overloaded lifting/carrying demand, where RNLE outputs show RWL values well below the actual handled loads, and Snook MAW estimates (≈12–13 kg) remain far lower than the box panel mass range (18–37 kg). The proposed device is expected to reduce manual lifting and awkward postures by supporting stable load transport and transfer, thereby lowering overall ergonomic risk (see Fig. 6 – Fig. 9). A consolidated before–and–after summary is provided in Table 7.

Table 7. Summary of Improvement Before and After Intervention

Ergonomic Indicator	Manual Handling	With an Assistive Device	Interpretation
REBA score	12	1	Reduced bending and improved posture during handling
Lifting Rasio (LI)	> 1.0	< 1.0	Lower low-back injury risk
Load-to-MAW ratio	> 1.0	< 1.0	Reduced overload condition
Overall ergonomic risk	High	Reduced	Engineering control improves safety and usability

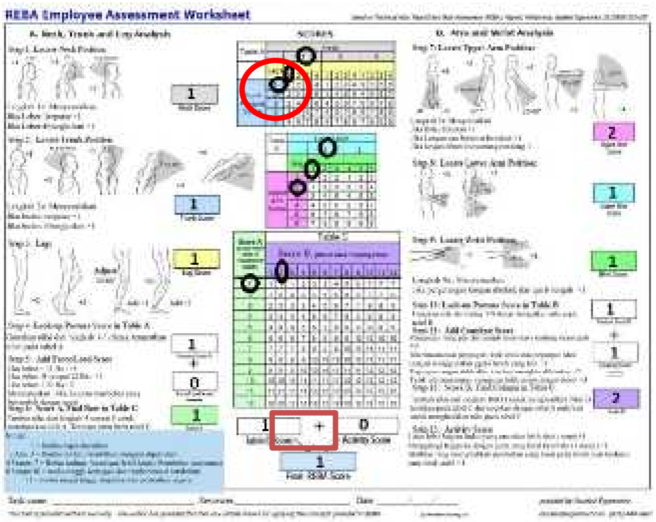

Figure 6: REBA assessment output after using the Assistive Device

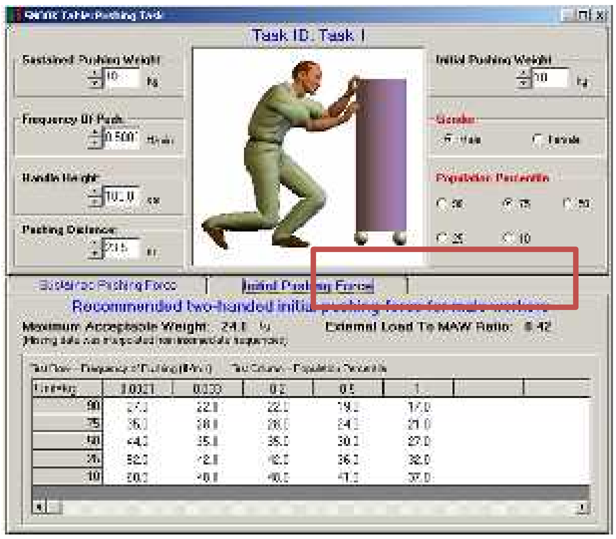

Figure 7: Snook output after using the Assistive Device

DOI: https://doi.org/10.36456/tibuana.9.02.11149
p-ISSN 2622-2027
e-ISSN 2622-2035

Figure 8: RNLE output after using the Assistive Device

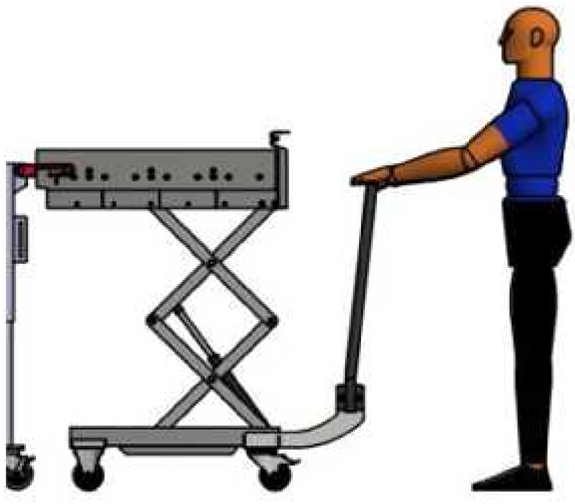
Figure 9: Illustration of an Assistive Device in use for Manual Material Handling

IV. Conclusion

The ergonomic evaluation demonstrates that the implementation of the assistive device significantly improves working conditions compared to manual handling. The REBA score decreased from 12 to 1, indicating a substantial reduction in postural risk and excessive bending during material handling activities. In addition, both the Lifting Index (LI) and Load-to-MAW ratio were reduced from values greater than 1.0 to below 1.0, confirming that the mechanical load on workers is maintained within acceptable ergonomic limits. Consequently, the overall ergonomic risk level was reduced from high to a controlled condition. These findings confirm that the proposed engineering intervention effectively enhances safety, usability, and workload management, thereby reducing the potential for musculoskeletal disorders and supporting a more sustainable and ergonomically sound work system.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support provided by the Internal Research Grant of Universitas Jenderal Achmad Yani (UNJANI) under Rector’s Decree No. SKEP/188/UNJANI/VI/2025. The authors also express their sincere appreciation to all workers who participated in this study, as well as to the management and technical staff for their cooperation, access to the workplace, and support during the implementation of the ergonomic intervention.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11344 *e*-ISSN 2622-2035

Optimization Of Packing Material Inventory Using ABC Analysis, Forecasting Methods, and Economic Order Quantity

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***Abstract*—Inventory management of packing materials in the flexible packaging industry often faces high investment value, inaccurate demand planning, and inefficient ordering quantities. This study aims to determine material priorities and optimal order quantities to minimize total inventory costs through an integrated approach. The methodology combines ABC Analysis for material classification, forecasting methods (Simple Average, Moving Average, Weighted Moving Average, and Single Exponential Smoothing) to predict demand, and Economic Order Quantity (EOQ) to determine optimal purchasing quantities. The results show that PLY material is categorized as class A with an investment contribution of 64.53%. Among forecasting methods, the 3-period Weighted Moving Average provides the best accuracy with the lowest MAPE value of 15.81%. EOQ calculations indicate optimal order quantities of 15,849 units for Plywood Multi 0280x0280x09 dia 77 and corresponding optimal quantities for other PLY materials. The integration of ABC, forecasting, and EOQ improves inventory efficiency and supports more reliable production planning.**

***Keywords* : ABC Analysis; Demand Forecasting; Economic Order Quantity; Inventory Management.**

I. INTRODUCTION

The flexible packaging industry requires effective inventory control to prevent stock shortages and overstock conditions, maintain production continuity, reduce operational costs, and ensure stable supporting material flow. Proper inventory management contributes significantly to manufacturing efficiency, operational sustainability, and supply chain resilience, as highlighted in studies on stock management and sustainable manufacturing practices [1],[2].

One of the commonly applied approaches to determine material control priorities is ABC analysis [3]. This method classifies materials based on their investment value and consumption level, enabling companies to focus on category A items that contribute the largest portion of total inventory value. Several studies conducted by [4], [5] and [6] demonstrate that ABC classification effectively identifies critical materials requiring stricter monitoring. Furthermore, the application of ABC analysis has been proven to reduce waste and improve procurement planning efficiency [1]. Research by [7] confirms that accurate classification minimizes the risk of high-value material shortages, while [8] emphasize the importance of sufficient inventory levels to maintain smooth production flow.

In addition to classification, companies must accurately forecast material demand to support timely procurement decisions. Various studies indicate that forecasting methods such as Moving Average, Weighted Moving Average, and Single Exponential Smoothing are capable of representing demand patterns based on historical data [9]. Research by [10] shows that Weighted Moving Average and Exponential Smoothing methods provide competitive prediction results compared to simpler techniques. These findings are supported by [11], who reported a MAPE value of 14.539%, and by [12], who obtained an RMSE value of 368617.362 using the Weighted Moving Average method.

Further studies by [13], [14], [15] strengthen the evidence that quantitative forecasting approaches improve demand prediction accuracy, particularly under fluctuating demand conditions. [16] emphasize the importance of selecting the most appropriate forecasting method in a Moving Average-based system. Meanwhile, [17] demonstrate that the Single Exponential Smoothing method achieved a MAPE value of 5.481%, indicating high forecasting accuracy. Similar conclusions are reported by [18], and further supported by [19] and [20], who state that accurate forecasting supports more efficient procurement strategies. Additionally, [21] assert

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11344 *e*-ISSN 2622-2035

that precise demand estimation enables companies to avoid excessive stock accumulation while ensuring material availability according to production needs.

After demand estimation, companies must determine the optimal order quantity. The Economic Order Quantity (EOQ) model is widely used to estimate the ideal purchasing quantity at minimum total cost [22]. Research by [23] indicates that EOQ implementation significantly reduces holding and ordering costs. According to [24], mathematical inventory models help companies understand material consumption patterns and determine the most efficient ordering frequency. Similar findings are reported by [7] and [15], who conclude that EOQ supports procurement stability and reduces reliance on urgent and costly emergency orders.

Several researchers have explored the integration of classification, forecasting, and optimal ordering methods. [25] reveal that effective inventory management is strongly influenced by the integration of these approaches. [26] demonstrate that combining forecasting, ABC analysis, and EOQ improves material control accuracy and inventory turnover. The approach was further enhanced using Fuzzy AHP to improve classification decision quality [26]. Moreover, [27] show that ABC integration provides more cost-oriented procurement prioritization, while [28] propose the ABC–XYZ and service-level combination to enhance safety stock determination accuracy.

From a technological perspective, [29] integrate Big Data analytics with ABC, forecasting, and EOQ to improve productivity and stock availability. Similarly, [30] combine machine learning, lean logistics, ABC, and EOQ to enhance inventory efficiency in the automotive accessories industry. However, most of these studies were conducted in different industrial contexts and have not specifically addressed the integrated application of ABC, forecasting, and EOQ in the flexible packaging sector.

Moreover, previous studies generally apply ABC, forecasting, or EOQ separately. In industrial practice, these three methods are interrelated: ABC determines priority materials, forecasting predicts the demand of priority items, and EOQ calculates the most economical purchasing quantity. The limited number of studies integrating these three methods comprehensively creates a significant research gap, particularly in the flexible packaging industry, which is characterized by high material variation and strong dependency on stock stability [31].

Based on this research gap, this study proposes a novelty in the form of integrating three methods: (1) ABC analysis to determine material priority based on investment value, (2) selection of the most accurate forecasting method among several alternatives, and (3) application of EOQ to determine the optimal purchasing quantity. Packing materials are selected as the research object because they possess relatively high investment value and directly affect production continuity in flexible packaging operations [32]. Therefore, the objectives of this study are:

1. To identify material priorities using ABC analysis.
2. To determine the most accurate forecasting method for predicting material demand.
3. To calculate the optimal order quantity using the Economic Order Quantity (EOQ) method to minimize inventory cost and improve material planning efficiency in the flexible packaging industry.

II. RESEARCH METHODOLOGY

This study employs a quantitative descriptive approach to optimize packing material inventory in the flexible packaging industry. The research integrates three analytical methods: ABC analysis, demand forecasting, and Economic Order Quantity (EOQ). The integration of classification, forecasting, and optimal ordering models is considered essential to improve inventory effectiveness and cost efficiency, as emphasized by [25] and [26].

A. Research Design

The research follows a sequential analytical framework. First, ABC analysis is applied to classify packing materials based on their annual investment value. Second, forecasting methods are evaluated to determine the most accurate demand prediction model for category A materials. Finally, the EOQ model is used to calculate the optimal purchasing quantity.

This structured approach aligns with the concept that inventory control should prioritize high-value items before determining demand patterns and economic order quantities [3], [4]. The integration of forecasting and EOQ is further supported by [7], who highlight the importance of combining demand estimation with optimal

Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11344 *e*-ISSN 2622-2035

purchasing strategies.

B. Data Collection

The data used in this study consist of:

1. Historical usage data of packing materials from January to August 2024.
2. Annual investment value of each packing material category (FIT, PLY, and CB).
3. Ordering cost per order.
4. Holding cost per unit per year.

The data were obtained from company documentation records and internal operational reports. Forecasting calculations were conducted using WinQSB software and manually verified using Microsoft Excel to ensure computational accuracy and reliability.

C. ABC Analysis Procedure

ABC analysis was conducted to classify packing materials according to their contribution to total annual investment value. The method is based on the Pareto principle, which states that a small proportion of items contributes to the majority of total inventory value [3].

The classification procedure involved:

1. Calculating total annual investment value for each packing material.
2. Computing the percentage contribution using:

$$\textit{Investment (\%)} = \frac{In \quad V \quad o \quad M}{T \quad In \quad V} x100\% \quad (1)$$

3. Sorting materials from highest to lowest investment value.
4. Grouping materials into:
   - Category A (approximately 70–80% of total investment value),
   - Category B (15–25%),
   - Category C (5–10%).

This classification approach is consistent with previous applications of ABC analysis in inventory control studies [4], [5].

D. Forecasting Methods

Demand forecasting was performed on category A material, namely Plywood Multi 0280x0280x09 dia 77. Several quantitative forecasting methods were evaluated to determine the most accurate prediction model.

1. Simple Average (SA)

The Simple Average method calculates the arithmetic mean of historical demand data. This method is suitable for relatively stable data patterns and is commonly used as a baseline forecasting model [10].

2. Moving Average (MA)

The three-period Moving Average method was applied to smooth short-term fluctuations and provide a more stable demand estimate [9]. However, previous research indicates that MA may be less accurate under highly fluctuating demand conditions [33], [34].

3. Weighted Moving Average (WMA)

The Weighted Moving Average method assigns different weights to historical observations, giving greater emphasis to recent data [35], [9]. In this study, weights of 0.2, 0.3, and 0.5 were applied to represent increasing relevance of recent demand data.

4. Single Exponential Smoothing (SES)

Single Exponential Smoothing was applied using a smoothing constant $\alpha = 0.8$. A higher alpha value increases responsiveness to recent demand changes, which is suitable for fluctuating data patterns [12], [14].

Forecasting performance was evaluated using standard error indicators:

- Mean Squared Error (MSE)
- Mean Absolute Deviation (MAD)
- Mean Absolute Percentage Error (MAPE)
- Cumulative Forecast Error (CFE)
- Tracking Signal

The use of MAPE and error tracking indicators to assess forecasting accuracy is consistent with previous empirical studies [11], [17]. The forecasting method with the lowest MAPE value and acceptable tracking signal was selected for further EOQ calculation.

E. Economic Order Quantity (EOQ) Model

After selecting the most accurate forecasting method, the EOQ model was applied to determine the optimal purchasing quantity. The EOQ model minimizes total inventory cost by balancing ordering cost and holding cost [22].

The EOQ formula is expressed as:

$$EOQ= \sqrt{\frac{2D}{H}} \quad (2)$$

where:

D = Annual demand
S = Ordering cost
H = Holding cost per unit

The effectiveness of EOQ in reducing total inventory cost and improving procurement stability has been demonstrated in previous studies [23], [24], [15].

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11344 *e*-ISSN 2622-2035

F. Research Framework

The research framework can be summarized as follows:

Inventory Data → ABC Classification → Selection of Category A Material → Forecasting Model Comparison → Selection of Best Forecast → EOQ Calculation → Inventory Optimization.

This integrated framework is consistent with the findings of [25] and [26], who emphasize that combining classification, forecasting, and optimal ordering methods produces more effective inventory control decisions.

III. RESULTS AND DISCUSSION

A. ABC Analysis Results

ABC analysis was conducted to classify packing materials based on inventory control priority by considering their annual investment value [4], [3]. In this study, three types of packing materials FIT, PLY, and CB were analyzed using the number of items and total annual investment value the ABC classification results are presented in Table 1.

Table 1. ABC Classification of Packing Materials

Packing Material	Item PM	Item PM (%)	Nilai Investasi (Rp)	Nilai Investasi (%)	Keterangan
ply	193	39.07%	765.432.560	64.53%	A
cb	225	45.55%	2.986.575.430	18.94%	B
fit	76	15.38%	876.543.675	16.54%	C
TOTAL	494	100	4.628.551.665	100	

ABC analysis shows:

- PLY: 64.53% investment value → Category A
- CB: 18.94% → Category B
- FIT: 16.54% → Category C

The results indicate an unequal distribution of investment value among materials. PLY accounts for 39.07% of total items but contributes 64.53% of total inventory investment value, placing it in category A. CB and FIT fall into categories B and C respectively, as their contribution to total investment is significantly lower relative to item quantity. This distribution reflects the Pareto principle, where a relatively small proportion of items represents the majority of financial value. The high contribution of PLY is influenced by its higher unit cost and consumption rate in production activities. Therefore, financial risk is concentrated on this category, requiring stricter monitoring, tighter procurement scheduling, and more accurate demand forecasting.

These findings are consistent with previous studies stating that selective control of high-value items significantly improves inventory efficiency and cost effectiveness [4]. Effective ABC classification enables companies to allocate managerial attention proportionally according to financial impact.

B. Forecasting Analysis

Forecasting was conducted on Plywood Multi 0280x0280x09 dia 77, which belongs to category A and therefore requires precise demand estimation. Four quantitative forecasting methods were compared: Simple Average (SA), Moving Average (MA), Weighted Moving Average (WMA), and Single Exponential Smoothing (SES).

Simple Average (SA)

The Simple Average method produced a forecast value of 10,465.5 units for the next period. The model generated a MAPE of 18.002%, indicating moderate forecasting accuracy. Although the tracking signal (0.507) shows no significant bias, the relatively high error values suggest that SA is less responsive to demand fluctuations shown on Table 2.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11344 e-ISSN 2622-2035

Table 2. Forecasting Results Using Simple Average Method

Keterangan	Excel	Software
forecast next month	10.465,5	10.465,5
Mean Squared Error (MSE)	4.548.103,873	4.548.103,873
Mean Absolute Deviation (MAD)	1.834,095	1.834,095
Mean Absolute Percentage Error (MAPE)	18002%	18002%
Cumulative Forecast Error (CFE)	929,333	929,333
Tracking Signal	0,507	0,507

Moving Average (3-MA)

The 3-period Moving Average method resulted in a forecast of 9,581.33 units with a MAPE of 16.944%. However, the Cumulative Forecast Error (–4,730.67) and tracking signal (–3.04) indicate a negative bias tendency, meaning the model consistently underestimates actual demand. As noted by [33] and [34], MA performs well under stable demand patterns but becomes less reliable when fluctuations are significant, the forecasting accuracy comparison can be seen in Table 3.

Table 3. Forecasting Results Using 3-Period Moving Average

Keterangan	Nilai (Excel)	Nilai (Software)
forecast Next Month	9.581,33	9.581,33
Mean Squared Error (MSE)	3.459.857,8	3.459.857,8
Mean Absolute Deviation (MAD)	1.554,13	1.554,13
Mean Absolute Percentage Error (MAPE)	16944%	16944%
Cumulative Forecast Error (CFE)	-4.730,67	-4.730,67
Tracking Signal	-3,04	-3,04

Weighted Moving Average (WMA)

The Weighted Moving Average method applied weights of 0.2, 0.3, and 0.5 for the three most recent periods. This method generated a forecast of 9,249.2 units with the lowest MAPE value of 15.81% and MAD of 1,444.

Compared to other models, WMA shows better responsiveness to recent demand changes due to its weighting structure [35], [9]. Although the tracking signal (–3.047) indicates slight underestimation bias, the error level remains within acceptable control limits. These findings align with [17], who emphasized that weighted forecasting improves prediction performance under fluctuating demand conditions, the forecasting accuracy comparison can be seen in Table 4.

Table 4. Forecasting Results Using Weighted Moving Average

Keterangan	Nilai (Excel)	Nilai (WINQSB)
forecast Next Month	9.249,2	9.249,2
Mean Squared Error (MSE)	3.274.619	3.274.619
Mean Absolute Deviation (MAD)	1.444	1.444
Mean Absolute Percentage Error (MAPE)	15,81%	15,81%
Cumulative Forecast Error (CFE)	-4.4	-4.4
Tracking Signal	-3,047	-3,047

Single Exponential Smoothing (SES)

SES was implemented with a smoothing constant $\alpha = 0.8$ to increase sensitivity to recent data [12], [14]. The method produced a forecast of 8,947.77 units with a MAPE of 15.987%.

Although SES shows relatively good accuracy and no significant bias (tracking signal = 0.2395), its MAPE value is slightly higher than WMA.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11344 *e*-ISSN 2622-2035

Therefore, among the four tested models, WMA provides the best forecasting performance for this material.

Overall comparison confirms that assigning higher weights to recent observations improves forecasting accuracy for fluctuating material consumption patterns, the forecasting accuracy comparison can be seen in Table 5.

Table 5. Forecasting Results Using Single Exponential Smoothing

Keterangan	Nilai (Excel)	Nilai (WINQSB)
Forecast Next Month	8.947,77	8.947,77
Mean Squared Error (MSE)	4.652.160	4.652.160
Mean Absolute Deviation (MAD)	1.606,218	1.606,218
Mean Absolute Percentage Error (MAPE)	15987%	15987%
Cumulative Forecast Error (CFE)	384,71	384,71
Tracking Signal	0,2395	0,2395

C. Economic Order Quantity (EOQ) Analysis

After determining forecasted demand, EOQ was calculated to identify optimal purchasing quantities that minimize total inventory cost. EOQ balances ordering cost and holding cost to determine the most economical order size. The EOQ calculation results are shown in Table 6.

Table 6. Economic Order Quantity (EOQ) Calculation Results

Material	Satuan	D	S	H	EOQ
Plywood Multi 0280x0280x09 dia 77	pc	12.5592	10,000,000	10,000	15,849
Plywood Multi 0310x0310x09 dia 77	pc	88.092	10,000,000	10,000	13,273
Plywood Multi 0365x0365x09 dia 77	pc	24.444	10,000,000	10,000	6,992
Plywood Multi 0365x0385x12 dia 77	pc	17.256	10,000,000	10,000	5,875

These results suggest that the company's current ordering policy has not yet reached cost-minimizing levels. By applying EOQ, ordering frequency can be reduced while avoiding excessive holding cost. This finding supports the theoretical concept that EOQ identifies the optimal trade-off point between ordering and storage costs.

The integration of ABC classification, accurate forecasting selection, and EOQ calculation provides a structured and financially efficient inventory control framework for flexible packaging operations.

IV. CONCLUSION

The results show that ABC analysis classifies PLY as category A with an investment contribution of 64.53% despite representing only 39.07% of total items, indicating that inventory cost concentration follows the Pareto principle and requires priority control. Among the forecasting methods, Weighted Moving Average provides the highest accuracy with a MAPE of 15.81%, compared to 18.00% (Simple Average), 16.94% (Moving Average), and 15.98% (Single Exponential Smoothing), producing a forecast of 9,249.2 units for the next period. Furthermore, the EOQ calculation determines optimal order quantities of 15,849 units, 13,273 units, 6,992 units, and 5,875 units for the respective plywood materials, demonstrating that economically optimal purchasing can reduce total inventory costs by balancing ordering and holding costs. These findings confirm that the integration of ABC classification, accurate forecasting, and EOQ provides a quantitative and effective framework for inventory optimization in flexible packaging operations.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

Optimization of Production Processes in Micro, Small, and Medium Metal Enterprises (SMEs Metal) using Fuzzy-Kano, QFD, and SPC Methods: a Systematic Literature Review

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***Abstract*—Micro, Small, and Medium Enterprises (MSMEs), particularly in the metal industry, play a pivotal role in Indonesia's economic development but face significant challenges in maintaining product quality, reducing defects, and responding to customer needs. This study conducts a Systematic Literature Review (SLR) to investigate the integration of Fuzzy-Kano, Quality Function Deployment (QFD), and Statistical Process Control (SPC) methods as a comprehensive approach for optimizing production processes in metal MSMEs. The literature was sourced from databases such as Scopus, Crossref, and Google Scholar, yielding 562 records, of which 35 relevant journal articles were analyzed in depth. Findings reveal that while QFD and SPC are frequently applied separately in MSMEs, research integrating these methods with Fuzzy-Kano remains limited. The review highlights that such integration offers substantial potential to improve product quality, align production with customer satisfaction, and enhance decision-making under uncertainty—ultimately supporting sustainable competitiveness. This study also identifies research gaps and proposes future directions, including the development of localized models tailored to SME contexts and the deeper integration of SPC within customer-oriented product development frameworks.**

***Keywords*: Deployment (QFD), Fuzzy-Kano, Metal SMEs, Production Optimization, Systematic Literature Review**

I. Introduction

Micro, Small, and Medium Enterprises (MSMEs) are vital and strategic in the Indonesian economy. According to [1], MSMEs contribute approximately 60.5% to the national Gross Domestic Product (GDP). This significant contribution highlights the vast potential of MSMEs in Indonesia to be further developed, enhancing their impact on the country's overall economic growth.

However, Micro, Small, and Medium Enterprises (MSMEs) in Indonesia face several significant challenges that hinder their growth and competitiveness. These challenges include financial constraints, limited knowledge and skills, human resource shortages, marketing and distribution difficulties, heavy dependence on owners, technological limitations, vulnerability to economic fluctuations, as well as organisational and management issues.

In East Java Province, there are numerous MSMEs, including those located in Waru District, Sidoarjo Regency, which consist of groups of MSMEs engaged in the metal sector. According to [2], quoting the Head of the Makmur Abadi Village-Owned Enterprise (Bumdes) in Ngingas Village, Zaenudin Arifin, there are a total of 340 small and medium industries (SMEs) actively producing in the area. However, only 215 IKMs have been recorded in detail. A common issue faced by IKMs in this region is their weak bargaining power, as products are often rejected by the market due to minor defects. Despite these defects being relatively small, they prevent the products from entering industrial orders, causing frequent losses for the SMEs. This situation arises because IKMs lack statistical quality control methods to reduce process variability, identify defect causes, and enhance product consistency. Additionally, there is no effective approach in place to systematically identify customer needs.

Therefore, an effective approach is needed to address these challenges. The integration of Fuzzy-Kano-QFD (Quality Function Deployment) and Statistical Process Control (SPC) offers a promising method for optimizing

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

the production process. Fuzzy-Kano-QFD enables a more systematic identification of customer needs by incorporating subjective aspects through fuzzy logic. This approach helps classify customer preferences based on their expected level of satisfaction and translates these needs into technical product attributes. [3], In her research, she explained that QFD is a product planning and development method that allows a company to clearly define consumer desires and requirements, enabling the evaluation of the strengths and weaknesses of each product or service offered.

Conventional QFD has a limitation in that the determination of the relationship scale between technical characteristics and customer needs tends to be highly subjective. To address this, the present study develops a mathematical model that integrates Quality Function Deployment (QFD) with the Kano Model to establish more objective product quality improvement targets. [4] proposes an integrative framework combining SERVQUAL, Analytical Kano (A-Kano), and QFD using a fuzzy approach to support decision-making for service improvements in the education sector, demonstrating that the integration of these methods is feasible. Although the focus is on education, the methodology can be adapted to optimize production processes in metal MSMEs. Furthermore, Jin [5] integrates the Fuzzy Kano method, Analytic Hierarchy Process (AHP), Decision Making Trial and Evaluation Laboratory (DEMATEL), and QFD to design product development processes. Such integrations illustrate viable approaches for combining multiple methods to enhance decision-making and process optimization.

The integration of various methods into QFD serves to translate customer requirements into product characteristics and to prioritize design alternatives by considering both interdependencies and ambiguities. First, customer requirements are identified. Second, the Fuzzy Kano model is applied to evaluate the impact of each requirement, which is often ambiguous, on customer satisfaction. Third, design alternatives are proposed, and the relative importance of each requirement is determined using the Analytic Hierarchy Process (AHP). Finally, QFD is employed to select the optimal product design. The integration of fuzzy logic into QFD provides a powerful tool for enhancing product design and quality, enabling the development of a customer-focused quality system. This approach was successfully implemented in a company in Turkey that manufactures PVC window and door systems. [6].

Meanwhile, the application of Statistical Process Control (SPC) enables statistical-based quality control to reduce process variability, identify defect-causing factors, and enhance product consistency. By implementing this method, metal MSMEs can improve product quality, reduce defect rates, and increase operational efficiency, ultimately boosting their competitiveness in the market. As explained by Fakih [7], SPC can be used to identify product defects, quantify the percentage of those defects, determine their root causes, and, using the 5W + 1H method, propose appropriate corrective actions. Similarly, Ignatio [8] emphasizes that SPC allows for early detection and prevention of production issues and has distinct advantages over traditional quality methods, such as final product inspection. Furthermore, Michaela [9] discusses the integration of QFD and SPC in product design and manufacturing processes. This integration demonstrates how combining QFD and SPC can lead to improved product quality by translating customer requirements into engineering characteristics and monitoring process performance statistically. The approach also allows for dynamic updates in QFD during production based on customer feedback, thereby enhancing the quality of delivered products and increasing customer satisfaction. SPC, in this context, plays a vital role in identifying significant deviations or abnormalities in product characteristics and in maintaining key process parameters by deriving from updated customer requirements in a stable and controlled state over the long term. This ensures that products meet the desired performance quality as specified by the customer. Therefore, these combined methods are highly applicable for improving product quality in metal MSMEs.

This article aims to explore the extent to which methods such as Fuzzy-KANO, Quality Function Deployment (QFD), and Statistical Process Control (SPC) have been developed by researchers and how they can be utilized by SMEs to support sustainable product development. To achieve this, a systematic literature review was conducted to examine the potential of these methods in assisting metal SMEs in enhancing

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

product development, reducing product defects, and maintaining product quality—ultimately contributing to the sustainability of their businesses.

1.1 *Micro, Small, and Medium Enterprises (MSMEs)*

Micro, Small, and Medium Enterprises (MSMEs) are types of productive businesses owned by individuals or business entities that meet certain criteria based on the number of workers, annual turnover, and assets. In Indonesia, the classification of MSMEs refers to Law No. 20 of 2008, which divides them into: [10]

a. Micro Business: Assets ≤ Rp 50 million, turnover ≤ Rp 300 million per year.
b. Small Business: Assets > Rp 50 million–500 million, turnover > Rp 300 million–2.5 billion per year.
c. Medium Business: Assets > Rp 500 million–10 billion, turnover > Rp 2.5 billion–50 billion per year.

Metal SMEs refer to small and medium enterprises engaged in metal-based manufacturing activities, including casting, machining, fabrication, and assembly of metal products. Their product range typically includes automotive components, agricultural tools, household appliances, and light construction materials.

Metal SMEs have a strategic role in the Indonesian economy and manufacturing industry, including. [11]:

1. Local Component Suppliers:
   Metal SMEs supply components or spare parts for the automotive, agricultural, and household appliances sectors. This helps reduce dependence on imports and strengthens the local supply chain.
2. Labor Absorber:
   This sector absorbs a lot of labor, especially in areas with metal industry centers such as Tegal, Ceper (Klaten), and Sidoarjo.
3. Driver of Local Innovation:
   Metal SMEs often modify and adapt products to meet the specific needs of local consumers, thus supporting innovation based on market needs.
4. Regional Economic Equity:
   Many metal SMEs develop outside large industrial centers, thus playing a role in the equitable distribution of national economic development.

According to data from the Ministry of Cooperatives and SMEs in 2021 [12], MSMEs are one of the most important pillars in the Indonesian economy. Currently, the number of MSMEs has reached 64.2 million with a contribution to GDP of 61.07 percent or 8,573.89 trillion rupiah. The contribution of MSMEs to the Indonesian economy includes the ability to absorb around 117 million workers or 97 percent of the total workforce, as well as collecting up to 60.4 percent of total investment.

1.2 *Fuzzy Logic Method*

Fuzzy logic is a mathematical approach that enables the handling of uncertainty and imprecision in data, decision-making, and human judgment. Unlike classical (binary) logic, which only recognizes two absolute values (true or false), fuzzy logic allows for degrees of truth that range continuously between 0 and 1.

Fuzzy logic is used to handle uncertainty and subjectivity in decision-making, especially in the context of customer preferences and uncertain production conditions. In the manufacturing industry, fuzzy logic helps in designing adaptive and flexible control systems. For example, a study by Elamvazuthi et al [13] Applied fuzzy programming techniques to production planning in the textile industry, showing increased efficiency in production scheduling. In the application of Fuzzy Logic in Handling Data Uncertainty, fuzzy logic can be applied in the context of optimizing production processes in metal SMEs. Fuzzy logic has several significant applications to overcome data uncertainty and decision complexity. Some of the main applications of fuzzy logic in this context are:

a. Production Planning and Scheduling
   In production planning, there is often uncertainty regarding market demand, production cycle time, or raw material availability. Using fuzzy logic, we can estimate the degree of uncertainty in each variable and generate a more flexible and realistic schedule. For example, in a fuzzy-based production planning model, parameters such as "sufficient raw material quantity" or "fast turnaround time" are not only assessed in terms of exact numbers, but through membership degrees that reflect uncertainty.
b. Quality Control and Defect Detection
   - Quality control in metal casting or

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

machining processes is often affected by factors that cannot be measured precisely, such as varying temperature or material hardness. Fuzzy logic is used to assess product quality by combining various uncertain variables (such as "hot enough" or "few defects").

- By using fuzzy systems, decisions to accept or reject products can be made based on more adaptive quality constraints, rather than just rigid threshold values.

c. Customer Needs Assessment and Classification
In the metal industry, understanding customer needs is often subjective and not quantitatively measurable. By applying fuzzy logic, companies can more accurately classify customer needs into categories (e.g., “very important”, “important”, “moderately important”) based on membership degrees.

1.3 *Application of Fuzzy Logic in Measuring Customer Perception and Qualitative Preferences*

Customer perceptions and qualitative preferences are important factors in determining the quality of products and services. However, these perceptions are often subjective and not easily measured quantitatively, especially in the context of the manufacturing industry. This is where fuzzy logic can play a very important role. Fuzzy logic allows companies to deal with uncertainty and ambiguity in subjective qualitative data, such as customer satisfaction levels, product quality desires, and features that are considered important by customers. [14] for measuring customer perception and qualitative preference assessment.

1.4 *Implementation in the Kano Model System with Fuzzy Logic*

The Kano model is used to identify and classify product attributes based on customer preferences, which are divided into three main categories: must-be, one-dimensional, and attractive. Using fuzzy logic, this system can help measure the degree of customer satisfaction with various product attributes and adjust for uncertainty or imprecision in their preferences. For example, an attribute such as “delivery speed” can be assigned a fuzzy membership degree that describes whether the delivery meets customer expectations (e.g., fast, very fast, or slow) based on the feedback received. [15] Their research is used to develop more realistic and accurate decision models in the context of product development by combining Kano fuzzy with other methods such as FMEA and MCDM. In other research, [16] Fuzzy Kano and Fuzzy Axiomatic Design (FAD) Integration: The authors propose a new methodological framework for New Product Development (NPD) by integrating fuzzy-based Kano model and FAD. The goal is to improve the accuracy of product attribute classification based on customer satisfaction and company expectations under conditions of uncertainty. This article concludes that the innovatively developed Fuzzy Kano method combined with FAD can be a powerful and reliable tool in new product development.

1.5 *Implementation in Quality Function Deployment (QFD) with Fuzzy Logic*

Quality Function Deployment (QFD) is a tool used to translate customer needs and preferences into technical product requirements. Fuzzy logic can be used to measure and analyze uncertain or inconsistent customer preference data, providing more flexibility in prioritizing product improvements or innovations. For example, if customers express that “product strength” is very important but with variations in their ratings, fuzzy logic allows the conversion of qualitative data into information that is more easily processed in product planning. [17] In their research, they conclude that the developed Fuzzy-QFD approach is a superior design tool in dealing with uncertainty, highly relevant for the design of human-centered metaverse-based interactive systems. In other research [18], This article concludes that the Fuzzy QFD and ARIZ-based approaches can produce innovative and realistic product designs to meet the needs of modern households with high complexity.

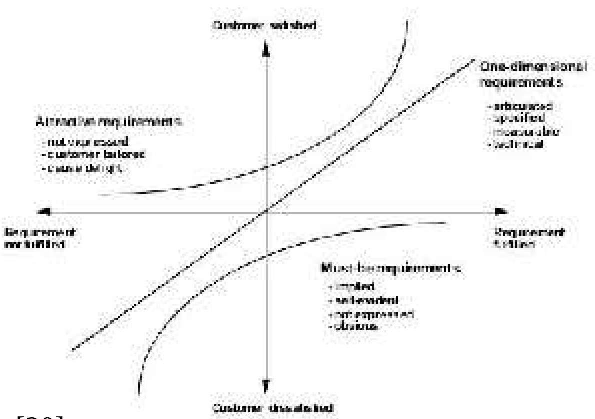
1.6 *KANO Model*

The Kano Model is a tool used to classify and analyze customer needs based on how each of these needs affects customer satisfaction. Developed by Noriaki Kano in 1984, the model helps companies identify and prioritize product features that are important to customers. It is particularly relevant in product innovation, as it allows the development of products that not only meet basic expectations but can also create higher

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

levels of customer satisfaction and loyalty. [19]. The Kano model classifies customer needs into five categories: must-be, one-dimensional, attractive, indifferent, and reverse. This classification helps in understanding customer priorities and designing products that meet or exceed their expectations. Integrating the Kano model into QFD allows companies to focus on product features that have the greatest impact on customer satisfaction.

Zhao et al. [20] reported that their case study demonstrated that the combined Kano model with Attention-BiLSTM achieves high prediction accuracy, enabling companies to develop product innovation strategies that are more responsive to evolving market needs. Prihono and Indra [21]said, Fuzzy logic is one technique of MCDM which is commonly used for affirmation of decisions.



[20]

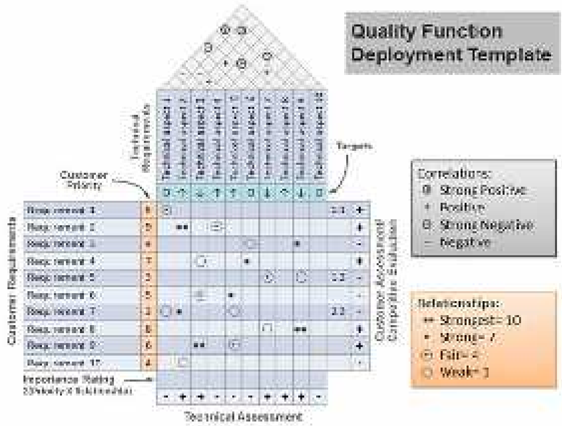
Figure 1. KANO Model

Xin Yang et al. [21] Conducted a study concluding that the Kano model can be effectively used to determine service priorities based on their impact on elderly satisfaction. The findings provide both theoretical and practical guidance for policymakers and public sports service providers to develop more targeted, responsive, and needs-oriented services for the elderly, thereby supporting the promotion of healthy aging.

1.7 *Quality Function Deployment (QFD)*

The Quality Function Deployment (QFD) method was first developed by Yoji Akao in Japan during the 1960s and has since been widely applied in the automotive, electronics, and various other manufacturing industries. In the context of metal SMEs, QFD can be utilized to align production processes with customer expectations, thereby producing products with higher added value that are more competitive in the market. Santoso et al. [22] stated in their research that QFD, whether applied independently or in integration with other methods, has proven to be a highly effective tool for driving sustainable product innovation in the agro-industrial sector. They further recommend expanding the application of QFD to micro and medium enterprises and improving strategies to enhance the success of its implementation.

Ishak et al. [23] revealed that QFD is employed to translate customer requirements into technical characteristics, while AD (Analytical Design) is utilized to develop design solutions that optimally meet functional requirements. Their results indicate that the most critical technical attributes in the product design are product composition, frame strength, and measurement duration. The newly developed design exhibits a lower information complexity value compared to the current design, suggesting that it is more efficient and better aligned with user needs.



[24]

Figure 2. QFD (Quality Function Deployment) Template

Quality Function Deployment (QFD) is implemented in the development of the mechanical engineering curriculum by making Course Learning Outcomes (CLOs) as Voice of the Customer (VoC) and ABET Student Outcomes as Technical Requirements (HOWs) to meet ABET accreditation standards. [24]. In another study [25], A combination of QFD and Fuzzy MCDM has been conducted. Where a product development method has been developed with Fuzzy Quality Function Deployment (Fuzzy QFD) to identify customer needs and technical characteristics, and Fuzzy Multi-Criteria Decision Making (Fuzzy MCDM)

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

to evaluate and select the best product prototype systematically, taking into account the uncertainty of customer data and the complexity of technical decisions.

1.8 *Integration of Fuzzy, KANO, and QFD*

Research related to the integration of Fuzzy, KANO, and QFD has been carried out, such as [26], The implementation of the models, it will be tested for the transportation of persons with disabilities. The study started with the identification of Voice of Customer (VoC) by employing the Kano method, that is, by administering the functional and dysfunctional questionnaire to the respondent. The next step was to use the Fuzzy method to reduce the subjectivity of respondents' answers. Each of the attributes was then classified into the Kano categories: must be, one-dimensional, attractive, and indifferent. To design the service system, the QFD was employed. Based on the result of QFD analyses, there were eleven criteria for the service needs of VoC and 21 attributes of technique responses used to design the service system.

In another study, a two-stage integrative model was developed that combines fuzzy sets, the Kano model, and Quality Function Deployment (QFD) to identify critical factors in air conditioning (AC) product innovation during the COVID-19 pandemic, focusing on the air purification function. This model combines multi-actor preferences (consumers, designers, and manufacturers), classifies demand through the Kano model, and then transforms it into technical property indices using QFD. This study shows that the approach can handle linguistic uncertainty and product design complexity more accurately, and generate product innovation priorities that are more realistic and responsive to market needs and technological developments. [27]. The Fuzzy QFD method has proven to be effective in the supplier selection process, as it can manage uncertainty and subjectivity in evaluations, resulting in more accurate and structured decisions compared to conventional approaches. [28]. In another study, researchers identified 11 attributes of unmet patient needs in a private hospital in Bandung. By integrating Servqual, Kano, and two-stage QFD methods, they developed 21 critical recommendations to enhance hospital service quality and better meet patient expectations. [29]. This research combined Servqual, Fuzzy, Kano, and QFD methodologies, demonstrating that such multi-method integrations are feasible and effective. Collectively, these studies indicate that integrating various methods can be successfully implemented to improve decision-making and service quality.

1.9 *Statistical Process Control (SPC)*

Statistical Process Control (SPC) is a quality control method that uses statistical tools to monitor and control the production process. Tools such as $\bar{X}$ and R control charts are used to detect variations in the production process and ensure that the process remains within established control limits. The application of SPC helps in identifying quality problems early and preventing defective products from reaching customers. [30]. Statistical Process Control (SPC) provides a systematic, statistically based approach to monitoring, controlling, and improving production processes to stay within the desired specification limits. SPC aims to detect process variations early, so that corrective action can be taken immediately before producing defective products. SPC is not only used for final product inspection, but also to control quality throughout the production process by observing data in the form of graphs and statistics. Where it has the Main Tools in SPC (Seven Tools of Quality).

1.10 *Combination of SPC and QFD in SMEs*

The combination of QFD and SPC in the SME industry has not been widely found, perhaps because SME resources are limited, or researchers are not interested in researching it. The research that is often found related to SMEs is still on the use of SPC or SMEs with QFD. [31], Their paper highlights the importance of integrating SMEs (Small and Medium Enterprises) into the aerospace industry supply chain and identifies a number of key factors for the success of such integration. Through an exploratory study of SMEs in this sector. [32] In other studies, the new product development (NPD) process in SMEs is different from that in large companies, characterized by informal processes, limited resources, and the need for technological support. Collaboration with external parties, the use of tools such as QFD, and an adaptive design approach are essential. Effective NPD process design in SMEs must consider aspects of product design, innovation collaboration, and appropriate tools and techniques. In another study, it was

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

highlighted that the use of personal protective equipment (PPE) in SMEs is still low, which is related to the low level of knowledge, attitude, and safety culture of workers. This study shows that the absence of adequate supervision and legal regulation in small industries is the main factor in the low use of PPE. Increased supervision, occupational safety training, and expansion of labor laws, especially for SMEs, are recommended in order to significantly increase the use of PPE and reduce the risk of work accidents [33].

However, research using QFD and SPC for the manufacturing industry already exists. Like [9]. The combination of Quality Function Deployment (QFD) and Statistical Process Control (SPC) methods enables organizations to systematically transform customer requirements into product design and production processes, and ensure the stability and quality of output through continuous statistical monitoring. This approach enhances customer satisfaction by enabling dynamic updates to their needs based on feedback, thereby driving continuous improvement in the quality and competitiveness of the organization. Then, Statistical Process Control (SPC) and Quality Function Deployment (QFD) methods have proven to be the most impactful quality techniques in the industrial engineering domain, especially in production planning and control. Through the AHP approach, this study shows that the application of quality engineering techniques can increase productivity and sustainability by approximately 70%, making it an effective strategy to improve overall industrial performance. [34]. For the implementation of the Kano-QFD approach, it has been proven effective in increasing the intention to transfer learning in technology-based SMEs, especially through increasing one's abilities and the relevance of training materials. This program helps SMEs design product strategies that suit customer needs and can be applied across industries. [35].

II. RESEARCH METHODOLOGY

This research is used as an SLR if SMEs need to implement approaches to ensure the sustainability of their business. For this reason, it is necessary to apply appropriate methods so that SMEs can be competitive. Approaches that can be applied include: SPC, QFD, and Fuzzy-KANO.

The initial research began by identifying relevant search terms in databases such as Publish or Perish, which are known for their extensive coverage of a wide range of material. Nowadays, to survive in the “publish or perish” era, scientific publishers must adopt innovative publishing models, establish collaborations between institutions, and enhance researchers’ understanding of global scientific publishing trends and strategies [36]. However, the study shows that Scopus has experienced exponential growth since 1900 in terms of the number of articles, journals, field coverage, and the author country of origin. A significant increase occurred after the launch of Scopus in 2004. The use of abstracts in articles has also increased dramatically, from only 1% of articles having long abstracts in 1900 to 95% in 2020. In addition, international contributions to publications have become more even, with the initial dominance by the US and Germany being replaced by China and India in 2020 [37].

The literature search in this study used databases from Google Scholar, Crossref, and Scopus. Where researchers use the Scopus database because its scope is wider and the information related to the article is more structured to be processed with Bibliometrix [38]. And [39] also using Scopus using the keywords: "Optimization of Production Processes in Micro, Small and Medium Metal Enterprises" OR "SMEs" OR "SMEs Metal" AND "SPC" OR "Statistics Process Control" OR "QFD" OR "Quality Function Deployment". The screening process was conducted by assessing the appropriateness of both the abstract and the title in relation to the study topic. Articles that passed to the next stage were screened in full text, containing discussions on using SMEs, SPC, and the QFD method. In this screening, Open Refine is used to view the results from the database, which is continued with a worksheet to ensure the completeness of the data. The VOS Viewer generates a visual display of bibliographic materials using custom input data. The search terms represent the inclusion criteria and are closely linked to the study's objectives, scope, limitations, and areas for further exploration. Moreover, only English-language original articles were taken into account.

This study is an applied research aimed at developing a risk-based calibration system model in the copper foil industry using a quantitative approach. This approach was selected because the

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

problems addressed are practical in nature and related to evaluating the actual condition of measurement instruments. The study integrates two main methods: Fuzzy Failure Mode and Effects Analysis (Fuzzy FMEA) for risk assessment and Measurement System Analysis (MSA) with Gauge Repeatability and Reproducibility (GRR) for evaluating measurement system capability. This research also adopts risk-based thinking as recommended in ISO 9001:2015 and ISO/IEC 17025:2017, which emphasizes the importance of risk identification and control throughout the measurement process. Therefore, this study develops a calibration system that is not solely time-based but also adjusted according to the actual performance and risk level of each instrument.

2.1 *Integration of Small and Medium Enterprises (SMEs), SPC, and QFD*

The integration of SMEs with both SPC and QFD has not been extensively explored in previous studies. Existing research mostly focuses on the integration of SMEs with either SPC or QFD separately. As illustrated in Figure 3, a total of 562 records were retrieved from Google Scholar, Crossref, and Scopus databases. After an initial screening, 475 records were excluded, leaving 87 for further processing. However, among these 87 records, 31 were found to be books, reports, or theses and were therefore excluded from the analysis. Consequently, only 56 journal articles were examined in detail. Of these, 35 full-text articles were accessible, as many others required payment for access.

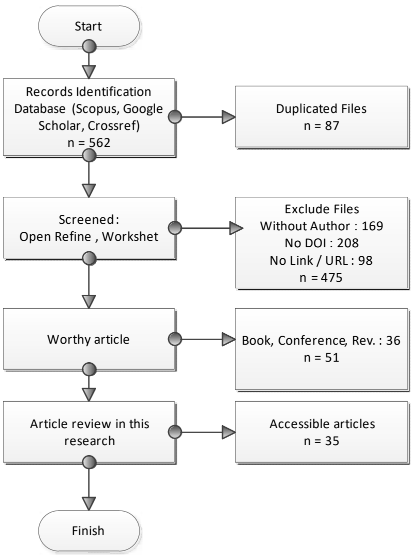


Figure 3. Flow Chart of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis)

Thus, this study utilized 35 articles, as shown in Figure 3, which were successfully downloaded and included in the reference list.

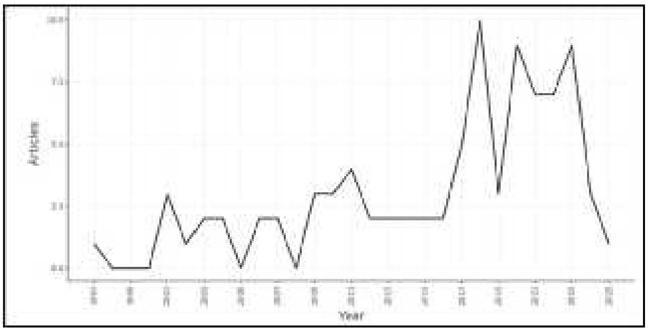


Figure 4. Annual Scientific Production

As shown in Figure 4, research development on the integration of Small and Medium Enterprises (SMEs), SPC, and QFD remains limited, with publications only beginning to emerge around early 2017.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1997:2025
Sources (Journals, Books, etc)	69
Documents	87
Annual Growth Rate %	0
Document Average Age	9.02
Average citations per doc	12.37
References	3409
DOCUMENT CONTENTS	
Keywords Plus (ID)	439
Author's Keywords (DE)	258
AUTHORS	
Authors	260
Authors of single-authored docs	3
AUTHORS COLLABORATION	
Single-authored docs	3
Co-Authors per Doc	3.28
International co-authorships %	12.64
DOCUMENT TYPES	
article	51
book chapter	2
conference paper	31
conference review	2
review	1

Figure 5. Main Information from the Bibliometrix Output

Furthermore, the data was processed using Bibliometrix, as shown in Figure 5. The analysis identified a total of 87 documents, spanning the period from 1997 to 2025. Among these, 51 are journal articles, while the remaining 36 consist of books and conference papers. The main information also revealed a total of 260 contributing authors and 489 keywords.

Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

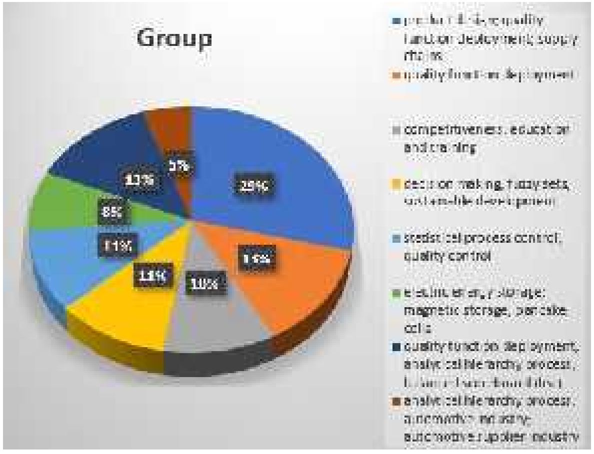


Figure 6. Distribution of Document Groups Generated by Bibliometrix

As shown in Figure 6, Bibliometrix grouped the documents into eight categories, as detailed in Table 1.

Table 1. Group Documents Based on Bibliometrix

Label	Group	Freq.
product design; quality function deployment; supply chains	1	11
quality function deployment	2	5
competitiveness; education and training	3	4
decision making; fuzzy sets; sustainable development	4	4
statistical process control; quality control	5	4
electric energy storage; magnetic storage; pancake coils	6	3
quality function deployment; analytical hierarchy process; balanced scoreboard (BSC)	7	5
analytical hierarchy process; automotive industry; automotive supplier industry	8	2

Table 1 indicates that Group 1, which comprises the largest number of research topics, includes themes such as product design, quality function deployment, and supply chains.

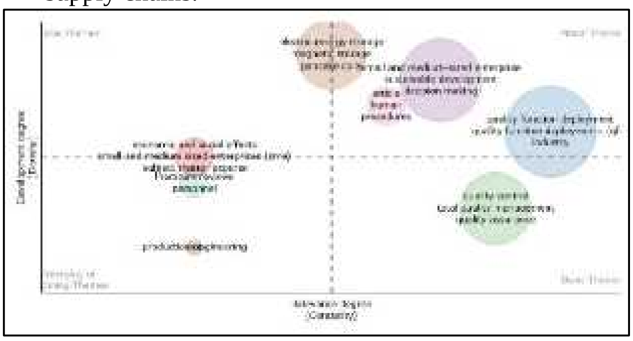


Figure 7. Thematic Map Based on Bibliometrix

Based on the thematic mapping analysis results using Bibliometrix, as shown in Figure 7, four categories of research themes were identified, representing the strategic position of each topic within the scientific landscape. Themes located in the motor themes quadrant, such as small and medium-sized enterprises, sustainable development, decision making, and procedures, exhibit high levels of both relevance and development. This positioning indicates that these themes play a central and dynamic role in the field, serving as the main focus of current literature. Their dominance reflects conceptual and methodological maturity, as well as significant potential to shape future research directions. Conversely, themes such as quality control, total quality management, and quality assurance fall in the quadrant of the basic themes. Although highly relevant to the field, these themes have shown limited development. This suggests a need to update theoretical frameworks and integrate contemporary issues to prevent stagnation. In contrast, themes like electric energy storage and pancake coils are categorized as niche themes. These show high development but possess limited relevance, typically representing highly specialized and in-depth areas with significant contributions within narrow applications or specific scientific communities. Themes, including production engineering, personnel, and subject matter experts, are positioned in the emerging or declining themes quadrant, characterized by low relevance and development. This may indicate that these themes are either in the early exploratory stages or beginning to be abandoned by the scientific community. Additionally, several transitional themes, such as economic and social effects, literature reviews, and small and medium-sized enterprises (SMEs), are located at the center of the map. This positioning highlights their potential either to evolve into motor themes with sustained research attention or to decline without adequate scientific support. Overall, this thematic mapping provides a strategic overview of the structure and dynamics of the field of study being analyzed. The insights gained are valuable not only for tracking research trends but also for guiding future research directions by identifying emerging themes, relevant yet underdeveloped themes, and themes that require revitalization to sustain their contribution to scientific advancement. Next, a summary of themes related to SMEs, SPC, and QFD is shown in Table 2.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

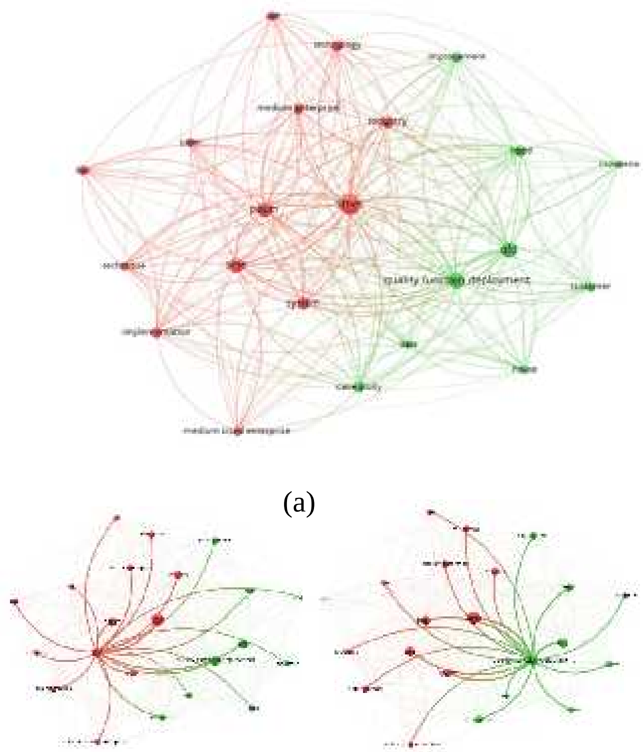
Table 2. Summary of themes for SMEs, SPC, and QFD-related articles

Topic	Description	Authors
SPC and SMEs Integration	Digital technologies play a crucial role in building antifragility in SMEs, enabling them not only to survive crises such as COVID-19 but also to grow stronger through these challenges.	[40]; [41];
QFD and Digital Transformation	Examining the integration of Quality Function Deployment (QFD) in industrial digital transformation strategies.	[42];
QFD and Industry 4.0	Examining the application of Quality Function Deployment (QFD) within the Industry 4.0 technology framework to enhance product quality.	[42];
Hybrid QFD–AHP/KANSEI	Developing a hybrid approach combining Quality Function Deployment (QFD) and the Analytical Hierarchy Process (AHP) for design decision-making.	[43]; [44];
Hybrid QFD–Kano	Integrating QFD and the Kano Model in product design that focuses on SME customer needs.	[45]; [46]; [47];
QFD and Customer Satisfaction	The relationship between Quality Function Deployment (QFD) methods and customer satisfaction in product development.	[48]; [49]; [50]
SPC and QFD for Customer Satisfaction	Evaluating the relationship between Statistical Process Control (SPC) and Quality Function Deployment (QFD) implementation and customer feedback in quality improvement.	[51]

Table 3. Potential Directions for Future Research

Aspect	Findings	GAP	Opportunity
QFD and Quality	Important but underdeveloped	Low integration and the need for new approaches	Fuzzy-Kano-QFD specifically for SMEs
SMEs & Socio-Economic	Not strongly connected to quality themes	Still developing	Relevance of QFD in the local context of SMEs
Sustainability & Decision Making	Advanced but not integrated into QFD	Lack of connection between themes	QFD as a decision-making tool for sustainability
Production Engineering	Not specific	Not closely or linked to quality	Connect QFD with production processes & SPC.

In Table 3, we can see several research opportunities that still need to be explored.



(a)

(b) (c)

Figure 7. Visualization of keyword usage frequency. Network visualization by VOSviewer, the relationship between frequently used keywords in SMEs, SPC, and QFD.

In Figure 7, part (a) presents a VOSviewer network visualization that includes terms related to SMEs, Statistical Process Control (SPC), and Quality Function Deployment (QFD), showing the overall network formed from all related documents. In part (b), the network specifically illustrates the relationship between SMEs and Statistical Process Control (SPC). There are no connections linking this network to Quality Function Deployment (QFD), indicating a lack of direct association. Similarly, part (c) shows the network between SMEs and Quality Function Deployment (QFD), where no visible connections to Statistical Process Control (SPC) are found. Upon closer examination of the enlarged VOSviewer visualization, it becomes clear that there is no relationship or network connection between Statistical Process Control (SPC) and Quality Function Deployment (QFD). The networks appear disconnected, highlighting the gap in the literature that integrates these three elements.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

III. RESULTS AND DISCUSSION

The limited number of literature reviews on the subject of Metal SMEs, Statistical Process Control (SPC), and Quality Function Deployment (QFD) integrated with the Fuzzy-KANO model indicates that no comprehensive study has been conducted. This condition is very different when compared to studies on the metal industry with SPC or industries that apply Quality Function Deployment (QFD) separately. The role of Quality Function Deployment (QFD) in the manufacturing industry has been previously studied, and even more extensively in the service industry, as the Quality Function Deployment (QFD) approach effectively captures customer needs and translates them into technical responses aimed at fulfilling those needs. This process is expected to enhance customer satisfaction and, ultimately, support the sustainability of the business.

Thus, the integration of several methods into QFD, such as Fuzzy-KANO, along with the incorporation of SPC to address challenges in Metal SMEs, remains novel and holds significant potential to provide effective solutions for the issues faced by these enterprises. This integrated approach can contribute substantially to the sustainability of Metal SMEs. Furthermore, this potential is reinforced by previous studies that have successfully combined various methods in industries beyond Metal SMEs. Research on SPC and SMEs Integration by Vincenzo Corvello et al., [40]; Radicic & Petkovic, [41] gives the idea that digital technologies play a crucial role in building antifragility in SMEs, enabling them not only to survive crises such as COVID-19 but also to grow stronger through these challenges. SPC and QFD for Customer Satisfaction by Kelblerová & Vykydal, [51], gives an idea that evaluating the relationship between Statistical Process Control (SPC) and Quality Function Deployment (QFD) implementation and customer feedback in quality improvement. Hybrid QFD–Kano by Shanmugaraja, et al., [45]; Pujianto et al., [46]; and Neira-Rodado et al., [47] gives an idea that integrating Quality Function Deployment (QFD) and Kano Model in product design that focuses on SME customer needs. Quality Function Deployment (QFD) and Customer Satisfaction by Ce, et al., [48]; Zhang et al., [49] and Prihono & Nurcahyanie, [26] give an idea of the relationship between Quality Function Deployment (QFD) methods and customer satisfaction in product development.

IV. CONCLUSION

The integration of Statistical Process Control (SPC) and Quality Function Deployment (QFD) approaches with Fuzzy-KANO provides a systematic methodology that effectively incorporates customer needs and expectations into the product design and development processes within SMEs. This study finds that combining Quality Function Deployment (QFD) with Fuzzy-KANO yields better outcomes than conventional Quality Function Deployment (QFD) techniques by incorporating additional factors relevant to the SMEs sector, such as environmental sustainability, regulatory compliance, and supply chain considerations. Additionally, Statistical Process Control (SPC) supports product quality assurance by continuously monitoring the production process and minimizing the occurrence of defects.

However, the integration of Quality Function Deployment (QFD) with various supporting methods remains an area that requires further comprehensive research, particularly as part of advancing engineering applications. This study explores an integrated methodology combining Fuzzy-KANO, Quality Function Deployment (QFD), and Statistical Process Control (SPC) within the context of Metal SMEs, with a focus on the effectiveness of this approach. Furthermore, the study highlights sustainability as a critical factor for Metal SMEs and examines its role in the application of the integrated Statistical Process Control (SPC) and Quality Function Deployment (QFD) approach enhanced by Fuzzy-KANO.

The results of this study indicate that, over the past decade, there has been a fluctuating trend in the number of publications related to the application of SPC and QFD in SMEs, particularly in the context of sustainability-oriented products. Research activity peaked in 2017 and 2023, with 6 publications in 2017 and 9 in 2023. While studies exploring the relationship between SPC and SMEs, as well as between SMEs and QFD, are available, there is a notable absence of research that directly integrates all three elements: SMEs, SPC, and QFD. This highlights the need for further research that explicitly connects these three components in a unified framework. Based on the findings of this review, several potential

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11607 *e*-ISSN 2622-2035

directions for future research are identified, including: (a) the integration of Fuzzy-Kano and QFD specifically tailored to the characteristics and needs of SMEs, particularly in local contexts; (b) the utilization of QFD as a decision-making tool to support sustainability initiatives within SMEs; and (c) the integration of QFD with production processes and Statistical Process Control (SPC) to enhance overall product quality and operational efficiency.

- Authors' contribution
  All authors contributed equally to the preparation of this article.
- Declaration of competing interest
  The authors declare no conflicts of interest.
- Funding source
  This study didn't receive any specific funds.
- Data availability
  The data that support the findings of this study are available from the corresponding author upon reasonable request.
- Acknowledgments
  The authors would like to thank Malang State University and PGRI Adi Buana University Surabaya for their continued support for high-quality research.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

Evaluation of Measurement Instruments Using Fuzzy FMEA and MSA/GRR for Determining Calibration Intervals

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***Abstract*— Laboratory testing instruments are critical for ensuring accurate measurement results and maintaining product quality. Failures or performance decline in these instruments may affect testing reliability. This study evaluates potential instrument failures using Fuzzy Failure Mode and Effects Analysis (Fuzzy FMEA) and assesses measurement system capability via Measurement System Analysis (MSA) with Gage Repeatability and Reproducibility (GRR). Five instruments, the Thickness Gauge, Roughness Tester, Tensile Tester, Density Tester, and Chromium Analyzer, were analyzed. Fuzzy FMEA results show the Roughness Tester has the highest Fuzzy Risk Priority Number (FRPN = 8.93), followed by the Chromium Analyzer (8.20), Tensile Tester (6.40), Thickness Gauge (5.47), and Density Tester (3.33). Historical data validate that higher FRPN values correspond to more frequent operational failures. GRR analysis indicates all instruments maintain acceptable measurement system performance (%GRR < 30%). Based on these findings, calibration intervals are recommended according to risk level and system stability, promoting efficient calibration management and reliable testing results.**

***Keywords*: Calibration Interval Evaluation, Fuzzy FMEA, GRR, Measurement Instruments, Measurement System Analysis**

I. INTRODUCTION

Measurement systems play a critical role in laboratories to ensure accurate measurement results and maintain consistent product quality, particularly in industries such as metal manufacturing, where adherence to technical specifications is essential. [1]–[3]. Accuracy, precision, and stability are key attributes of measurement systems, affecting the reliability of testing results and operational decisions. [4], [5]. Instrument failures or declines in performance may lead to false rejects or false accepts, which can compromise product quality, customer satisfaction, and operational costs.[6], [7].

In practice, most laboratories implement time-based calibration schedules, usually every 12 months, based on manufacturer recommendations or operational convenience. However, such schedules do not consider the actual condition of each instrument. [8], which can lead to over-calibration, wasting resources, or under-calibration, risking inaccurate results [9]. Conventional Failure Mode and Effects Analysis (FMEA) is commonly used to identify potential failures based on severity, occurrence, and detection, but it often suffers from subjectivity and ambiguity in Risk Priority Number (RPN) calculations. [10]–[12]

To address these limitations, Fuzzy FMEA integrates fuzzy logic, converting linguistic assessments (“low,” “medium,” “high”) into Triangular Fuzzy Numbers (TFN), resulting in a Fuzzy Risk Priority Number (FRPN) that better captures uncertainty and expert judgment variability. [13], [14]. Complementarily, Measurement System Analysis (MSA) using Gauge Repeatability and Reproducibility (GRR) quantifies variations caused by instruments (repeatability) and operators (reproducibility), providing a reliable evaluation of the measurement system’s performance. [13], [15], [16].

Fuzzy FMEA effectively prioritizes measurement risks by incorporating uncertainty and expert judgment, and MSA/GRR evaluates the capability and consistency of the measurement system. These approaches are rarely integrated into a unified framework for determining optimal calibration intervals. [11]. Calibration intervals are often established based on fixed schedules or

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

manufacturers' recommendations rather than the actual performance and risk profile of measurement instruments. [17], [18]. Consequently, instruments with stable performance may be calibrated more frequently than necessary, leading to unnecessary costs and downtime, whereas instruments with deteriorating performance may remain in service beyond appropriate intervals, increasing the risk of inaccurate measurements. [19].

By integrating Fuzzy FMEA and GRR, this study evaluates both the potential failures of instruments and the actual performance of measurement systems. The combined analysis serves as the basis for condition-based calibration intervals, adjusting calibration frequency according to each instrument's risk level and stability. This approach allows laboratories to improve measurement reliability, optimize calibration resources, and reduce operational risks caused by inaccurate testing results [20], [21], [22].

II. RESEARCH METHODOLOGY

Research Approach

This study employed an applied quantitative research design to develop a risk-based calibration interval model for measurement instruments used in the metal manufacturing industry. The research aims to improve conventional time-based calibration practices by integrating instrument risk assessment with measurement system capability evaluation. The proposed framework combines Fuzzy Failure Mode and Effects Analysis (Fuzzy FMEA) and Measurement System Analysis (MSA) using Gauge Repeatability and Reproducibility (GRR). This integrated approach aligns with the principles of risk-based thinking promoted by ISO 9001:2015 and ISO/IEC 17025:2017, which emphasize identifying, evaluating, and controlling risks throughout the measurement process. Consequently, calibration intervals are determined according to both the operational risk and the actual performance of each measuring instrument rather than relying solely on fixed calibration schedules.

Research Object and Scope

The research was conducted in the quality control laboratory of a metal manufacturing company. Five critical measuring instruments routinely used in product quality inspection were selected as research objects:

1. Thickness Gauge
2. Surface Roughness Tester
3. Tensile and Elongation Tester
4. Density Tester
5. Chromium Content Analyzer

The study focuses on evaluating the reliability of these instruments through two complementary perspectives. First, the operational risks associated with each instrument are analyzed using Fuzzy FMEA to identify potential failure modes that may affect measurement reliability. Second, the capability of each measurement system is evaluated through MSA using Gauge Repeatability and Reproducibility (GRR). The integration of these analyses provides the basis for determining optimal calibration intervals.

Data Collection

This study utilized both primary and secondary data.

Primary data were collected through structured questionnaires administered to laboratory operators, maintenance engineers, quality assurance personnel, and laboratory supervisors. The questionnaire was designed to evaluate the three FMEA risk factors—Occurrence (O), Severity (S), and Detection (D)—using linguistic variables instead of numerical ratings. Secondary data consisted of:

1. historical calibration certificates,
2. maintenance records,
3. equipment failure reports,
4. measurement deviation records,
5. laboratory nonconformity reports,
6. Production quality records.

These secondary data were used to validate the identified failure modes and verify the consistency between expert assessments and actual instrument performance.

SOP Analysis and Operational Gap Identification

Before conducting the risk assessment, all Standard Operating Procedures (SOPs) related to instrument operation, calibration, maintenance, and verification were reviewed. The objective of this analysis was to identify discrepancies between documented procedures and actual laboratory practices. The identified operational gaps included:

1. inconsistent operating procedures,

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

2. inadequate preventive maintenance,
3. operator-related errors,
4. environmental influences,
5. delayed calibration activities.

The results of the SOP analysis became the primary reference for identifying potential failure modes during the Fuzzy FMEA process.

Instrument Risk Identification and Assessment Using Fuzzy FMEA

a. Failure Mode Identification

Potential failure modes for each measuring instrument were identified through:

1. SOP review,
2. direct field observations,
3. interviews with experts,
4. historical maintenance records,
5. calibration history,
6. Laboratory nonconformity reports.

Each failure mode was evaluated based on three classical FMEA criteria: Occurrence (O): likelihood of failure occurrence; Severity (S): impact of failure on measurement accuracy and product quality; Detection (D): ability of existing controls to detect the failure before affecting measurement results.

Linguistic Assessment

Instead of assigning crisp numerical scores, experts expressed their judgments using linguistic variables. Each linguistic term was represented by a **Triangular Fuzzy Number (TFN)**.

Linguistic Scale	**TFN (l, m, u)**
Very Low	(0,1,2)
Low	(1,2,3)
Medium	(2,3,4)
High	(3,4,5)
Very High	(4,5,6)
Critical	(5,6,7)

Aggregation of Expert Judgments

In Fuzzy FMEA, the three risk factors—Occurrence (O), Severity (S), and Detection (D)—are converted into Triangular Fuzzy Numbers (TFN) to handle the uncertainty in expert assessments:

$$\tilde{X} = (l, m, u)$$

The **Fuzzy Risk Priority Number (FRPN)** is calculated by combining the TFNs of the three factors:

$$\text{FRPN} = \tilde{O} \times \tilde{S} \times \tilde{D}$$

This provides a representative risk value that accounts for the fuzziness in linguistic assessments such as “Low,” “Medium,” and “High”

Table 1. Linguistic Scale

Linguistic Scale	TFN (l, m, u)
Very Low / Rare	(0, 1, 2)
Low / Unlikely	(1, 2, 3)
Medium	(2, 3, 4)
High / Frequent	(3, 4, 5)
Very High / Very Frequent	(4, 5, 6)
Critical / Extremely High	(5, 6, 7)

Development of Risk Register and Risk Visualization

After the completion of the Fuzzy FMEA process, the next step was the preparation of a Risk Register to map potential failures for each instrument based on the analysis results. The Risk Register functions as a tool to classify and prioritize risks faced by each instrument according to the combination of Occurrence, Severity, and Detection values. These risk values were visualized in the form of a heatmap to facilitate the identification of areas with the highest risk levels. This heatmap assists in determining which instruments require further attention in terms of calibration and maintenance. The risk visualization also serves as the basis for decision-making in determining more adaptive and condition-based calibration intervals.

Evaluation of Measurement System Performance (MSA/GRR)

The evaluation of measurement system performance was conducted using Measurement System Analysis (MSA) with a focus on Gauge Repeatability and Reproducibility (GRR). GRR was used to measure two main types of variation in the measurement system: repeatability (variation caused by the measuring instrument) and reproducibility (variation caused by the operator). Data obtained from the GRR experiment was used to assess whether the measurement system utilized in the laboratory could provide consistent and reliable results. The GRR evaluation criteria applied were the standards commonly accepted in industry: if the

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

%GRR value is %, the measurement system is considered excellent; if 10% < %GRR ≤ 30%, the system is still acceptable with consideration; and if %GRR > 30%, the measurement system is considered inadequate.

The **GRR** method quantifies measurement system variation, separating repeatability (equipment) and reproducibility (operator) components. The total %GRR is calculated as:

$$\%GRR = \frac{\sqrt{\sigma^2_{\text{repeat}} + \sigma^2_{\text{reprod}}}}{\text{Tolerance}} \times 100\%$$

Interpretation:

- %GRR ≤ 10% → Excellent measurement system
- 10% < %GRR ≤ 30% → Acceptable
- %GRR > 30% → Inadequate

Integration of Fuzzy FMEA and GRR

The final stage integrated the results of Fuzzy FMEA and MSA/GRR to establish a risk-based calibration interval model. Each measuring instrument was classified according to two dimensions:

1. Operational risk represented by the FRPN value.
2. Measurement capability represented by the %GRR value.

The integration matrix provides the basis for calibration decision-making:

1. High FRPN + High %GRR: Calibration interval should be shortened, and corrective maintenance should be prioritized.
2. High FRPN + Low %GRR: Maintain calibration frequency while strengthening preventive maintenance and operational controls.
3. Low FRPN + High %GRR: Improve measurement capability before extending calibration intervals.
4. Low FRPN + Low %GRR: Calibration intervals may be safely extended, subject to compliance with organizational and regulatory requirements.

This integrated framework enables calibration decisions to be based on both operational risk and measurement performance, thereby improving laboratory reliability, reducing unnecessary calibration costs, and supporting continuous quality improvement.

III. RESULTS AND DISCUSSION

Historical Data Description

In this section, the analysis of historical data from testing instruments is essential for validating the results of risk evaluation conducted through Fuzzy FMEA and MSA/GRR. The historical data used include records of out-of-tolerance (OOT) incidents, drift deviations, downtime, and operator complaints that occurred during the testing period (January 2024 – February 2026). The analyzed instruments include the Thickness Gauge, Roughness Tester, Tensile Tester, Density Tester, and Chromium Analyzer.

Based on the collected historical data, instruments with high usage frequency, such as the Roughness Tester and Tensile Tester, experienced nonconformities or deviations more frequently than the other instruments. In contrast, instruments such as the Density Tester and Thickness Gauge demonstrated more stable performance with fewer nonconformity incidents.

Table 2. Historical Instrument Data (January 2024 – February 2026)

Instrument	OOT (Times)	Drift (Exceeded Limits)	Downtime (Hours)	Operator Complaints	Usage Frequency
Thickness Gauge	2	5	7	6	680
Roughness Tester	4	11	16	14	930
Tensile Tester	3	7	12	8	590
Density Tester	1	3	3	2	340
Chromium Analyzer	3	8	13	7	460

These data reveal that the Roughness Tester and Chromium Analyzer have higher numbers of OOT incidents, drift, and downtime, indicating that both instruments are more prone to nonconformities during the testing period. The Density Tester exhibited the most stable data, with minimal OOT incidents and downtime.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

Fuzzy FMEA Results

Distribution of Occurrence–Severity–Detection Questionnaire Responses

This section presents the response patterns of respondents for the three main risk parameters in FMEA, namely Occurrence (O), Severity (S), and Detection (D). The analysis of this linguistic distribution aims to provide an initial overview of users' risk perceptions toward each laboratory instrument.

The distribution of linguistic values is important because it represents the initial stage in the fuzzification process, in which each linguistic category (e.g., Medium, High, Difficult) is converted into a Triangular Fuzzy Number (TFN) based on a predetermined fuzzy scale (see Appendix or Methodology Chapter).

This approach is consistent with recommendations in the Fuzzy FMEA literature (Tsai et al., 2017; Zadeh, 1975) as well as common practices in operator perception-based risk analysis according to ISO 31000:2018 and the metrological evaluation principles of ISO/IEC 17025:2017.

The questionnaire data consisted of 15 respondents for each instrument. The three risk parameters collected were:

1. Occurrence (frequency of potential failure occurrence)
2. Severity (severity level of failure impact)
3. Detection (ease of detecting potential failures)

Thickness Gauge

The following table presents the distribution of respondents' assessments for the Occurrence, Severity, and Detection parameters of the Thickness Gauge instrument.

Table 3. Thickness Gauge

Linguistic Scale	Occurrence	Severity	Detection
Very Rare	0	0	0
Rare	1	0	0
Medium	11	13	10
Frequent	3	0	0
Very Frequent	0	0	0
Low	-	1	-
High	-	1	-
Critical	-	0	-
Easy	-	-	0
Difficult	-	-	5
Very Difficult	-	-	0

The response distribution indicates that the majority of respondents assessed Occurrence as Medium, suggesting that the Thickness Gauge has a tendency to experience minor deviations periodically, but not at an alarming frequency. This is consistent with the characteristics of thickness measurement instruments, which experience wear and thermal drift over time.

The Severity assessment was also concentrated in the medium category. Thickness measurement deviations tend to have a moderate impact on product quality, especially for materials with tight tolerances. However, most errors can still be corrected through re-verification, so the "High" category was selected by only one respondent.

For the Detection parameter, there were two major groups: Medium (10 respondents) and Difficult (5 respondents). This indicates that some deviations, particularly micro drift, are not immediately visible to operators during daily measurements. The inability to detect small drift is consistent with findings in metrology literature, which state that micro deviations in thickness sensors are often only detected during calibration or standard verification.

The Thickness Gauge demonstrates a moderate risk level, with the dominant factors being difficult in detecting drift and moderate deviation frequency.

Roughness Tester

The following table presents the distribution of respondents' assessments for the Occurrence, Severity, and Detection parameters of the Roughness Tester instrument.

Tabel 4. Roughness Tester

Linguistic Scale	Occurrence	Severity	Detection
Medium	2	0	0
Frequent	11	0	0
Very Frequent	2	0	0
High	-	11	-
Critical	-	4	-
Difficult	-	-	11
Very Difficult	-	-	4

The Roughness Tester exhibited the highest risk pattern among all reviewed instruments. For the Occurrence parameter, responses were concentrated in the Frequent and Very Frequent

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DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

categories, indicating that performance deviations occur relatively often. This is consistent with the mechanical characteristics of stylus systems, which are sensitive to wear, contamination, and vibration, as reported in tribology and surface metrology literature. [23][24], [25].
The Severity parameter was dominated by the High and Critical categories. Errors in surface roughness measurements may result in false acceptance or false rejection of products, thereby significantly impacting production quality.
For the Detection parameter, most respondents assessed it as Difficult or Very Difficult, which is consistent with the characteristics of stylus-based sensor instruments, where damage or drift is often hidden and only detected when deviations become significant. ISO 4287 literature also emphasizes that sensor noise and stylus damage are common causes of deviations that are difficult to diagnose.
The Roughness Tester is considered a very high-risk instrument and, therefore, should become a priority in risk control and Fuzzy FMEA evaluation.

Tensile Tester
The following table presents the distribution of respondents' assessments for the Occurrence, Severity, and Detection parameters of the Tensile Tester instrument.

Tabel 5. Tensile Tester

Linguistic Scale	Occurrence	Severity	Detection
Rare	1	0	0
Medium	14	2	8
High	-	12	-
Critical	-	1	-
Difficult	-	-	7

The Tensile Tester demonstrated a medium-to-high risk pattern. The Occurrence parameter tended to fall within the medium category, reflecting failures related to jig alignment, load cell drift, or sample preparation errors commonly encountered in material testing.
For the Severity parameter, most respondents selected the High category, with one respondent assigning a Critical rating. This indicates that errors in tensile strength and elongation measurements have serious consequences for evaluating material integrity, as emphasized in ASTM E8/E8M standards.
The Detection distribution was divided between Medium and Difficult. Errors in the Tensile Tester may be detected through observation of stress–strain curves; however, load cell drift or internal damage is not always directly visible, making detection relatively challenging according to some respondents.
The Tensile Tester is categorized as a medium-to-high risk instrument, influenced by the significant impact of errors and the moderate difficulty of detection.

Density Tester
The following table presents the distribution of respondents' assessments for the Occurrence, Severity, and Detection parameters of the Density Tester instru ment.

Tabel 6. Density Tester

Linguistic Scale	Occurrence	Severity	Detection
Rare	11	-	-
Medium	4	11	4
Low	-	4	-
Easy	-	-	11

The Density Tester exhibited a low-risk pattern. Most respondents rated Occurrence as Rare, consistent with the instrument's stable construction and relatively simple measurement process.
The Severity parameter was distributed between Low and Medium, indicating that density measurement errors do not have major consequences in quality control processes, particularly since density values can still be verified through repeated measurements.
The Detection parameter showed very positive results, with most respondents selecting Easy. This indicates that performance errors in the Density Tester are usually clearly visible, such as reading fluctuations or unstable values.
In conclusion, the Density Tester is a low-risk instrument and therefore occupies a lower priority level in the risk mitigation plan.

Chromium Analyzer
The following table presents the distribution of respondents' assessments for the Occurrence, Severity, and Detection parameters of the Chromium Analyzer instrument.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

Tabel 7. Chromium Analyzer

Linguistic Scale	Occurrence	Severity	Detection
Rare	1	0	0
Medium	14	0	0
High	-	14	-
Critical	-	1	-
Difficult	-	-	14
Very Difficult	-	-	1

The Chromium Analyzer demonstrated high-risk characteristics. The Occurrence parameter fell within the medium category, while Severity showed an extreme pattern in the High and Critical categories. This indicates that errors in chromium concentration measurements may have significant implications, especially regarding environmental regulations and metal finishing product quality compliance.
The Detection parameter was also categorized as Difficult and Very Difficult. According to optical instrument literature (Skoog & Holler, 2013), spectral noise, reduced light source intensity, and optical contamination often cause deviations that are not immediately detected by operators.
In conclusion, the Chromium Analyzer is a high-risk instrument, mainly due to the substantial impact of measurement errors and the difficulty in detecting early failure symptoms.
This questionnaire distribution analysis provides an initial overview of risk perceptions for each instrument. The results serve as the basis for the fuzzification process, in which all linguistic values are converted into Triangular Fuzzy Numbers (TFN). The fuzzification process and subsequent fuzzy calculations are presented in the following subsection (4.2.2).

Measurement System Analysis (MSA)
Gauge Repeatability and Reproducibility (GRR) was used to evaluate variations in the measurement system caused by the instrument itself (repeatability) and by operators (reproducibility). The GRR evaluation results indicate that instruments with higher %GRR values tend to exhibit greater variation in measurement performance between operators and instruments.

Table 8. GRR Evaluation Results for Instruments

Instrument	%GRR	Interpretation
Roughness Tester	9.57%	Excellent
Tensile Tester	7.31%	Excellent
Chromium Analyzer	19.33%	Very Good
Density Tester	8.41%	Excellent
Thickness Gauge	19.67%	Very Good

From the GRR results, instruments such as the Roughness Tester showed higher %GRR values, indicating that variation between operators and instruments is relatively significant. This demonstrates that calibration and operator training are highly important to ensure measurement consistency for these instruments.
The Density Tester and Thickness Gauge showed better performance with lower %GRR values, indicating that measurement variations in these instruments are more controlled.

Evaluation and Determination of Calibration Intervals
Based on the results of Fuzzy FMEA and GRR, calibration intervals are recommended to be adjusted according to the actual condition of each instrument. Instruments with high risk and high %GRR values, such as the Roughness Tester, should be calibrated more frequently, while instruments with low risk and low %GRR values, such as the Density Tester, may have longer calibration intervals.

Table 9. Recommended Calibration Intervals Based on Fuzzy FMEA and GRR

Instrument	Recommended Calibration Interval
Roughness Tester	Every 3 months
Tensile Tester	Every 6 months
Chromium Analyzer	Every 6 months
Density Tester	Every 12 months
Thickness Gauge	Every 9 months

These calibration interval recommendations indicate that calibration based on actual instrument conditions provides benefits in optimizing resources and improving the reliability of measurement results. More efficient calibration interval determination can reduce the risk of operational failures without compromising

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

product quality.

Final Fuzzy Risk Priority Number (FRPN) Ranking

The defuzzified Fuzzy Risk Priority Numbers (FRPN) for all measurement instruments are summarized in Table 4.3. This ranking illustrates the priority of instruments based on their potential failure risk, guiding calibration and maintenance strategies. Instruments with higher FRPN values require closer attention and more frequent calibration.

Table 10. Final Fuzzy Risk Priority Number (FRPN) Ranking

Instrument	FRPN (Crisp)	Risk Level	Ranking
Roughness Tester	8.93	Very High	1
Chromium Analyzer	8.20	High	2
Tensile Tester	6.40	Medium-High	3
Thickness Gauge	5.47	Medium	4
Density Tester	3.33	Low	5

This table shows the defuzzified FRPN values for each measurement instrument, indicating their risk levels and ranking. Higher FRPN values correspond to higher potential failure risk, which guides priority for calibration and maintenance. The FRPN values were obtained using the centroid method from Triangular Fuzzy Numbers (TFNs) of the Occurrence, Severity, and Detection ratings.

IV. DISCUSSION

Risk Analysis Using Fuzzy FMEA

The results of the Fuzzy FMEA indicate that each measurement instrument has a different level of risk, which affects the recommendations for calibration intervals. Based on the assessment of Occurrence, Severity, and Detection, high-risk instruments such as the Roughness Tester and Chromium Analyzer require special attention in terms of calibration and routine maintenance.

The Roughness Tester showed the highest Fuzzy Risk Priority Number (FRPN), indicating that this instrument has a very high level of risk (Pacana & Olearczyk, 2017). This instrument frequently experiences nonconformities that are difficult to detect and have significant impacts on product quality. The difficulty in detecting errors before testing is completed is one of the reasons why the Roughness Tester should have a shorter calibration interval, namely every three months. This finding is consistent with previous studies showing that instruments with high FRPN values require greater attention in terms of maintenance and more frequent calibration. [26], [27].

In contrast, instruments such as the Density Tester and Thickness Gauge demonstrated lower risk levels, with significantly smaller FRPN values. The Density Tester exhibited low risk due to the rare occurrence of failures and low severity, where density measurement errors do not significantly affect final product quality. This finding also supports that low-risk instruments may be calibrated at longer intervals without affecting product quality. [28].

Evaluation of Measurement System Performance Using GRR

The results of the Measurement System Analysis (MSA) using Gauge Repeatability and Reproducibility (GRR) indicate that the %GRR value for the Roughness Tester is relatively high, meaning that measurement variation is more influenced by the instrument and operator than by the characteristics of the tested samples. This indicates that more frequent calibration is necessary to maintain the accuracy of measurement results and reduce the influence of human factors. [29]. This finding is consistent, which suggests that instruments with high %GRR values require routine calibration to maintain consistent measurement quality. [28].

Instruments with low %GRR values, such as the Density Tester and Thickness Gauge, demonstrated better measurement stability. With low %GRR values, the occurring variations remain acceptable within the specified tolerance limits, and these instruments do not require overly frequent calibration. This finding supports studies stating that instruments with stable performance may have longer calibration intervals. [30], [31]

Implications of the Research Findings

This study provides an important contribution to the management of laboratory instrument calibration through a more flexible and efficient condition-based approach. The Roughness Tester,

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11482 *e*-ISSN 2622-2035

which demonstrated high risk and large measurement variation, requires greater attention in terms of calibration and maintenance to ensure consistent measurement quality. [29]. On the other hand, the Density Tester and Thickness Gauge, which demonstrated more stable performance, may be calibrated at longer intervals, thereby optimizing laboratory resource utilization and calibration costs. This risk-based approach is more efficient than the time-based approach commonly implemented in many laboratories. [30], [32].

The simultaneous use of Fuzzy FMEA and GRR provides significant advantages in identifying instruments that require more frequent calibration based on their risk levels and performance stability. By adopting this approach, laboratories can improve the reliability of measurement systems and extend instrument service life without compromising testing accuracy [32], [33].

Based on the results of this analysis, it is recommended that the Roughness Tester be calibrated every three months, while the Density Tester may have a longer calibration interval of every 12 months. The Thickness Gauge, which has a low % GRR and moderate risk level, may be calibrated every 9 months. This risk-based approach will not only improve calibration efficiency but also reduce costs associated with excessive calibration for instruments that do not require it. This is consistent with the findings of [34], [35], which suggests that condition-based calibration can reduce operational costs and improve measurement accuracy.

V. Conclusion

This study successfully developed a risk-based calibration system model for measurement instruments used in testing laboratories. Based on the results of the Fuzzy FMEA and GRR analyses, it can be concluded that high-risk instruments, such as the Roughness Tester, require shorter calibration intervals, namely every 3 months. This is because the Roughness Tester exhibited a high Fuzzy Risk Priority Number (FRPN), which reflects a high frequency of failures, significant impacts on product quality, and difficulties in detecting instrument errors. In contrast, instruments with low %GRR values and low risk levels, such as the Density Tester and Thickness Gauge, demonstrated better measurement stability and may be calibrated at longer intervals, namely every 12 months and 9 months, respectively, in accordance with the findings obtained.

The condition-based calibration approach proposed in this study enables more efficient calibration management, reduces excessive calibration for instruments that do not require it, and still maintains measurement accuracy for high-risk instruments. By using Fuzzy FMEA and GRR simultaneously, laboratories can improve efficiency in managing calibration resources, optimize calibration costs, and ensure product quality without compromising the reliability of measuring instruments.

Overall, this study provides an important contribution to improving the efficiency of calibration systems in testing laboratories, while also introducing a more data-driven model that aligns with the guidelines of ISO 9001:2015 and ISO/IEC 17025:2017 regarding risk management in calibration and quality control of measuring instruments. The recommendation from this study is to implement a more flexible risk-based calibration approach, with calibration intervals adjusted according to the actual performance and condition of the measurement instruments used.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

Operational Risk Analysis and Prioritization of Mitigation Strategies in the Production Process of Processed Sweet Potato Products at Ummah Cookies

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***Abstract*—The development of the local food industry in Indonesia faces challenges due to the increasing dominance of modern and imported food products, which have caused local food-based processed products to be increasingly marginalized. Ummah Cookies, as a local food processing MSME based on sweet potatoes and cassava, still faces various operational risks that have the potential to affect product quality and the stability of the production process. This study aims to analyze operational risks and determine risk mitigation strategies in the production process of sweet potato processed products at Ummah Cookies. The method used in this study is a combination of Failure Mode and Effects Analysis (FMEA) and Analytical Hierarchy Process (AHP). The FMEA method is used to identify and prioritize risks based on Severity, Occurrence, and Detection values through the calculation of the Risk Priority Number (RPN), while the AHP method is used to determine the priority of risk mitigation strategies. The results of the study showed that the highest risk in sweet potato brownie products was at the production stage in the form of the emergence of a strong sweet potato aroma with an RPN value of 330. Meanwhile, in sweet potato porridge products, the highest risk was at the post-production stage in the form of products that spoil quickly during storage, with an RPN value of 342. The results of the AHP analysis showed that the priority of risk mitigation in sweet potato brownies lies in the production aspect, with an eigenvector value of 0.61, while in sweet potato porridge, it lies in the post-production aspect with an eigenvector value of 0.49. Recommended risk mitigation strategies include controlling the quality of raw materials, controlling the temperature and cooking process, implementing production SOPs, and optimizing product storage and packaging systems. The implementation of these strategies is expected to be able to maintain product quality stability, increase production process efficiency, and minimize potential losses in local food MSMEs.**

Keywords : **AHP, FMEA, Local Food, Risk Mitigation**.

I. Introduction

The development of the local food industry in Indonesia currently faces increasingly complex challenges due to the increasing dominance of imported snack products and modern foods that prioritize practicality over nutritional value. This phenomenon has increasingly marginalized traditional snacks made from local foods amidst changing consumption patterns of modern society. In fact, Indonesia has abundant local agricultural resources, such as sweet potatoes and cassava, which are rich in carbohydrates, fiber, and vitamins, and have great potential to be developed into processed food products with high economic value [Estiasih et al, 2018]. Furthermore, the use of local food ingredients is considered capable of supporting national food security and reducing dependence on imported food products [Widowati, 2019]. On the other hand, increasing public awareness of the importance of consuming healthy and natural foods opens up opportunities for micro, small, and medium enterprises (MSMEs) to present innovative, healthy, and competitive local food products in the market [Widianarko, 2020]. The development of sweet potato and cassava-based processed products is also a strategy to increase the added value of local agricultural commodities while supporting the preservation of traditional Indonesian culinary arts [Nurhayati and Prasetyo, 2021].

One micro-enterprise specializing in local food processing is Ummah Cookies, located in

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

Glonggongan Hamlet, Sumbertebu Village, Bangsal District, Mojokerto Regency. Founded in 2020, the business focuses on producing healthy snacks made from local resources, such as sweet potatoes, cassava, palm sugar, and coconut, as part of an effort to develop traditional food products with nutritional and economic value.

In the early stages of its production, Ummah Cookies produced various types of traditional snacks made from sweet potato and cassava, such as klepon, gethuk, kue talam, and lemet, which were marketed through traditional markets in the Mojokerto region, namely Sawahan Bangsal Market and Mojosari Market. These products represent a form of utilizing local foods that have cultural and economic value as part of the preservation of traditional regional cuisine [Widowati, 2018]. As consumer demand for more innovative and practical local food products increases, Ummah Cookies has diversified its products by developing various modern processed products made from sweet potato and cassava, such as sweet potato-filled soes, sweet potato croquettes, sweet potato balls, sweet potato brownies, and sweet potato bubu. Product diversification is an important strategy in increasing the competitiveness of local food businesses by creating product variations that suit the needs and preferences of the modern market [Winarno, 2020]. The development of this business is also demonstrated by the increasing operational capacity of the company, which is currently supported by 10 employees and has 5 sales outlets as a means of distributing products to consumers. This situation indicates that the development of local food-based products has significant potential to increase the growth of micro-enterprises while supporting the economic empowerment of the surrounding community [Nurhayati and Prasetyo, 2021]. Although Ummah Cookies has good economic potential and has experienced increased production, its production process still faces various operational risks, such as limited raw materials, inconsistent quality of sweet potatoes and cassava, product damage, and distribution delays. Dependence on local raw materials also causes the production process to be affected by supply conditions and seasonal factors [Pujawan and Mahendrawathi, 2017]. Poorly managed operational risks can reduce product quality, production efficiency, and business sustainability. Therefore, operational risk analysis is necessary to determine appropriate mitigation strategies to maintain production process stability [Pujawan, 2019]. In the local food industry, operational risk management is a crucial aspect for maintaining production process stability and increasing business competitiveness. Operational risk analysis is needed to identify potential failures at each stage of production so that business actors can determine risk management priorities and appropriate mitigation strategies. The implementation of planned risk mitigation can minimize losses, maintain product quality, increase production efficiency, and support the sustainability of local food businesses [Yuniarti, 2021].

The purpose of this study is to analyze operational risks in the local food industry to maintain the stability of the production process and increase the competitiveness of Ummah Cookies' business. Operational risks that are not managed properly can lead to decreased product quality, production delays, and even business losses. Therefore, a risk analysis is needed to identify potential failures at each stage of production and determine appropriate mitigation strategies [Yuniarti, 2021]. In this study, the method used is Failure Mode and Effects Analysis (FMEA), used to identify and analyze risk levels based on Severity, Occurrence, and Detection values, and the Analytical Hierarchy Process (AHP) method is used to systematically determine the priority of risk mitigation strategies [Stamatis, 2003]. Research on the yogurt production process shows that the FMEA method is able to identify dominant risks in yogurt production by showing the highest risks including bacterial contamination in fresh milk, decreased quality of starter bacteria during the production process, and the presence of competitors of similar products while the results of AHP calculations show three priority strategies to minimize risks, namely improving the quality of raw materials through training, strengthening business partnerships, and improving maintenance of production machines and equipment [Prasetiyo et al, 2017]. Another study on the Elfath Macaroni and Cheese food processing MSME showed that the integration of Fuzzy FMEA and Fuzzy AHP successfully identified 14 production risks originating from raw materials, processing, and packaging, with priority mitigation results in the form of partnerships with suppliers and maintenance of

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

production machines as the main strategy [Riana and Ghofari, 2024]. In addition, research on the shallot supply chain proved that the combination of FMEA and AHP methods is effective in determining risk priorities and mitigation strategies to maintain the stability of supply and quality of food products [Winanto and Santoso, 2017]. The novelty of this research lies in the application of the integration of the Failure Mode and Effects Analysis (FMEA) and Analytical Hierarchy Process (AHP) methods in risk analysis and determination of mitigation strategies in the production process of local food-based processed products, especially sweet potatoes at the Ummah Cookies MSME. The integration of these two methods is not only used to identify the level of risk through the Risk Priority Number (RPN), but also to produce priority mitigation decisions based on multi-criteria more objectively and systematically. Thus, this research contributes to the development of an integrated risk management model that is applicable for local food MSMEs in order to improve quality consistency, production process efficiency, and the competitiveness of local commodity-based products in a sustainable manner.

II. Research method

This study uses a risk management approach that includes identification, analysis, evaluation, and determination of risk mitigation strategies to analyze operational risks in the production process of processed sweet potato products at Ummah Cookies. Risk management is used to anticipate potential disruptions during the production process so that the company can minimize the impact of possible losses. In the production process of processed sweet potato products, risks can arise at the stages of raw material procurement, processing, packaging, and product storage. The method used in this study is a combination of Failure Mode and Effects Analysis (FMEA) and Analytical Hierarchy Process (AHP). The FMEA method is used to identify potential failure modes that can occur at each stage of the production process, along with their resulting impacts. FMEA is a systematic method that aims to analyze the possibility of failure, the causes of failure, and the consequences that can arise so that companies can determine preventive measures more effectively. FMEA is effectively used to identify sources of process failures preventively so as to improve the quality and reliability of production systems [Stamatis, 2003]. In addition, FMEA is one of the most widely used methods in industrial risk analysis because it is able to prioritize risks based on their critical level [Liu, 2013]. Another study, the application of FMEA in the manufacturing sector, can help companies in determining risk control strategies in a more structured and systematic manner [Kutlu, 2012]. Through this method, each risk is analyzed based on three main parameters, namely the severity of the impact (severity), frequency of occurrence (occurrence), and detection ability (detection). The values of these three parameters are then used to calculate the Risk Priority Number (RPN) with the formula.

$$\mathrm{RPN} = \mathrm{Severity} \times \mathrm{Occurrence} \times \mathrm{Detection} \quad (1)$$

The RPN value is used to determine the priority level of operational risks that require immediate corrective action in the production process of sweet potato food products at Ummah Cookies. Furthermore, the Analytical Hierarchy Process (AHP) method is used to determine the priority of risk mitigation strategies based on the results of risk identification using FMEA. The AHP method was chosen because it is able to solve complex problems through the preparation of a decision hierarchy and pairwise comparisons between criteria and alternative mitigation strategies. The assessment is carried out through pairwise comparisons between mitigation criteria such as control effectiveness, implementation costs, ease of application, and impact on the smoothness.

Of the quality of the production process.
of the production process. The results of the AHP calculation produce priority weights that can be used as a basis for decision-making in determining the most effective risk mitigation strategy [Triantaphyllou and Mann, 1995]. AHP is able to increase the accuracy of determining decision priorities because it consistently considers the level of importance of each criterion [Chopra and Meindl, 2016]. In addition, AHP is effective for use in decision support systems because it has the ability to integrate subjective assessments and quantitative data into a single decision model. Other research also explains that integrating FMEA and AHP methods can help companies determine risk mitigation priorities more objectively and measurably, thereby supporting

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

improvements in the quality of production processes [Vaidya, 2016].

III. Result and discussion

3.1 Risk Identification in the Sweet Potato Processed Product Production Process at Ummah Cookies

The identification process was conducted through direct observation of production activities, interviews with business owners and workers, and analysis of the production process flow of processed sweet potato products. The identification results revealed several potential risks, such as non-conformity in the quality of sweet potato raw materials, errors in the dough mixing process, damage to production equipment, inconsistent baking temperatures, and errors in the product packaging process. These risks have the potential to cause a decrease in product quality, production delays, increased operational costs, and losses for the company. During the data collection process, operational risks in the production of processed sweet potato products at Ummah Cookies were grouped into three main stages: pre-production risks, production process risks, and post-production risks. This grouping was carried out to facilitate the identification of risk sources in each production flow in a systematic and measurable manner.

3.1.1 Operational Risks in Sweet Potato Brownie Production

Table 1. The results of the operational risk identification in the sweet potato brownie production process at Ummah Cookies are presented

Risk Factor	**Risk**
Pre-Production Risks	Delay in sweet potato supply
	Sweet potato quality does not meet standards.
	Sweet potatoes experience spoilage
	Limited availability of raw materials
	Fluctuation in raw material prices
	Wheat flour becomes clumpy or has a musty odor.
	Eggs are not fresh
Production Risks	Errors in brownie batter formulation
	The batter is not mixed evenly.
	Workers' hands were injured by production equipment.
	Damage to mixers or production ovens
	Unstable baking temperature
	Brownies become overbaked or burnt.
	Brownie texture is too soft.
	The sweet potato aroma is too strong.
	The product does not rise properly.
Post-Production Risks	Product packaging is damaged.
	Product labeling errors
	Quality deterioration during storage
	Delay in product distribution
	Product damage during delivery
	Consumer complaints regarding product quality

3.1.1 Operational Risks in Sweet Potato Porridge Production

The results of the operational risk identification in the sweet potato porridge production process at Ummah Cookies are presented in Table 2.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

Table 2. Risk Identification in Sweet Potato Porridge at Ummah Cookies

Risk Factor	Risk
Pre-Production Risks	Delay in sweet potato supply
	Sweet potato quality does not meet standards.
	Sweet potatoes undergo spoilage.
	Limited availability of raw materials
	Fluctuation in raw material prices
	Inadequate raw material storage
Production Risks	Sweet potatoes are not fully cooked during boiling.
	Workers' hands are exposed to hot steam during processing.
	The porridge texture is too watery.
	The porridge texture is too thick.
	Milk or coconut milk curdles during cooking.
	Sugar does not dissolve completely.
	Porridge forms lumps during the stirring process.
	Contamination by foreign materials during production
	Production equipment malfunction
	Porridge gets burnt due to unstable cooking temperature.
Post-Production Risks	Packaging leaks or becomes damaged.
	The product spoils quickly during storage.
	Product labeling errors
	Delay in product distribution
	Product damage during the delivery process

3.2 Risk Level Measurement in Sweet Potato Processed Product Production Activities at Ummah Cookies

3.2.1 Risk Priority Number (RPN) Calculation Results for Sweet Potato Brownies Products

Based on the Risk Priority Number (RPN) calculation in the sweet potato porridge production process at Ummah Cookies, the highest priority risk in the pre-production stage is the non-conformity of sweet potato quality with production standards, with an RPN value of 315. This risk is caused by the presence of boleng sweet potatoes, characterized by physical damage, increased water content, soft texture, and indications of decay due to storage of raw materials beyond the standard shelf life. Prolonged storage of sweet potatoes can increase microbial activity and accelerate the post-harvest senescence process, causing softening of the texture and a decrease in the sensory quality of the product [Song et al, 2021]. In the production stage, the risk with the highest RPN value, 330, is the emergence of a strong sweet potato aroma during processing. This risk is influenced by the quality of raw materials that are starting to experience quality decline, inaccurate control of temperature and cooking time, and an unbalanced product formulation composition, so that the distinctive sweet potato aroma becomes too dominant in the final product. According to several studies, the aroma characteristics of sweet potatoes are influenced by the composition of volatile compounds formed during the heating process, including aldehydes, furans, terpenoids, and compounds resulting from the Maillard reaction. Other studies have shown that formulations with high sweet potato concentrations have the potential to produce an overly dominant aroma profile, thereby reducing the balance of sensory attributes and consumer acceptance of the product [Zhou et al, 2024]. Meanwhile, in the post-production stage, the risk with the highest priority level is a decrease in product quality during the storage process, with a

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

Risk Priority Number (RPN) value of 160. This risk is influenced by the water content in sweet potato brownies, suboptimal storage conditions, a packaging system that is not able to maintain optimal product quality stability, and products produced without the use of preservatives. These conditions have the potential to cause changes in the texture, aroma, and taste of the product, thereby reducing the shelf life and quality of sweet potato brownies before distribution to consumers at Ummah Cookies.

The calculation results of the Risk Priority Number (RPN) value can be the basis for Ummah Cookies MSME in developing risk mitigation strategies at each production stage. The integration of FMEA and AHP is carried out sequentially, with the highest RPN at each process stage, and then used as the basis for compiling a decision hierarchy in AHP to evaluate and determine the priority of the most effective mitigation alternatives. Based on the results of the research on brownie products, Ummah Cookies MSME needs to strengthen control at all stages of production. In the pre-production stage, control is carried out by tightening the raw material selection process through visual inspection to ensure compliance with sweet potato quality standards, implementing a first-in-first-out (FIFO) system in inventory management, and limiting the storage time of raw materials to prevent quality degradation. In the production stage, standardization of formulations and the preparation of Standard Operating Procedures (SOPs) related to temperature and cooking time settings are needed to ensure consistent product sensory characteristics between batches. Meanwhile, in the post-production stage, improvement efforts are focused on improving the quality of packaging that has better protection capabilities, controlling storage conditions, and determining shelf life based on product quality testing results.

3.2.2 Risk Priority Number (RPN) Calculation Results for Sweet Potato Porridge

Based on the Risk Priority Number (RPN) calculation for the sweet potato porridge production process at Ummah Cookies, the highest risk occurs in the post-production stage, namely rapid product spoilage during storage, with an RPN of 342. This risk is influenced by the product's relatively short shelf life, suboptimal storage conditions, and potential contamination during storage and distribution. Other research shows that the highest risks in food products generally occur during the storage stage due to short shelf life, environmental conditions, and microbiological contamination [Kumar et al, 2023]. In the pre-production stage, the greatest risk comes from substandard sweet potato quality, with an RPN of 315. This risk is caused by inappropriate levels of ripeness, texture, and condition of raw materials, which can affect the quality of the final product. Meanwhile, in the production stage, the greatest risk is burnt porridge due to unstable cooking temperatures, with an RPN of 105. This risk has the potential to reduce the quality of the product's taste, aroma, and texture, thereby increasing the number of defective products during the production process.

The results of the FMEA risk identification and assessment are then used as the basis for integration with the Analytical Hierarchy Process (AHP) method. The results of this integration have significant operational implications for the Ummah Cookies MSME in controlling the production process. In the pre-production stage, strengthening is carried out through the implementation of stricter raw material selection standards based on visual inspection and quality control during the receiving process to ensure conformity to specifications. In the production stage, stabilization of process parameters is required, especially temperature control and standardization of cooking procedures to minimize process variation and reduce the potential for defective products. Meanwhile, in the post-production stage, optimization of the packaging system, control of storage conditions, and determination of shelf life based on quality testing results are priority aspects in maintaining product quality stability until the distribution stage.

3.3 Determining Priority Risk Mitigation Strategies for Processed Sweet Potato Products at Ummah Cookies

In this study, prioritization of mitigation strategies was conducted using the Analytical Hierarchy Process (AHP) method. Alternative mitigation strategies were developed based on interviews and questionnaires distributed to respondents directly involved in Ummah Cookies' operational activities. Respondents included

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

business owners and production workers who understood the production process conditions and potential risks that arise at each stage of product processing. The results of the risk mitigation strategy formulation for sweet potato brownies and sweet potato porridge are presented in Tables 3 and 4.

Table 3. Alternative risk mitigation strategies for Sweet Potato Brownies

Risk Variable	**Risk**	**Alternative Risk Mitigation Strategies**
Pre-Production Risks	Sweet potato quality does not meet standards	1. Establish sweet potato specification standards, including size, maturity level, flesh color, moisture content, and level of damage, before raw materials are accepted.
	Sweet potatoes undergo spoilage	2. Implement a raw material storage system with temperature and humidity control, as well as the FIFO (First In First Out) method.
	Delay in sweet potato supply	3. Control the steaming process and batter formulation by regulating time, temperature, and adding aroma-balancing ingredients such as vanilla or chocolate.
	Limited availability of raw materials	4. Use standardized formulations and digital weighing to ensure ingredient composition complies with production standards.
	Fluctuation in raw material prices	5. Conduct routine calibration and maintenance of mixers and ovens to maintain the stability of mixing and baking processes.
	Wheat flour becomes clumpy or musty	6. Use airtight food-grade packaging and implement temperature and storage-time control for finished products.
	Eggs are not fresh	–
Production Risks	The sweet potato aroma is too strong.	–
	Errors in brownie batter formulation	–
	The batter is not mixed evenly.	–
	The product does not rise properly.	–
	Brownie texture is too soft.	–
	Brownies are overbaked or burnt.	–
	Baking temperature is unstable.	–
	Damage to mixers or production ovens	–
	Workers' hands were injured by production equipment.	–
Post-Production Risks	Quality deterioration during storage	–
	Product damage during delivery	–
	Consumer complaints regarding product quality	–
	Product labeling errors	–
	Delays in product distribution	–
	Product packaging damage	–

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

Table 4. Alternative risk mitigation strategies for Sweet Potato Porridge

Risk Variable	**Risk**	**Alternative Risk Mitigation Strategies**
Pre-Production Risks	Sweet potato quality does not meet standards	1. Conduct raw material inspections based on physical parameters, including tuber size, flesh color, level of damage, and maturity level, to ensure uniformity of raw material characteristics.
	Sweet potatoes undergo spoilage	2. Store sweet potatoes in a storage room at 15–20°C with controlled humidity to slow down the activity of spoilage-causing microorganisms.
	Limited raw material availability	3. Control the cooking temperature within the range of 80–90°C, accompanied by continuous stirring to maintain even heat distribution and prevent excessive gelatinization at the bottom of the container.
	Fluctuating raw material prices	4. Boil the sweet potatoes until optimal gelatinization occurs, then blend evenly and cook at 80–90°C with continuous stirring to prevent sedimentation and scorching at the bottom of the container.
	Delays in sweet potato supply	5. Implement the use of personal protective equipment such as heat-resistant gloves, aprons, and long-handled stirring tools during the boiling and cooking processes.
	Inadequate raw material storage	6. Package the product at temperatures below 40°C using airtight food-grade containers and store the product at refrigeration temperatures of 4–10°C to inhibit microbial growth.
Production Risks	Porridge burns due to unstable cooking temperature.	
	Sweet potatoes are not fully cooked during boiling.	
	The porridge texture is too thin.	
	The porridge texture is too thick.	
	Milk or coconut milk curdles during cooking.	
	Sugar does not dissolve completely.	
	Porridge forms lumps during stirring.	
	Foreign material contamination during production	
	Workers' hands are exposed to hot steam during processing.	
	Production equipment damage	
Post-Production Risks	The product spoils quickly during storage.	
	Packaging leaks or is damaged.	
	Product damage during transportation	
	Delays in product distribution	
	Product labeling errors	

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 e-ISSN 2622-2035

3.4. Hierarchical Model of Risk Mitigation Strategies in Sweet Potato Brownie Production

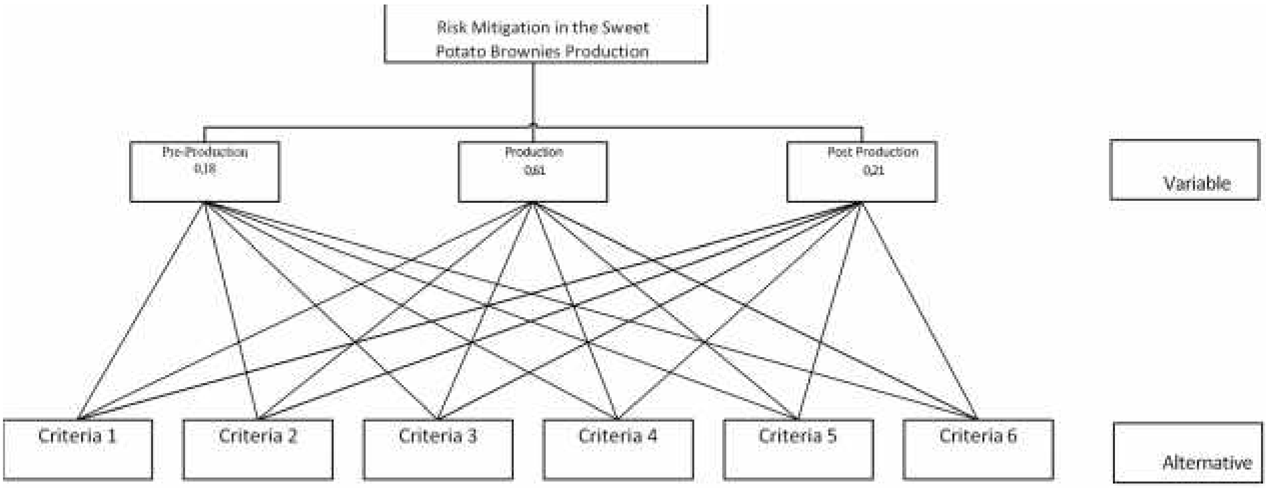

Figure 1. Hierarchical Model of Risk Mitigation Strategies in Sweet Potato Brownie Production

The eigenvector value for the production aspect is 0.61, indicating that the production stage is the top priority in developing a risk mitigation strategy for sweet potato brownies. Meanwhile, the post-production and pre-production aspects have weights of 0.21 and 0.18, respectively, indicating a relatively lower level of risk influence compared to the production stage.

3.5. Hierarchical Model of Risk Mitigation Strategies in Cassava Porridge Production

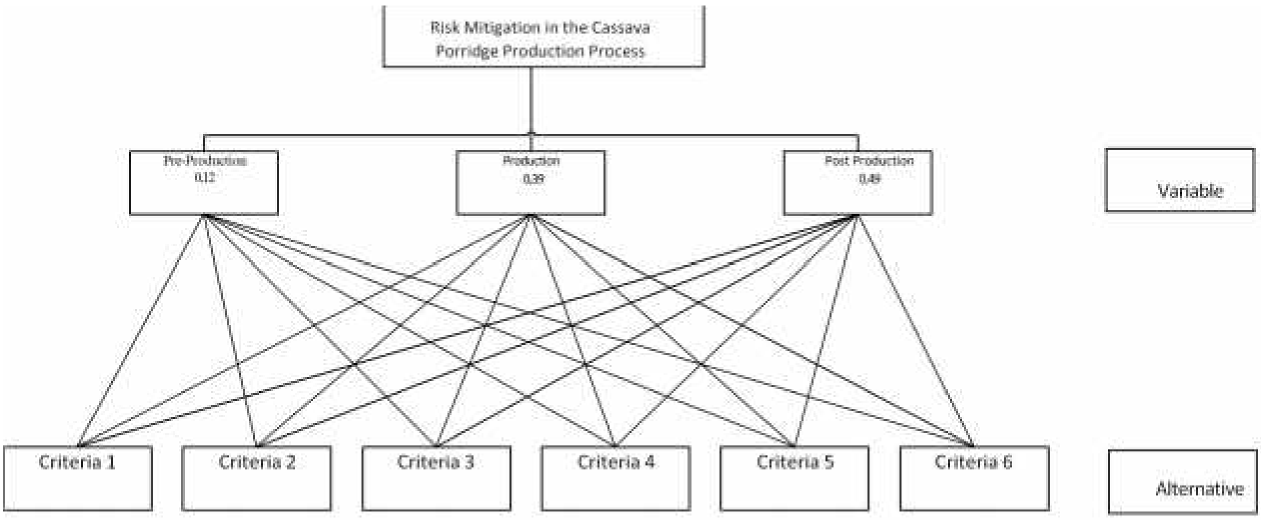

Figure 2. Hierarchical Model of Risk Mitigation Strategies in Cassava Porridge Production

The eigenvector value of 0.49 for the post-production aspect indicates that this stage carries the highest risk level in the sweet potato porridge production process. Meanwhile, the production and pre-production aspects have lower priority levels, with values of 0.39 and 0.12, respectively.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11518 *e*-ISSN 2622-2035

4. CONCLUSION

The production process at Ummah Cookies still faces various risks in the pre-production, production, and post-production stages that have the potential to affect product quality and stability. For sweet potato brownies, the highest priority risk is in the production stage, namely the emergence of a strong sweet potato aroma with a Risk Priority Number (RPN) of 330. This risk is influenced by the decline in the quality of raw materials, inaccurate cooking temperature control, and suboptimal product formulation. Meanwhile, for sweet potato porridge products, the highest risk is in the post-production stage in the form of products that spoil quickly during storage, with an RPN of 342, which is influenced by limited product shelf life, suboptimal storage conditions, and potential contamination during distribution. The results of the Analytical Hierarchy Process (AHP) analysis show that the priority for risk mitigation in sweet potato brownies lies in the production aspect, with an eigenvector value of 0.61, while for sweet potato porridge, it lies in the post-production aspect, with an eigenvector value of 0.49. Therefore, implementing risk mitigation strategies through controlling the quality of raw materials, controlling temperature and cooking processes, implementing production SOPs, and optimizing storage and packaging systems are important steps in maintaining product quality stability and minimizing potential damage during the production and distribution process.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11641 *e*-ISSN 2622-2035

Customer Segmentation in a Campus-Area Convenience Store Using K-Means Clustering

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***Abstract*—Customer segmentation is an important strategy for understanding differences in customer characteristics and supporting more targeted marketing decisions. In campus areas, convenience store customers generally consist of students with diverse demographic, economic, and accessibility characteristics, resulting in different purchasing behaviors. This study aims to identify customer segments of a convenience store located in the Campus X area of Yogyakarta using the K-Means Clustering algorithm. The study employed a quantitative approach with data mining techniques using customer data from students. The variables analyzed included age, income, shopping intensity, and residential distance from the store. The optimal number of clusters was determined using the Elbow Method before applying the K-Means algorithm. The results identified three customer segments with distinct characteristics. The largest segment consisted of customers living relatively close to the store and exhibiting high shopping intensity, while another segment was characterized by lower purchasing activity and greater residential distance. The smallest segment showed the highest income level and the most diverse product preferences. Furthermore, differences in customer characteristics were reflected in product purchasing patterns across the identified segments. These findings indicate that accessibility and economic factors play important roles in shaping customer purchasing behavior in campus-area convenience stores. The results can serve as a reference for developing more targeted promotional and product management strategies.**

***Keywords:* Customer Segmentation, K-Means Clustering, Convenience Store, Consumer Behavior**

I. INTRODUCTION

Yogyakarta is widely recognized as one of Indonesia’s major higher education centers, attracting students from various regions due to its high concentration of universities and vibrant academic environment [1]. This condition has stimulated the growth of economic activities that cater to student needs, including the modern retail sector, particularly convenience stores [2]. Convenience stores not only serve as providers of daily necessities but also constitute an integral part of student consumption activities, which are characterized by diverse purchasing patterns and consumer preferences [3]. Consequently, competition among convenience stores in campus areas is no longer solely determined by product availability but also by the ability of retailers to understand and identify customer characteristics more accurately [4].

Students, as the primary consumer group in campus areas, possess diverse social and economic backgrounds [5]. These differences contribute to variations in purchasing power and financial management capabilities among students [6]. Furthermore, student populations are heterogeneous not only in terms of socioeconomic characteristics but also in residential location. While some students reside close to campus and enjoy easier access to retail facilities, others live farther away. Such differences in economic conditions and accessibility may influence purchasing power, shopping frequency, and consumption patterns at convenience stores located around campus areas [7]. In addition, the spatial distribution of student residences within varying distances from campus makes residential distance an important factor that may affect customer mobility and shopping behavior toward nearby retail stores [8].

The management of convenience stores surrounding Campus X in Yogyakarta faces increasingly complex challenges due to customer mobility and substantial variations in purchasing

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11641 *e*-ISSN 2622-2035

power across consumer groups. The growing diversity of customer characteristics and needs has resulted in a more heterogeneous market. This situation highlights the importance of market segmentation as an approach to grouping consumers into relatively homogeneous segments, enabling marketing strategies to be tailored according to the characteristics of each segment [9]. As a result, mass marketing approaches are becoming less effective because they fail to capture the specific needs of distinct customer groups. Therefore, a data-driven approach is required to map customer characteristics more comprehensively by considering not only demographic attributes but also spatial factors such as residential distance and customers' economic capacity [10].

Although previous studies have examined retail customer segmentation using demographic and purchasing behavior attributes, most have focused primarily on consumer characteristics without incorporating spatial dimensions that influence retail accessibility. In educational areas characterized by high student mobility, the distance between students' residences and convenience stores may significantly affect shopping frequency and consumption patterns. Better accessibility enables consumers to reach retail locations more easily, potentially increasing store visits and purchasing activities [11]. Therefore, integrating demographic, economic, and consumption-related variables into the customer segmentation process is essential for developing a more comprehensive market profile.

Unlike conventional market segmentation approaches that primarily focus on psychographic or demographic attributes, this study integrates a spatial dimension, represented by accessibility (distance), together with economic factors (income), using the K-Means clustering algorithm. This approach is considered particularly relevant in the context of convenience stores located in educational areas, where student purchasing behavior is strongly influenced by geographic proximity and varying levels of monthly financial resources. Furthermore, the use of real transactional data collected from a strategically located convenience store in Yogyakarta enhances the empirical validity of the resulting model and provides a more accurate representation of market dynamics. Accordingly, this study aims to identify and classify convenience store customers in a campus area using the K-Means clustering algorithm based on demographic, economic, and accessibility-related attributes.

This study is expected to contribute to the literature on retail customer segmentation by integrating demographic, economic, and spatial attributes within a data mining–based clustering framework. From a practical perspective, the findings may assist convenience store managers in designing more targeted marketing strategies, including differentiated promotional programs, product assortment adjustments, and service management initiatives tailored to the characteristics of the identified customer segments.

II. Methods

This study employed a quantitative approach using data mining techniques to identify customer segmentation patterns in a convenience store located within a campus area in Yogyakarta. The dataset consisted of customer data collected from a convenience store operating near Campus X, with a total sample of 100 students. The variables analyzed included gender, age, income, shopping intensity, and residential distance from the store. These variables were selected because they represent customers' demographic, economic, and accessibility characteristics. In addition to customer profile data, this study utilized transaction data that were grouped into four product departments, namely snacks and bakery products (Dept 1), personal care products (Dept 2), beverages and dairy products (Dept 3), and household and toiletry products (Dept 4).

Customer segmentation was conducted using the K-Means algorithm, a non-hierarchical clustering technique that groups data based on the similarity of their characteristics [12]. The algorithm partitions observations into several clusters according to their proximity to cluster centers (centroids) [13]. The distance between data points and centroids was measured using Euclidean Distance, as expressed in Equation (1).

$$d(x,y) = |x-y| = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \quad (1)$$

Where:
$d(x,y)$ = The Euclidean distance between a customer data point and a cluster centroid;

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11641 *e*-ISSN 2622-2035

x_i = the value of the i -th attribute of the customer data point;
y_i= the value of the i -th attribute of the centroid;
i = denotes the attribute index.
n = the total number of attributes used in the distance calculation.

The analysis began with data preprocessing and standardization to ensure that all variables were measured on a comparable scale. Subsequently, the optimal number of clusters was determined using the Elbow Method based on the inertia value, also known as the Within-Cluster Sum of Squares (WCSS). After the optimal number of clusters had been identified, the K-Means algorithm was iteratively applied by assigning each customer to the nearest cluster and updating the centroid positions until stable cluster memberships were achieved. The resulting clusters were then analyzed to identify the characteristics of each customer segment based on age, income, shopping intensity, and residential distance. Finally, the clustering results were integrated with product transaction data to examine product category preferences across the identified customer segments.

III. Results and Discussion

1. Determination of The Optimal Numbers of Clusters

The optimal number of clusters was determined using the Elbow Method by evaluating changes in inertia values across several cluster alternatives (k). This method was employed to identify the most representative number of clusters by observing the point at which the decrease in inertia began to slow down. The results of the Elbow Method are presented in Figure 1.

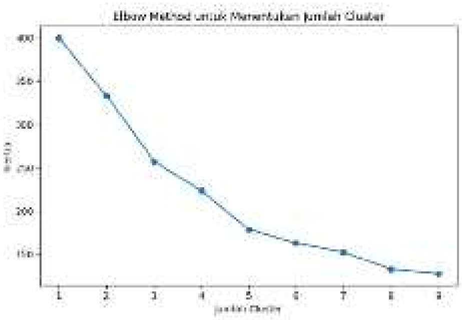

Figure 1. Elbow Method for Determining the Optimal Number of Clusters

As shown in Figure X, the inertia value decreases substantially up to k = 3 and then begins to level off for subsequent cluster numbers. This pattern indicates that increasing the number of clusters beyond k = 3 does not result in a significant reduction in inertia. Therefore, the elbow point can be identified at k = 3.

In this study, k = 3 was selected because it provides a balance between the model’s ability to capture data variability and the interpretability of the resulting customer segments. A larger number of clusters may produce more specific customer groups; however, it does not necessarily yield more meaningful insights. Therefore, the use of three clusters was considered sufficient to represent the differences in customer characteristics clearly and in accordance with the objectives of this study.

2. Customer Segmentation Results

The optimal number of clusters was determined using the Elbow Method by evaluating changes in inertia values across several cluster alternatives (k). This method was employed to identify the most representative number of clusters by observing the point at which the decrease in inertia began to slow down. The results of the Elbow Method are presented in Figure 2.

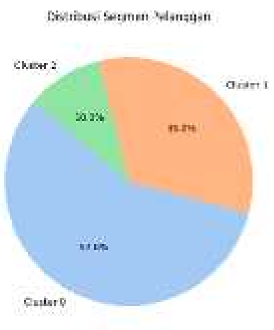

Figure 2. Distribution of Customers Across Clusters

Cluster 0 represents the largest segment, accounting for 57% of the total customers, followed by Cluster 1 with 33% and Cluster 2 with 10%. This distribution indicates that the majority of customers are concentrated within a single dominant segment, while the remaining customers are distributed across two smaller

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11641 *e*-ISSN 2622-2035

segments. The dominance of Cluster 0 suggests the presence of a customer group with relatively common characteristics compared to the other segments.

Meanwhile, the existence of Cluster 1 and Cluster 2 reflects variations in customer characteristics that are not fully represented by the dominant segment. In particular, Cluster 2, which accounts for the smallest proportion of customers, indicates the presence of a more specific customer group with distinctive characteristics that differ from those of the majority.

Overall, the segmentation results demonstrate that although one segment dominates the customer base, the customer structure remains heterogeneous and can be effectively classified into three major groups. These findings provide a foundation for further analysis of the characteristics and purchasing behavior associated with each customer segment in the following section.

3. Characteristics of Customer Segments

Based on the clustering results, customers can be classified into three distinct segments, each exhibiting different characteristics across the observed variables. The profile of each customer segment is presented in Table 1.

Table 1. Profile of Customer Segments

Cluster	Number of Customers	Percentage (%)	Average Age	Average Income	Average Shopping Intensity	Average Distance
0	57	57%	20.24	1.80	4.30	1.81
1	33	33%	20.36	1.45	2.09	3.61
2	10	10%	22.40	4.45	3.40	4.60

Cluster 0 represents the largest segment, accounting for 57% of the total customers. This segment is characterized by relatively short residential distances, the highest shopping intensity, and moderate-income levels. These characteristics suggest that the segment is largely composed of students living near the campus area, such as in boarding houses, which provides easier access to the convenience store. This geographical proximity may contribute to more frequent visits, which is reflected in the relatively high level of shopping activity. In addition, the average age of customers in this cluster indicates a tendency toward younger students, who generally exhibit routine purchasing behavior to meet their daily needs.

Cluster 1 accounts for 33% of customers and is characterized by greater residential distances, the lowest shopping intensity, and relatively lower income levels compared to the other clusters. These findings suggest that customers in this segment tend to be more selective in their purchasing decisions due to limitations in accessibility and purchasing power. Within the campus context, this segment may represent students living farther from the campus area or residents who do not rely heavily on the convenience store for their daily needs. The relatively low shopping intensity observed in this segment indicates that both distance and budget constraints may play an important role in shaping purchasing behavior.

Cluster 2 represents the smallest segment, comprising 10% of the total customers, yet it exhibits characteristics that differ considerably from the other clusters. This segment has the highest income level, a relatively older average age, and the greatest residential distance, while maintaining a moderate level of shopping intensity. These characteristics indicate the presence of customers with greater purchasing power and higher mobility. In the context of a campus area, this segment may consist of senior students or individuals with additional sources of income. However, since this study did not explicitly examine socio-economic background variables, further interpretation regarding the underlying factors of this segment should be made with caution.

Overall, the segmentation results indicate that customer behavior in convenience stores located within campus areas is influenced by a combination of accessibility and economic capacity. Customers living closer to the store tend to exhibit higher shopping intensity, whereas those located farther away generally

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11641 e-ISSN 2622-2035

show lower purchasing activity, except for customers with relatively high purchasing power. These findings suggest that integrating accessibility and economic variables into the segmentation process can provide a more comprehensive understanding of customer consumption patterns.

4. Customer Cluster Visualization

The customer segmentation results obtained using the K-Means algorithm can be visualized based on the relationship between income and shopping intensity, as presented in Figure 3.

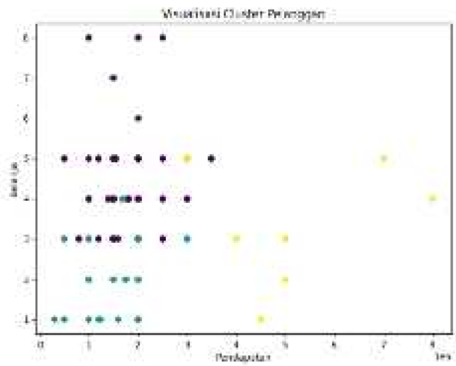

Figure 3. Customer Cluster Visualization

Figure 3 illustrates the distribution of customers according to income and shopping intensity. Each color represents a different cluster, allowing the distribution pattern of customers to be observed visually. In general, a separation can be identified between customers with low-to-moderate income levels and those with relatively higher incomes.

Customers with higher income levels tend to be located on the right side of the graph and exhibit moderate to high shopping intensity. In contrast, most customers are concentrated within the low-to-moderate income range, with a wider variation in shopping intensity. This pattern is consistent with the segmentation results discussed previously, indicating differences in economic characteristics and purchasing behavior among customer segments. Although some overlap between clusters is still visible, the visualization demonstrates that the K-Means algorithm was able to identify customer groups with relatively distinct characteristics. These results further support the effectiveness of the clustering approach in distinguishing customer segments within the context of a convenience store located in a campus area.

5. Product Preferences Across Customer Segments

Based on the customer segmentation results, each cluster exhibits different purchasing tendencies across product categories. The distribution of product purchases for each customer segment is presented in Figure 4.

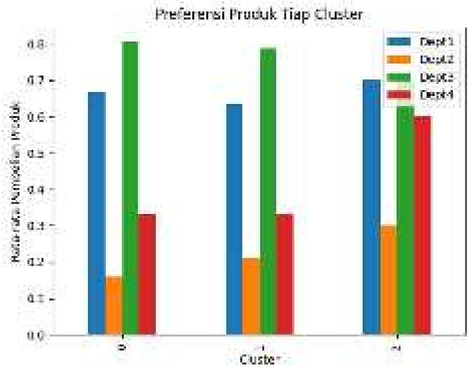

Figure 4. Product Preferences Across Customer Segments

Figure 4 shows variations in purchasing levels across product categories among the identified customer segments. In general, products in Dept 1 and Dept 3 exhibit relatively higher purchase levels than the other categories. In contrast, Cluster 2 demonstrates a more diverse consumption pattern, with relatively high purchase levels across almost all product categories.

To provide a more detailed understanding of product preferences within each customer segment, the average purchase values for each product department are presented in Table 2.

Table 2. Average Product Purchase Values by Customer Segment

Cluster	Dept 1	Dept 2	Dept 3	Dept 4
0	0,67	0,16	0,80	0,33
1	0,63	0,21	0,79	0,33
2	0,70	0,30	0,70	0,60

Overall, Dept 3 represents the most frequently purchased product category among customers in Cluster 0 and Cluster 1, with average values of 0.80 and 0.79, respectively. This finding suggests that customers in these two segments share relatively similar needs and tend to focus on routine consumption products commonly purchased by students. In addition, Dept 1 also

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11641 *e*-ISSN 2622-2035

records relatively high purchase levels within both segments.

Although Cluster 0 and Cluster 1 exhibit similar product preferences, the characteristics of customers within these segments differ. Cluster 0, which is dominated by customers living closer to the convenience store and displaying higher shopping intensity, demonstrates slightly higher purchase levels than Cluster 1. This finding suggests that accessibility may influence the consumption level of specific product categories.

In contrast to the other segments, Cluster 2 exhibits a more diverse purchasing pattern. Besides showing relatively high purchase levels in Dept 1 and Dept 3, customers in this segment also demonstrate a greater tendency to purchase products from Dept 2 and particularly Dept 4, with average values of 0.30 and 0.60, respectively. These values are considerably higher than those observed in Cluster 0 and Cluster 1, which range from 0.16–0.21 for Dept 2 and approximately 0.33 for Dept 4.

This pattern indicates that customers in Cluster 2 possess a broader range of consumption needs than those in the other segments. The findings are consistent with the characteristics of Cluster 2, which has the highest income level and a relatively older average age. With greater purchasing power, customers in this segment are not only focused on basic consumption products but also tend to purchase products from a wider variety of categories.

Overall, the results indicate that differences in customer characteristics identified through the clustering process are reflected in product purchasing patterns. These findings suggest that product management and promotional strategies can be tailored according to the characteristics of each customer segment. For the dominant segment (Cluster 0), maintaining the availability of products in Dept 1 and Dept 3 should be prioritized. Meanwhile, customers in Cluster 2 may represent a promising target for cross-selling and multi-category promotional strategies due to their tendency to purchase a more diverse range of products.

IV. Conclusions

This study identified three customer segments of a convenience store located in the Campus X area of Yogyakarta using the K-Means Clustering algorithm based on age, income, shopping intensity, and residential distance attributes. The results indicate that the largest segment consists of customers who live relatively close to the store and exhibit high shopping intensity, while the remaining segments display distinct characteristics in terms of accessibility, purchasing power, and product preferences. Customers with the highest income levels tend to demonstrate more diverse consumption patterns than other customer groups. These findings suggest that accessibility and economic capacity play important roles in shaping customer purchasing behavior within a campus environment.

From a theoretical perspective, this study contributes to the customer segmentation literature by integrating demographic, economic, and accessibility attributes into the clustering process, thereby providing a more comprehensive customer profiling approach than segmentation methods that rely solely on demographic characteristics. From a practical perspective, the segmentation results can assist convenience store managers in developing more targeted marketing strategies, including the design of promotional programs, product category management, and service strategies tailored to the characteristics of each customer segment. Future research is recommended to incorporate additional variables that may provide a deeper understanding of customer differences across segments, such as academic major, year of study, residential status, and socio-economic background. Furthermore, the application of alternative clustering techniques may be explored to compare segmentation consistency and to gain a more comprehensive understanding of customer consumption patterns in educational environments.

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Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

Design of Fermentation Machine With Work System Evaluation Using Fishbone Diagram Method in Surabaya MSMES

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***Abstract*—Tempeh fermentation process in Micro, Small, and Medium Enterprises (MSMEs) in Surabaya is generally still carried out conventionally, without the support of tools that can control the temperature and fermentation environment stably. Process inefficiencies and product quality irregularities are the main problems that business actors often face. This research aims to design a tempeh fermentation machine based on working system evaluation using the Fishbone Diagram method as an effort to develop appropriate technology. The research method used was descriptive-qualitative with an engineering approach, which included observation, interviews, and field studies of three tempeh MSMEs in Surabaya. The results of the Fishbone Diagram analysis show that the main factors causing inefficiency include irregular work methods, lack of technical knowledge, lack of fermentation equipment, and unsupportive working environmental conditions. Based on the results of this evaluation, an MSME-scale fermentation machine was designed with automatic temperature control, a capacity of 10–15 kg per batch, and an ergonomic design. Trials show that the machine is able to maintain a stable fermentation temperature, produce tempe products with more consistent quality, and reduce the physical workload of business actors. This research shows that the work systems approach in technology design is able to produce solutions that are contextual, functional, and adaptive to the needs of MSMEs. These findings contribute to the development of science and technology in the fields of food technology, work ergonomics, and production equipment innovation based on local needs.**

***Keywords*: tempeh fermentation, MSME, fermentation machine, fishbone diagram**

I. Introduction

Micro, small, and medium enterprises (MSMEs) play a crucial role in supporting the national economy.[1], particularly in the food sector [2]. According to data from the Ministry of Cooperatives and SMEs in 2023, MSMEs contributed more than 60% to Indonesia's Gross Domestic Product (GDP) [3]. In addition to making a significant contribution to GDP, MSMEs also play a key role in creating jobs in the agriculture, fisheries, and food sectors. [4][5]. Tempeh is a traditional food product with high nutritional value and widespread consumption in Indonesia. Tempeh production, which relies on soybean fermentation using Rhizopus sp., is generally still carried out manually and conventionally, especially among MSMEs[6]. Unstandardized fermentation processes can potentially produce products that vary in quality, texture, and flavor. Furthermore, dependence on environmental conditions such as temperature and humidity without proper control can lead to fermentation failure, resulting in wasted raw materials and time. As part of Indonesia's culinary heritage, tempeh not only has economic value for home producers and small industries but also plays a crucial role in national food security.[7]

The Surabaya Tempe MSME Village, located on Jl. Tenggilis Kauman, Gg. Buntu 27 No. 10, Surabaya, faces challenges in its quest to survive in the Indonesian economy. The fermentation process in this MSME community still relies on wooden storage, resulting in suboptimal tempeh production during the rainy season or extreme temperatures. Furthermore, rising prices for soybeans and yeast have also led to a 40% decline in production and turnover by 2024.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

Figure 1. Storage of Fermented Tempeh at the Surabaya Tempeh MSME

In general, the tempeh-making process involves several stages: washing and cleaning, boiling, soaking, peeling, draining, cooling and drying, yeast application, packaging, and finally, incubation or fermentation.[8]. One key factor influencing the fermentation process is temperature. The optimal temperature for tempeh fermentation ranges from 30-35°C, with a humidity level of around 60%-80%. Unstable weather conditions can prevent the growth of Rhizopus oligosporus mold and can even lead to its death. [9].

For tempeh producers, temperature control is crucial because, historically, soybean fermentation into tempeh has often failed, which can reduce tempeh production due to unfavorable weather and temperatures. A device with a temperature setpoint of 33°C, 35°C, or 37°C is needed to regulate the temperature during the tempeh fermentation process in an effort to maintain temperature stability.[10]. Running a business is not an easy task; it is full of risks, both in terms of capital losses and damage to the products produced. [11]. The process of making tempeh, which is sourced from soybeans, requires precision and cleanliness to ensure good results and is suitable for consumption. The most important stage in the tempeh-making process that can determine the quality of the tempeh is during the fermentation and inoculation process. [12].

Despite the development of various technological innovations, the adoption of technology by MSMEs in the tempeh sector—particularly in the Surabaya area—remains very limited. Most business operators still rely on experience and traditional practices passed down through generations for the fermentation process, without the aid of specialized equipment or monitoring systems. This situation is exacerbated by a lack of awareness regarding the importance of evaluating work systems, leading to operational inefficiencies, human error, and unbalanced workloads.[13] To date, few studies have integrated a work-system approach—such as analyzing the root causes of process issues using the Fishbone Diagram method—with the design of fermentation equipment tailored to the specific operational characteristics of these MSMEs.

The Fishbone Diagram, or Cause and Effect Diagram, is a widely used quality analysis tool to systematically identify the causal factors of a problem. [14]. In the context of tempeh production, this method can be used to evaluate various sources of irregularity in the fermentation process, including human factors, methods, machines, the environment, and materials. With systematic mapping, fermentation machine design can be more precisely directed to address actual problems in the field.

The research gap (delta) arises from the lack of a holistic and contextual approach, namely, the design of appropriate technology accompanied by a comprehensive evaluation of the work systems of MSMEs [15]. Most previous research has focused solely on the technical aspects of the machine without considering the work patterns, workloads, or habits of the business owners as the primary users. Therefore, there is an urgent need to develop a tempeh fermentation machine that is not only technically efficient but also compatible with the needs, limitations, and work systems of tempeh MSMEs in Surabaya.[16].

Based on this background, the research questions are as follows: What are the main causes of inefficiency in the tempeh fermentation process in MSMEs in Surabaya? How can a tempeh fermentation machine be designed to address these issues based on a Fishbone Diagram analysis? And to what extent can the proposed tempeh fermentation machine design improve efficiency and consistent product quality in tempeh MSMEs?

The objectives of this research are to identify and analyze the root causes of problems in the tempeh fermentation process using the Fishbone Diagram method in tempeh MSMEs in Surabaya. To design an appropriate tempeh fermentation machine based on the results of the MSME work system analysis. To evaluate the effectiveness of the machine design in consistently improving process efficiency and tempeh quality.

With this approach, this research is expected to make a significant contribution to the development of appropriate technology based on the real needs of MSMEs and to enrich the

Tibuana
Journal of applied Industrial Engineering-University of PGRI Adi Buana
p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

scientific knowledge in the fields of industrial ergonomics and work systems engineering in the traditional food sector.

II. RESEARCH METHODS

This research uses a descriptive-qualitative approach with an engineering approach to designing appropriate technology products. In general, this research method combines two main approaches: first, a work system analysis based on problem identification using the Fishbone Diagram (Cause and Effect Diagram) method; second, the design of a tempeh fermentation machine based on the needs and field context obtained from the analysis results.

The descriptive approach is used to describe the actual conditions of the tempeh fermentation process in MSMEs, specifically regarding factors that cause inefficiency or inconsistent quality. [17]. Meanwhile, the engineering approach is applied in the development and design of the fermentation tool based on the results of the work system evaluation. This research is applicable because it produces a concrete product in the form of a fermentation machine and simultaneously provides solutions to real-life problems faced by tempeh MSMEs in Surabaya.

This research was conducted on several tempeh MSMEs operating in the Surabaya area, particularly in areas with a high concentration of home-based tempeh producers, such as Rungkut District and Tenggilis Mejoyo. The location selection was carried out purposively based on the following criteria: MSMEs actively and consistently produce tempeh at least 3 times a week, the fermentation process is carried out conventionally without the aid of modern tools, and MSMEs are willing to be research partners and are open to observation and interviews.

The research subjects consisted of MSMEs (owners and workers) directly involved in the tempeh production process, technical experts (technicians/engineers) to validate the machine design, and ergonomic consultants/work systems experts (if necessary) to verify the results of the fishbone analysis. Three MSMEs participated in this study, each with 2–3 key respondents (owners/workers), resulting in a total of approximately 9–10 informants.

To obtain comprehensive data, this study used the following data collection techniques:

a. Field Observation

Observations were conducted directly of the tempeh production process at each MSME. The main focus of the observations included: soybean preparation (soaking, boiling, peeling), yeast inoculation, fermentation (placement, time, temperature, environment), work system observations, task division, and production workflow. Data collected consisted of field notes, photo/video documentation, and work process observation sheets.

b. In-Depth Interviews

Semi-structured interviews were conducted with business actors to explore their perceptions, experiences, and challenges encountered during the fermentation process. Questions focused on experiences with fermentation failures, product quality variations, technical and non-technical issues in the work process, expectations regarding fermentation aids/machines, and work environment conditions and ergonomics.

c. Documentation Study

Secondary data was collected in the form of literature, scientific articles, and journals related to tempeh fermentation equipment design, work ergonomics, and the application of Fishbone Diagrams in work system evaluation. Production documents, schedules, and work records, if available, from MSMEs were also analyzed.

d. Literature Review and Comparative Study

References from national and international journals were used as comparisons in analyzing research results and assessing gaps between actual practice and scientific theory. This study also provided the basis for the principles of fermentation machine design and design validation.

The instruments used in this study included work process observation sheets, semi-structured interview guidelines, a Fishbone Diagram format to organize root causes, fermentation machine design sketches (paper design and CAD), an evaluation form and initial machine design trial, a tool functionality validation checklist, and instruments developed independently and tested for feasibility through initial trials before widespread use.

The research procedure consisted of six main stages, as follows:

a. Stage I: Preliminary Study

This stage included a literature search on the tempeh fermentation process and production aids, a site visit to MSMEs to identify partners willing to participate in the research, and initial identification of problems and field needs through

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

exploratory interviews.

b. Stage II: Work System Observation and Interviews

Stage II began with direct observation of production activities. Data was then recorded via video, observation notes, and documentation of the physical conditions of the workplace. In-depth interviews were conducted to strengthen the observations and gather subjective information.

c. Stage III: Problem Evaluation Using a Fishbone Diagram

The data obtained was analyzed using a Fishbone Diagram to identify the root causes of inefficient work processes or inconsistent fermentation results. Factors analyzed included:

- Man: skills, work habits, workload.
- Machines: lack of tools, damage, and incompatibility.
- Materials: quality of raw materials, availability of yeast starter.
- Methods: unwritten SOPs, variations in fermentation techniques.
- Environment: room temperature, cleanliness, ventilation.

Based on the results of the root cause analysis using the Fishbone Diagram method, the dominant factors that will be the focus of the solution design will be determined.

d. Stage IV: Fermentation Machine Design

Based on the main findings, a tempeh fermentation machine was designed, taking into account the principles of energy efficiency (electricity savings, insulation system), automatic temperature control (using sensors and temperature controls), capacity appropriate for the MSME scale, ease of operation and maintenance by non-technicians, and design ergonomics (equipment height, working position, workload). The initial design was created in the form of hand sketches and a CAD (Computer Aided Design) model. Technical specifications were outlined, including materials, dimensions, control systems, and operating mechanisms.

e. Stage V: Manufacturing and Initial Trial

The machine was assembled on a prototype scale using locally available materials in Surabaya. After manufacturing and assembly were completed, an initial trial (alpha test) was conducted under controlled conditions, with parameters including fermentation temperature stability, fermentation duration, yield, and operator comfort.

f. Stage VI: Evaluation and Revision

Following the initial trial, an evaluation was conducted based on the technical performance of the machine, user satisfaction among tempeh MSMEs, and work efficiency and time values. If necessary, design improvements were made before larger-scale production of the machine.

III. RESULTS AND DISCUSSION

Based on observations and in-depth interviews with three tempeh MSMEs in Surabaya, it emerged that the fermentation process is still carried out conventionally, without the aid of temperature or humidity control devices. The fermentation process typically lasts between 24 and 48 hours, depending on weather conditions, room temperature, and the subjective experience of the entrepreneur. Some MSMEs even rely on instinct and habit (tacit knowledge) to determine the fermentation endpoint.

Production activities are carried out in closed spaces without ventilation and a proper temperature control system. The raw materials used vary depending on market prices, and tempeh starter is often inconsistently available. The MSMEs studied also lack written standard operating procedures (SOPs), resulting in inconsistent tempeh production from day to day.

In general, the main obstacles identified include dependence on environmental temperature, the lack of fermentation equipment or incubators, a lack of technical understanding of the fermentation process, substandard or worn-out work equipment, and unstable tempeh quality (odor, texture, and taste).

3.1 Fishbone Diagram Analysis

Through the Fishbone Diagram approach, five main groups of causes of inefficiency in the tempeh fermentation process were identified. The results of the fishbone diagram analysis conducted on the working system of the Surabaya Tempeh MSME are as follows.

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

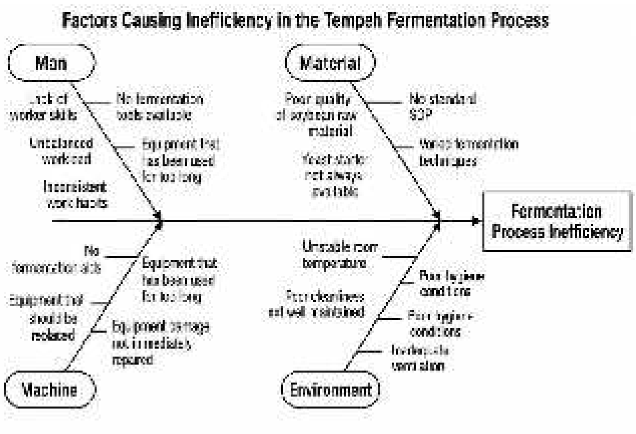

Figure 2. Fishbone Diagram Analysis

a. Human Factors

• Lack of worker expertise: Workers generally lack a food education background or specialized training related to fermentation. Knowledge is passed down through generations.

• Unbalanced workload: One person can handle multiple tasks, from soaking and peeling to inoculation to packaging.

• Inconsistent work habits: Each worker has a different approach and habits, resulting in variations in the final product.

b. Machine Factors

• Lack of fermentation aids: All fermentation processes rely solely on plastic containers and a natural environment without temperature control.

• Aging equipment: Many tools, such as fermentation vessels, scales, and sieves, are worn out or inaccurate.

• Damage is not promptly repaired: MSMEs tend to delay repairs due to limited funds and technical knowledge.

c. Material Factors

• Fluctuating quality of soybean raw materials: Local and imported soybeans are used interchangeably depending on market prices. Quality is not always stable.

• Yeast starter is not always available: Yeast is sometimes out of stock and substituted with other, less optimal sources.

d. Method Factors

• No standard SOP: All work steps are carried out based on experience, without written documentation or guidance.

• Fermentation techniques vary: There are differences in inoculation times, yeast quantities, and packaging techniques among workers.

e. Environmental Factors

• Unstable room temperature: There is no temperature control in the fermentation room. During the rainy season, the fermentation process often fails.

• Poor ventilation and poor hygiene: Closed rooms with poor air circulation and limited sanitation create the potential for contamination.

From this analysis, it was found that the lack of fermentation aids and the lack of temperature control were the dominant root causes, significantly impacting production quality and efficiency. This became the primary consideration in designing the fermentation machine to be developed.

3.2 Fermentation Machine Design

Based on the results of the work system evaluation and the identified problems, a tempeh fermentation machine was designed that meets the criteria of having automatic temperature control (using a temperature sensor and PTC heater/heating element), a small to medium capacity (10–15 kg per batch), thermal insulation for energy efficiency, an ergonomic design for ease of operation, and easy-to-clean food-grade stainless steel.

The first stage in the tempeh fermentation cabinet manufacturing process is product design. The design is carried out in two forms: 2D and 3D. The 2D design includes top, front, rear, and sectional views, while the 3D design is used to visualize the final appearance of the cabinet.

This design takes into account the fermentation space requirements, electronic component layout, ventilation, and user ergonomics. The placement of temperature and humidity sensors, fans, lights, and humidifiers is also planned from the outset to simplify installation and optimize the temperature inside the cabinet.

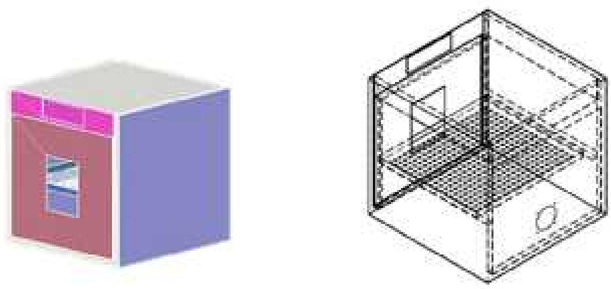

Figure 3. 3D Design of Fermentation Machine

Once the design is complete, the next step is to create the main cabinet frame. The main material used is a 1 mm-thick 304 stainless steel plate. This material was chosen for its rust resistance,

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

malleability, and food-grade safety. The frame formation process involves the following steps:

• Cut the plate to the specified dimensions.

• Bend the plate on the right, left, and top sides to form the frame.

• Welding is performed at the joints between the front, back, bottom, and bent sides.

• After the assembly process is complete, smooth the joints and sharp surfaces using a grinder or sandpaper to avoid potential injuries and enhance the product's appearance.

At the rear of the cabinet, a special ventilation hole is made for the fan, measuring 8 cm x 8 cm, corresponding to the dimensions of the 220V AC fan to be installed. The purpose of installing this fan is to help regulate air circulation when the humidity inside the cabinet is too high and to maintain even temperature distribution. The holes were drilled using a power drill or metal cutting tool, using precision techniques to ensure smooth fan installation.

The cabinet door was constructed separately from the main body, measuring 55 cm x 50 cm. This door features a 14 cm x 19 cm square hole in the center, which will be fitted with 2 mm clear acrylic. This acrylic window allows users to view the fermentation process inside the cabinet without having to open the door, ensuring stable temperature and humidity.

The fermentation pan, measuring 41 cm x 45 cm, is equipped with 324 ventilation holes, each 1 cm in diameter. These holes maintain air circulation around the fermented soybeans, allowing the Rhizopus oligosporus fungus to grow evenly. The pan is also designed for easy removal and cleaning after the fermentation process is complete.

This step is part of the Functional Product Component (FPC) manufacturing process, which involves installing the electrical system and automatically controlling temperature and humidity. The equipment used includes:

• STC-3028 microcontroller: the primary device for measuring temperature and humidity.

• Temperature and humidity sensors: detect real-time conditions in the fermentation chamber.

• 3-watt heating lamp: serves as the primary heat source.

• 220V AC fan: activates when the temperature or humidity exceeds the set point.

• Ultrasonic humidifier module: generates water vapor to increase humidity if the relative humidity (RH) drops.

This system is designed to operate automatically based on the set point temperature of 33–35°C and humidity of 65–75%, according to the needs of tempeh fermentation. All cables are neatly arranged and insulated to prevent short circuits and ensure safety.

The final stage in manufacturing is product finishing, which includes the following activities:

• Cleaning all cabinet parts of welding residue, dust, and scratches.

• Rechecking the electrical system, such as testing sensors, activating fans, lights, and humidifiers.

• Simulating a fermentation trial to ensure stable temperature and humidity levels can be maintained for 24–48 hours.

• Evaluating the function of acrylic windows, doors, and locks to ensure there are no gaps for outside air to enter.

Figure 4. Results of the Tempe Fermentation Machine Design

Once this process is complete, the tempeh fermentation cabinet is declared ready to be used for tempeh production under controlled environmental conditions.

3.3 Fermentation Machine Performance Testing

Before the implementation of fermentation machines, MSMEs carried out the fermentation process using conventional methods that relied on ambient temperature for incubation. Consequently, the process was highly susceptible to weather fluctuations, often resulting in inconsistent tempeh quality. Following the design and assembly of the fermentation machine, preliminary trials were conducted to evaluate its ability to maintain temperature stability and

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

improve fermentation success rates.

Testing was conducted by comparing the fermentation process using the conventional method and a fermentation machine, using the same batch size. The parameters observed included temperature stability, fermentation duration, product quality, and the fermentation success rate.

Table 1. Comparison of Test Results

No	Parameter	Conventional Method	Fermentation Machine	Improvement
1	Number of test batches	10 batch	10 batch	-
2	Batch successful	7 batch	9 batch	+2 batch
3	Success rate	70%	90%	20%
4	Fermentation temperature	28–38°C	33–35°C	More stable
5	Fermentation duration	24–48 hours	30–32 hours	More consistent
6	Tempeh texture	Partially sparse	Dense and uniform	Increase
7	Mycelium color	Uneven	Evenly white	Increase
8	Smell	Some batches smell sour.	The distinctive aroma of tempeh	Increase

Based on test results, the use of a fermentation machine increased the fermentation success rate from 70% to 90%. This improvement demonstrates that the machine's automatic temperature control system creates more stable fermentation conditions compared to conventional methods. With conventional methods, the fermentation chamber temperature is heavily influenced by environmental conditions, leading to frequent temperature fluctuations that hinder the optimal growth of the Rhizopus oligosporus mold.

In addition to improving fermentation success, the use of the machine results in more uniform tempeh quality. During testing, the fermentation chamber temperature was maintained within the 33–35°C range—the optimum temperature for mold growth. These conditions produced a denser tempeh texture, even mycelium coloration, and a more consistent aroma compared to conventional fermentation.

Thus, the designed fermentation machine is not only capable of increasing fermentation success by 20 percentage points but also ensures production process stability, potentially boosting productivity and reducing the risk of fermentation failure for MSMEs.

3.4 Performance Testing of the Fermentation Machine

Table 2. Temperature Stability

Time	Conventional	Machine
0 hours	31°C	33°C
6 hours	28°C	33°C
12 hours	35°C	34°C
18 hours	38°C	35°C
24 hours	30°C	34°C

To evaluate the performance of the designed fermentation machine, tests were conducted on several performance parameters, including fermentation temperature stability, fermentation duration, the fermentation success rate, and the time required for the operator to monitor the process. The test results demonstrated that the fermentation machine maintained the temperature within the 33–35°C range, whereas the conventional fermentation process exhibited temperature fluctuations between 28–38°C in response to changing environmental conditions. The average temperature deviation decreased from ±4.8°C with the conventional method to ±0.7°C when using the fermentation machine. This reduction in deviation indicates that the automatic temperature control system creates more stable fermentation conditions. In addition to temperature stability, the use of the fermentation machine increased the fermentation success rate from 70% to 90%.

Out of ten test batches, nine successfully produced tempeh meeting the required quality criteria, whereas the conventional method yielded only seven successful batches. These results indicate a 20-percentage-point increase in fermentation success. From an operational standpoint, the use of the fermentation machine reduced the time required for operator monitoring from approximately 90 minutes to 30 minutes per day, as temperature regulation is automated. Consequently, operators do not need to perform continuous checks throughout the fermentation process. Overall, the test results demonstrate that the developed fermentation machine outperforms the conventional method in terms of temperature

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

stability, process efficiency, and product quality consistency.

3.5 Ergonomic Evaluation Using the REBA Method

To determine the impact of using the fermentation machine on the operator's working posture, an ergonomic evaluation was conducted using the Rapid Entire Body Assessment (REBA) method. The assessment focused on the operator's primary activities—loading soybeans into the fermentation chamber, retrieving fermentation trays, and monitoring the fermentation process—both before and after the machine's implementation. REBA evaluations were based on observations of the operator's body posture, specifically the positioning of the neck, back, legs, upper arms, forearms, and wrists, in accordance with the procedures established by Hignett and McAtamney (2000).

The assessment results indicate that the use of the fermentation machine improves the operator's working posture. Before using the machine, operators tended to work in a stooped position because the tempeh storage process involved wooden racks located close to the floor. After adopting the fermentation machine, the working posture became more upright; the machine's height was adjusted to the operator's elbow level, allowing for more comfortable loading and unloading of the fermentation trays.

Table 3. Ergonomics Assessment Results Using the REBA Method

Activity	Before the Engine	After the Engine	Decline
Adding the soybeans	9	4	-5
Retrieve the fermentation tray.	8	3	-5
Fermentation monitoring	6	2	-4
Average REBA Score	7,67	3	-4,67

Table 4. Risk Categories

REBA Score	Risk Level	Action
1	Very Low	No action required
2–3	Low	Needs monitoring
4–7	Moderate	Needs improvement
8–10	High	Needs immediate action
≥11	Very High	Needs immediate improvement

Based on the measurement results, the average REBA score decreased from 7.67 to 3.00. Before using the fermentation machine, the operator's working posture fell into the moderate-to-high risk category, necessitating corrective action. Following the machine's implementation, the REBA score dropped to the low-risk category, indicating that the machine's design successfully improved the operator's working posture.

The reduction in the REBA score is attributed to a change in the operator's working posture; previously, the operator had to bend over to arrange or retrieve *tempeh* from conventional fermentation racks. The designed fermentation machine features a working height of approximately 85–90 cm, allowing tasks to be performed in a more natural standing position. Furthermore, the use of a front door and a sliding rack system reduces the frequency of bending and excessive reaching. Consequently, utilizing the fermentation machine not only enhances the stability of the fermentation process but also improves the operator's ergonomic working conditions and potentially lowers the risk of musculoskeletal disorders.

IV. CONCLUSION

This study aims to design a tempeh fermentation machine that suits the needs of tempeh MSMEs in Surabaya with a work system evaluation-based approach using the Fishbone Diagram method. Based on the results of observations, interviews, and field analysis of the conventional tempeh production process. The inefficiency of the tempeh fermentation process in MSMEs is caused by various factors, namely: low worker skills and consistency (human factors), the absence of tools and poor equipment conditions (machine factors), fluctuations in the quality of raw materials (material factors), the absence of SOPs and varying production techniques (method factors), and an unconducive work environment such as unstable temperatures and poor sanitation (environmental factors). The Fishbone Diagram has proven effective as a tool to identify the main root causes of inefficiencies in the work process, thus providing a clear direction in designing appropriate solutions based on field needs. The developed tempeh fermentation machine design has the following specifications: automatic temperature control, small-medium capacity, thermal insulation, ergonomic design, and food-

p-ISSN 2622-2027
DOI: https://doi.org/10.36456/tibuana.9.02.11616 *e*-ISSN 2622-2035

safe materials. This machine is designed to be easy to operate by MSMEs without requiring high technical skills. Initial trials have shown that the fermentation machine has succeeded in increasing efficiency and product quality. Temperature can be controlled stably, the fermentation process is more consistent, and the resulting tempeh is more uniform in texture, aroma, and appearance. Furthermore, the fermentation success rate increases from an average of 70% to over 90%. In terms of ergonomics and work systems, this machine reduces physical workload, simplifies fermentation monitoring, and increases workplace comfort, thus supporting the productivity and well-being of MSMEs

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