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Effect of 3D Printing Parameters on Dimensional Accuracy Using the Taguchi and Response Surface Methodology (RSM)

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***Abstract*— Advances in technology in the manufacturing industry have driven the use of 3D printing as a fast and efficient prototyping solution. This study aims to optimize the process parameters of FDM 3D printing using PLA+ material with ASTM D-638-04 type specimens. The process parameters tested include printing speed, nozzle temperature, layer thickness, infill rate, and bed temperature, each at three levels. Optimization was performed using the Taguchi method and Response Surface Methodology (RSM), with a focus on dimensional accuracy (length, width, and thickness) as the primary response. The optimal parameters obtained from the Taguchi method are printing speed of 45 mm/s, nozzle temperature of 240°C, layer thickness of 0.30 mm, infill rate of 100%, and bed temperature of 55°C. Meanwhile, the RSM method yielded the following optimal parameters: printing speed of 50 mm/s, nozzle temperature of 240°C, layer thickness of 0.30 mm, infill rate of 100%, and bed temperature of 60.65°C.**

***Keyword*: 3D Printing, RSM Method, Taguchi Method, Dimensional Accuracy**

I. INTRODUCTION

Following the three previous ones, Industry 4.0 derives from the idea of the fourth industrial revolution. (Gilchrist, 2016; Xu et al., 2018). The first industrial revolution was distinguished by mechanization driven by steam power; the second was defined by mass manufacturing employing electricity; the advent of automation and information technology characterized the third (Karabegović et al., 2020; Xu et al., 2018). The current phase, Industry 4.0, is marked by the integration of digital technology into manufacturing processes, including cloud computing, smart sensors, and the Internet of Things(Karabegović et al., 2020). It aims to create smart, linked factories and supply networks to increase operating efficiency and production. (Xu et al., 2018). A great change in the manufacturing sector that merges modern digital developments with conventional industrial methods is known as Industry 4.0 (Edverton, 2024; KUMAR, 2024). The utilization of advanced data analytics, networked equipment, and the broad adoption of digital technologies across organizational structures are all part of this trend (KUMAR, 2024). Driving Industry 4.0 are the major technologies: the Internet of Things, advanced data analytics, artificial intelligence, cyber-physical systems, and additive manufacturing (Edverton, 2024). When Industry 4.0 is introduced in the industrial sector, a few administrative and technological problems show themselves. Two significant technical hurdles are a shortage of staff expertise and infrastructure. (Alsaadi, 2022). Managerial challenges encompass issues related to strategy, organization, and human resources (Bajic et al., 2021).

With the rapid development of technology in the modern era, particularly in the manufacturing sector, the concept of Industry 4.0 has become increasingly popular. The process of creating product design prototypes has become an important part of the development cycle in this field. On the other hand, the prototyping process often takes a lot of time. Therefore, a method is needed to speed up this stage, for example, by using a 3D printer. This technology has become a vital component in the industry due to its ability to produce prototypes quickly and efficiently. The term "3D printing" refers to the additive manufacturing process, which involves creating three-dimensional objects by layering material until the desired geometry is achieved. Usually referred to as 3D printing, additive manufacturing (AM) started in the 1980s with the invention of stereolithography (SLA), a method that produces items layer by layer using photopolymerization (Huang et al., 2020). Additive manufacturing (AM) has emerged as a game-changing technology across a wide range of industries, especially in aerospace. It provides notable benefits such as enhanced design flexibility, the ability to produce lightweight structures, and significantly faster prototyping (C et al., 2024;

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Khorasani et al., 2022). Additive Manufacturing (AM) facilitates the fabrication of intricate geometries, patient-specific implants, and tailored scaffolds designed for applications in tissue engineering (Mobarak et al., 2023).

Currently, technological advances in manufacturing are developing rapidly. One notable innovation is the emergence of 3D printing technology as an alternative in the production process of an object. This technology enables the direct creation of solid objects from digital files through a layered printing process, revolutionizing conventional methods of producing components and prototypes. Additive manufacturing, or 3D printing, is the process of building three-dimensional objects by gradually adding material layer after layer until the entended form is reached. (Helena et al., 2020). This technology has attracted considerable interest across multiple industries for its capability to manufacture intricate structures rapidly and at a reduce cost. (Helena et al., 2020).

The goal of a research study is to reduce surface roughness in PLA-printed goods by improving the FDM 3D printing process parameters. (Rosyadi et al., 2024). The work employed an L27 orthogonal array and the Taguchi method to systematically vary six important parameters: orientation, infill pattern, layer thickness, printing speed, infill density, and nozzle temperature. The findings show that nozzle temperature and printing speed are the most significant variables influencing surface quality; the ideal settings are 200°C for the nozzle, 100% infill density, 90 mm/s printing speed, 0.25 mm layer thickness, hexagonal infill pattern, and 30° orientation. Surface roughness measurements and ANOVA analysis supported these findings, and additional tests demonstrated how well the modified parameters produced smoother 3D printed surfaces.

Nugraha et al. (2022) describe how to optimize variables in the Fused Deposition Modeling (FDM) 3D printing process.(Nugraha & Wahyujati, 2022). The focus is on the use of recycled filament made from polypropylene (PP) plastic. The aim is to determine the optimal print temperature (print temperature), layer thickness (layer thickness), and print speed (print speed) to produce printed products with optimal dimensional quality and tensile strength. By using recycled plastic as the material for 3D printing filament, this study also aims to reduce the amount of plastic waste. For ASTM D638-10 Type 1 tensile test specimens, a print temperature of approximately 260°C, a layer thickness of 0.12 mm, and a print speed of 50 mm/s are the optimal choices. Printing temperature and layer thickness have a significant influence on the tensile strength of printed products, while printing speed does not have a significant influence, according to statistical ANOVA analysis. The mathematical model generated from the Box-Behnken Response Surface Methodology (RSM) can predict the most suitable parameter combinations to achieve the best printing results.

The research I conducted on dimensional accuracy in FDM 3D printing machines using PLA+ (Polylactic Acid) filament material with ASTM D-638-04 type specimens, using parameters to obtain length, width, and thickness dimensions with the process parameters used being printing speed (40 mm/s), (45 mm/s), (50 mm/s), nozzle temperature (240°C), (245°C), (250°C), layer thickness (0.20 mm), (0.25 mm), (0.30 mm), infill rate (98%), (99%), (100%), and bed temperature (55°C), (60°C), (65°C). The optimization of these process parameters was performed using the Taguchi method and RSM to print products using 5 parameters and 3 levels in the dimensional accuracy response.

This study aims to identify the most suitable parameters for the 3D printing process using PLA+ (polylactic acid) filament to achieve the desired length, width, and thickness of the printed object. The analysis method applied in this study is based on a review and evaluation of various relevant previous studies to support the achievement of accurate and high-quality results.

Optimization of the 3D printing process can be done by utilizing the Taguchi method and Response Surface Methodology (RSM) with the help of Minitab software. These two methods are proposed in this study to analyze the relationship between process variables and optimize the output response. In this context, the Taguchi method and RSM are used to examine and determine the best parameters to improve the dimensional accuracy of the printed results using PLA+ filament. Based on reviews of previous studies, this approach has proven effective in addressing process optimization issues and contributing to product quality improvement by identifying the most optimal parameter values.

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II. RESEARCH METHOD

II. 1. 3D Printing

3D printing is one of the additive manufacturing technologies that can print a 3-dimensional (3D) object at a relatively low cost and in a short period of time. This is very useful for faster manufacturing processes. Fused Deposition Modeling (FDM) is a widely adopted 3D printing technique due to its ease of use, accuracy, and low cost (Cano-Vicent et al., 2021). It creates 3D structures by layer-wise extrusion of melted plastic filaments, allowing for the production of complex geometries. The tests were conducted by ASTM D-638-04 specimen standards using a Creality K1 FDM-based 3D printer with

dimensions of 220 mm x 220 mm x 250 mm.

II. 2. Material PLA

PLA (Polylactic Acid) material was chosen as the filament in 3D printers because PLA is a filament material that is very often used for 3D printing processes with FDM systems. Polylactic acid (PLA) is a biodegradable polymer gaining attention as an alternative to conventional plastics in various industries (Hussain et al., 2024). While PLA exhibits promising strength and stiffness, it faces challenges such as brittleness and slow composting rates (Multari & Pearson, 2024).

II. 3. DOE (Design of Experiment)

a) Taguchi Method

Taguchi's method uses a structured matrix called an Orthogonal Array to determine the minimum number of trials required to obtain comprehensive information about the variables. This matrix enables efficient experimentation with systematic variation in input parameters, while ensuring a balanced combination of variable levels and statistically meaningful results. (Alenezi et al., 2022). The Taguchi approach is an important development of the Design of Experiments (DOE) method, which provides a structured and efficient way to design and conduct experiments. Its main focus is to improve quality by minimizing variation and finding optimal conditions through robust design. Taguchi loss functions are divided into three types: Nominal-is-Best (values closest to the target are best), Smaller-is-Better (smaller values are better, e.g., for error rates), and Larger-is-Better (larger values are better, such as for strength or efficiency) (George & Tembhurkar, 2022).

b) RSM Method

Response Surface Methodology (RSM) is a statistical technique employed to enhance processes and investigate the connections between input factors and resulting responses. (A, 2023). RSM includes experimental design methods to explore parameter space, data-based statistical modeling to establish estimated relationships between process variables and results, and optimization techniques to determine the optimal values of process variables (Sarabia & Ortiz, 2009).

c) Orthogonal Array Matrix

In this study, five controllable factors were selected, each at three levels. These factors included print speed (mm/s), nozzle temperature (°C), layer thickness (mm), infill level (%), and bed temperature (°C). The experimental design used an orthogonal $L2^7$ (3^5) arrangement, consisting of 5 factors with a total of 27 experimental combinations in the Taguchi method and 92 combinations in the RSM method, each repeated twice.

Table 1
Level Setting

Independent Variable	Level 1	Level 2	Level 3
Printing Speed	40	45	50
Nozzle Temperature	240	245	250
Layer Thickness	0,20	0,25	0,30
Infill Rate	98	99	100
Bed Temperature	55	60	65

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Table 2
Orthogonal Array Matrix

No.	printing speed (mm/s)	nozzle temperature (°C)	layer thickness (mm)	Infill rate (%)	bed temperature (°C)
1	40	240	0,20	98	55
2	40	240	0,20	98	60
3	40	240	0,20	98	65
4	40	245	0,25	99	55
5	40	245	0,25	99	60
6	40	245	0,25	99	65
7	40	250	0,30	100	55
8	40	250	0,30	100	60
9	40	250	0,30	100	65
10	45	240	0,25	100	55
11	45	240	0,25	100	60
12	45	240	0,25	100	65
13	45	245	0,30	98	55
14	45	245	0,30	98	60
15	45	245	0,30	98	65
16	45	250	0,20	99	55
17	45	250	0,20	99	60
18	45	250	0,20	99	65
19	50	240	0,30	99	55
20	50	240	0,30	99	60
21	50	240	0,30	99	65
22	50	245	0,20	100	55
23	50	245	0,20	100	60
24	50	245	0,20	100	65
25	50	250	0,25	98	55
26	50	250	0,25	98	60
27	50	250	0,25	98	65

$$d \quad (f) = \Sigma\, l - 1 \qquad (1)$$

d = degree of freedom
f = factor
L = level of each factor

By applying the formula mentioned above, the degrees of freedom (DOF) for each factor can be calculated as follows:

$d \quad (A) = 3 - 1 = 2$
$d \quad (B) = 3 - 1 = 2$
$d \quad (C) = 3 - 1 = 2$
$d \quad (D) = 3 - 1 = 2$
$d \quad (E) = 3 - 1 = 2$

d) S/N Ratio (Signal to Noise Ratio)

The Signal-to-Noise ratio is used to evaluate each factor's role in reducing response variability and enhancing product consistency, identifying key parameters affecting output quality (Rashid, 2023). Based on the type of quality characteristic (smaller is better, larger is better, or target is best), the S/N ratio is calculated and used to find optimal settings for controllable factors (Mitra, 2011). This study applies to the Nominal-the-better criterion, suitable when a fixed target is desired, with the S/N ratio indicating process accuracy and stability by measuring how closely results align with the nominal value. The following formula can be used to calculate the SN ratio:

- Smaller the better

$$S \quad K_S = -10\, l \left[\frac{1}{n}\sum_i^n y_i^2\right] \qquad (2)$$

$S \quad K_S$ = S/N Smaller the better
n = Amount of Data
y_i = i-th data

- Nominal the better

$$S \quad K_n = 10 \log\left[\frac{\mu^2}{\sigma^2}\right] \qquad (3)$$

$S \quad K_n$ = S/N Nominal, the better
μ = Average of Data

σ = Variation of Data

- The larger the better

$$S\ \ K_{L_i} = 10\log\left[\frac{1}{n}\sum_{i}^{n}\frac{1}{y_i^2}\right] \quad (4)$$

$S\ \ K_{L_i}$ = S/N The Larger the better
n = Amount of Data
y_i = i-th data

e) Multiple Regression Analysis and Analysis of Variance (ANOVA)

To determine the influence of each process parameter and the significance of experimental variables, regression analysis and ANOVA (Analysis of Variance) were employed (Perzyk et al., 2008). The steps involved in the multiple regression process are expressed through the following equation:

$$y_1 = \beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\beta_5x_5+\varepsilon \quad (5)$$
$$y_2 = \beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\beta_5x_5+\varepsilon \quad (6)$$
$$y_3 = \beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\beta_5x_5+\varepsilon \quad (7)$$

Were,
y_1 = response variable (length)
y_2 = response variable (width)
y_3 = response variable (thickness)
x_1, x_2, x_3, x_4, x_5 = Independent Variable
$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ = Coefficient Regression

Stages in working on multiple regression:

- Find the values of $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5$
- The simultaneous correlation coefficient (R) and the coefficient of determination (R2) must be computed to ascertain the strength of the link. R^2 shows the percentage of the response variable's variance that the model can account for, whereas R represents the overall correlation between all independent variables and the dependent variable. The simultaneous correlation (R) is calculated using the following formula.

$$K = \sqrt{\frac{\beta_1.\sum x_1y + \beta_2.\sum x_2y + ...\beta_n.\sum x_ny}{\sum y^2}} \quad (8)$$

- Perform an-F test

$$F = \frac{(R^2)/(k-1)}{(1-R^2)/(n-k)} \quad (9)$$

K = number of independent variables, including intercept or constant (β_0)
n = number of data points

II. 4. GRA Method (Grey Relational Analysis)

Grey Relational Analysis serves as a powerful approach for optimizing problems involving multiple responses by transforming them into an equivalent single-response optimization task (Fung & Tien, 2005). Through Grey Relational Analysis, Grey Relational Grade values are obtained to evaluate multiple responses (multiresponse), so that optimization of complex multiresponse can be converted into optimization of a single response with Grey Relational Grade as its objective function.

- Normalization

$$x'_i(k) = 1-\left|\frac{x_i(k)-x_0(k)}{m\ \ |x_j(k)-x_0(k)|}\right| \quad (10)$$

$x'_i(k)$ = Actual value of data-i
$x_0(k)$ = Target value (average of all data in that column)
$m\ \ |x_j(k)-x_0(k)|$ = Maximum deviationfrom the target value

- Grey Relational Coefficient (GRC)

$$\gamma_i = \frac{\Delta_m + \zeta.\Delta_m}{\Delta_i + \zeta.\Delta_m} \quad (11)$$

$$\Delta_i = |1 - x'_i| \quad (12)$$

γ_i = GRC value for data-i, which shows how close the i data point is to the reference data
Δ_i = The absolute difference between the reference data and data-i
Δ_m = Minimum value of all Δ_i
Δ_m = Maximum value of all Δ_i
ζ = Differential coefficient (distinguishing coefficient), usually ranges between 0 Dan 1. Generally, ζ = 0,5 is used to balance sensitivity.

- Grey Relational Grade (GRG)

$$G_i = \frac{1}{n}\sum_{k=1}^{n}\gamma_i(k) \quad (13)$$

G_i = GRG for the i data point
$\gamma_i(k)$ = GRG for criterion k on data i
n = number of criteria (length, width, thickness)

II. 5. Research Process Diagram

To systematically investigate the influence of various process parameters on the mechanical properties of 3D-printed specimens and optimize the printing conditions, this study employed a structured experimental approach. The research methodology involved designing experiments using orthogonal arrays, followed by specimen preparation, dimensional measurements, and comprehensive statistical analysis. The workflow, depicted in Figure 1, outlines the step-by-step procedure, starting from determination and level setting, progressing through specimen design and printing, and concluding with advanced analyses such as Taguchi methods, Response Surface Methodology (RSM), Grey Relational Analysis (GRA), regression modeling, and final

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optimization.

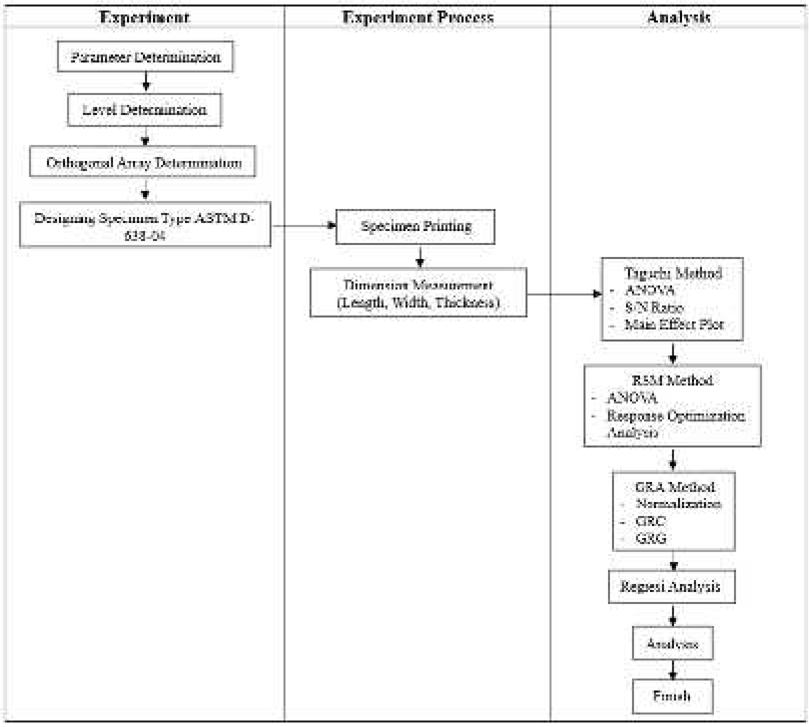

Figure 1: Research Process Diagram

III. RESULT AND DISCUSSION

III.1. Result

This section presents the findings of the statistical analyses conducted to evaluate the influence of process parameters on the geometrical accuracy of 3D-printed specimens. The primary objective was to identify significant variables and establish predictive models that can be used for process optimization. Two major statistical approaches were employed: the Taguchi method and Response Surface Methodology (RSM). Both methods were used to model the relationships between input parameters and output responses, enabling both single- and multi-objective optimization.

1. Taguchi Analysis

a) Dimensional Measurement of Specimen

Measurements on the specimens were conducted according to the specimen design outlined in ASTM Type 4 standards, with the standard dimensions as shown in Figure 2:

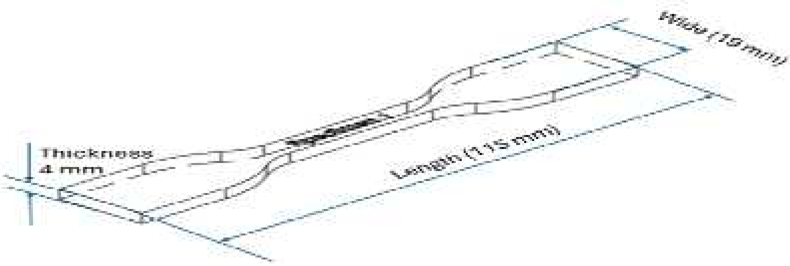

Figure 2: Specimen Dimensional

The dimensional measurement results of the specimens produced using the 3D printing machine are summarized in Table 3.

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Table 3
Results of Measurement Dimension Specimen

No Experiment	printing speed (mm/s)	nozzle temperature (°C)	layer thickness (mm)	Infill rate	bed temperature (°C)	Result of measurement		
						Length	Wide	Thickness
1	40	240	0,20	98	55	114,800	18,590	3,380
2	40	240	0,20	98	60	114,800	18,440	3,570
3	40	240	0,20	98	65	114,800	18,400	3,360
4	40	245	0,25	99	55	114,780	18,590	3,440
5	40	245	0,25	99	60	114,800	18,305	3,375
6	40	245	0,25	99	65	114,630	18,670	3,270
7	40	250	0,30	100	55	114,650	18,480	3,480
8	40	250	0,30	100	60	114,650	18,580	3,415
9	40	250	0,30	100	65	114,730	18,730	3,510
10	45	240	0,25	100	55	114,650	18,590	3,490
11	45	240	0,25	100	60	114,650	18,400	3,425
12	45	240	0,25	100	65	114,700	18,670	3,300
13	45	245	0,30	98	55	114,750	18,450	3,520
14	45	245	0,30	98	60	114,680	18,510	3,475
15	45	245	0,30	98	65	114,720	18,570	3,445
16	45	250	0,20	99	55	114,800	18,530	3,405
17	45	250	0,20	99	60	114,840	18,410	3,380
18	45	250	0,20	99	65	114,750	18,585	3,455
19	50	240	0,30	99	55	114,780	18,480	3,555
20	50	240	0,30	99	60	114,790	18,510	3,500
21	50	240	0,30	99	65	114,690	18,490	3,420
22	50	245	0,20	100	55	114,750	18,450	3,430
23	50	245	0,20	100	60	114,730	18,330	3,420
24	50	245	0,20	100	65	114,790	18,415	3,290
25	50	250	0,25	98	55	114,770	18,510	3,420
26	50	250	0,25	98	60	114,780	18,490	3,370
27	50	250	0,25	98	65	114,870	18,495	3,345

b) ANOVA Analysis

The Analysis of Variance (ANOVA) for the Signal-to-Noise (S/N) ratios was conducted to evaluate the significance of each process parameter in influencing the robustness of the system. The results, presented in Figure 4, indicate that layer thickness had a statistically significant effect on the S/N ratio, as evidenced by an F-value of 52.01 and a p-value of 0.022, which is well below the conventional threshold of 0.05. This suggests that variations in layer thickness significantly impact the system's robustness compared to other parameters.

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
printing speed (mm/s)	2	0,000401	0,000401	0,000200	1,51	0,250
nozzle temperature (°C)	2	0,000283	0,000283	0,000142	1,07	0,367
layer thickness (mm)	2	0,001291	0,001291	0,000645	4,87	0,022
Infill rate (%)	2	0,000017	0,000017	0,000009	0,06	0,938
bed temperature (°C)	2	0,000431	0,000431	0,000216	1,63	0,228
Residual Error	16	0,002121	0,002121	0,000133		
Total	26	0,004544				

Figure 3: ANOVA Result

In contrast, the other process parameters—printing speed, nozzle temperature, infill rate, and bed temperature—did not show significant effects on the S/N ratio. Their respective p-values were all greater than 0.05 (ranging from 0.396 to 0.930), indicating that these factors do not contribute substantially to the variability in the response. The residual error accounted for the remaining

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unexplained variance in the model.

c) Signal-to-Noise Ratios Analysis

The Signal-to-Noise (S/N) ratio analysis was conducted to evaluate the robustness of the process against variations in experimental conditions. The S/N ratios were calculated using the "Nominal is best" criterion, which is appropriate for responses where the target value is optimal and deviations from this target are undesirable. The results, presented in Figure 3, indicate that the layer thickness parameter had the highest impact on the S/N ratio, as evidenced by its rank of 1 and a delta value of 0.016. This suggests that variations in layer thickness significantly affect the robustness of the process compared to other parameters. In contrast, the bed temperature parameter ranked second (rank = 2) with a delta value of 0.010, indicating its moderate influence on the S/N ratio. The printing speed, nozzle temperature, and infill rate showed minimal differences in S/N ratios across their respective levels, as reflected by their small delta values (0.008, 0.007, and 0.002, respectively). These findings highlight that layer thickness plays a critical role in ensuring process stability and minimizing variability, while other parameters contribute less to the robustness of the system.

Response Table for Signal to Noise Ratios

Nominal is best (10×Log10(Ybar^2/s^2))

Level	printing speed (mm/s)	nozzle temperature (°C)	layer thickness (mm)	Infill rate (%)	bed temperature (°C)
1	-2,446	-2,445	-2,455	-2,449	-2,443
2	-2,445	-2,453	-2,451	-2,448	-2,453
3	-2,453	-2,446	-2,438	-2,447	-2,448
Delta	0,008	0,007	0,016	0,002	0,010
Rank	3	4	1	5	2

Figure 4: Response Table for S/N Ratios of Length, Width, and Thickness

d) Main Effect Plot S/N Ratios Analysis

The Main Effects Plot for Signal-to-Noise (S/N) Ratios provides a visual representation of how each process parameter influences the robustness of the system. The plot illustrates the meaning S/N ratios across different levels of five key parameters: printing speed (mm/s), nozzle temperature (°C), layer thickness (mm), infill rate (%), and bed temperature (°C).

The results indicate that layer thickness has the most significant impact on the S/N ratio, as evidenced by its steep decline in the plot (Figure 4). This suggests that variations in layer thickness led to substantial changes in the system's robustness compared to other parameters. In contrast, the effects of printing speed, nozzle temperature, infill rate, and bed temperature appear relatively minor, with their respective lines showing minimal fluctuations across different levels.

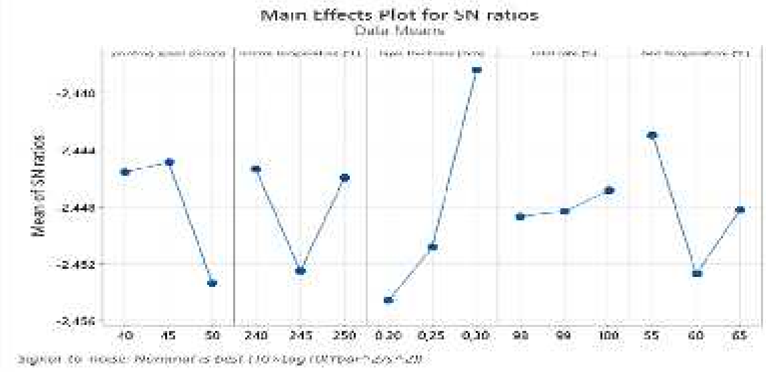

Figure 4: Main Effect Plot for S/N Ratios of Length, Width, and Thickness

2. RSM Analysis

a) Dimensional Measurement

The results of the specimen measurements conducted using Response Surface Methodology (RSM) are summarized in Table 4.

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Table 4
Results of Measurement Specimen for RSM

No Experiment	printing speed (mm/s)	nozzle temperature (°C)	layer thickness (mm)	Infill rate	bed temperature (°C)	Result of measurement		
						Length	Wide	Thickness
1	40	240	0,25	99	60	114,520	18,605	3,470
2	50	240	0,25	99	60	114,590	18,485	3,535
3	40	250	0,25	99	60	114,560	18,500	3,635
4	50	250	0,25	99	60	114,590	18,490	3,600
5	45	245	0,2	98	60	114,530	18,555	3,450
6	45	245	0,3	98	60	114,500	18,410	3,470
7	45	245	0,2	100	60	114,550	18,500	3,510
8	45	245	0,3	100	60	114,530	18,600	3,390
9	45	240	0,25	99	55	114,560	18,340	3,540
10	45	250	0,25	99	55	114,420	18,490	3,500
11	45	240	0,25	99	65	114,500	18,580	3,390
12	45	250	0,25	99	65	114,480	18,650	3,500
13	40	245	0,2	99	60	114,470	18,570	3,460
14	50	245	0,2	99	60	114,470	18,470	3,510
15	40	245	0,3	99	60	114,540	18,370	3,380
16	50	245	0,3	99	60	114,590	18,450	3,580
17	45	245	0,25	98	55	114,580	18,460	3,550
18	45	245	0,25	100	55	114,570	18,630	3,500
19	45	245	0,25	98	65	114,460	18,340	3,575
20	45	245	0,25	100	65	114,480	18,460	3,550
21	45	240	0,2	99	60	114,580	18,515	3,390
22	45	250	0,2	99	60	114,580	18,480	3,380
23	45	240	0,3	99	60	114,480	18,465	3,500
24	45	250	0,3	99	60	114,480	18,565	3,480
25	40	245	0,25	98	60	114,480	18,605	3,490
26	50	245	0,25	98	60	114,530	18,478	3,490
27	40	245	0,25	100	60	114,530	18,660	3,510
28	50	245	0,25	100	60	114,530	18,450	3,500
29	45	245	0,2	99	55	114,430	18,390	3,380
30	45	245	0,3	99	55	114,460	18,400	3,495
31	45	245	0,2	99	65	114,530	18,500	3,460
32	45	245	0,3	99	65	114,540	18,640	3,430
33	40	245	0,25	99	55	114,590	18,472	3,396
34	50	245	0,25	99	55	114,535	18,518	3,574
35	40	245	0,25	99	65	114,538	18,359	3,507
36	50	245	0,25	99	65	114,492	18,479	3,536
37	45	240	0,25	98	60	114,535	18,556	3,448
38	45	250	0,25	98	60	114,526	18,439	3,529
39	45	240	0,25	100	60	114,513	18,341	3,504
40	45	250	0,25	100	60	114,586	18,446	3,517
41	45	245	0,25	99	60	114,452	18,586	3,479
42	45	245	0,25	99	60	114,687	18,348	3,514
43	45	245	0,25	99	60	114,453	18,402	3,458
44	45	245	0,25	99	60	114,602	18,509	3,620
45	45	245	0,25	99	60	114,506	18,569	3,426
46	45	245	0,25	99	60	114,483	18,483	3,471
47	40	240	0,25	99	60	114,506	18,330	3,494
48	50	240	0,25	99	60	114,524	18,482	3,496
49	40	250	0,25	99	60	114,464	18,591	3,505
50	50	250	0,25	99	60	114,514	18,499	3,479
51	45	245	0,2	98	60	114,540	18,526	3,429
52	45	245	0,3	98	60	114,458	18,476	3,470
53	45	245	0,2	100	60	114,461	18,507	3,393
54	45	245	0,3	100	60	114,527	18,434	3,520
55	45	240	0,25	99	55	114,577	18,330	3,373
56	45	250	0,25	99	55	114,451	18,466	3,498
57	45	240	0,25	99	65	114,631	18,418	3,553
58	45	250	0,25	99	65	114,437	18,550	3,484
59	40	245	0,2	99	60	114,516	18,445	3,529
60	50	245	0,2	99	60	114,587	18,358	3,455
61	40	245	0,3	99	60	114,524	18,674	3,522
62	50	245	0,3	99	60	114,464	18,558	3,519
63	45	245	0,25	98	55	114,531	18,481	3,484
64	45	245	0,25	100	55	114,556	18,404	3,513
65	45	245	0,25	98	65	114,538	18,514	3,575
66	45	245	0,25	100	65	114,507	18,388	3,485
67	45	240	0,2	99	60	114,522	18,439	3,391
68	45	250	0,2	99	60	114,415	18,487	3,489
69	45	240	0,3	99	60	114,567	18,452	3,640
70	45	250	0,3	99	60	114,464	18,590	3,387
71	40	245	0,25	98	60	114,458	18,537	3,590
72	50	245	0,25	98	60	114,427	18,501	3,452
73	40	245	0,25	100	60	114,561	18,494	3,491
74	50	245	0,25	100	60	114,453	18,516	3,444
75	45	245	0,2	99	55	114,480	18,419	3,550
76	45	245	0,3	99	55	114,456	18,558	3,495
77	45	245	0,2	99	65	114,481	18,590	3,484
78	45	245	0,3	99	65	114,469	18,450	3,527
79	40	245	0,25	99	55	114,496	18,503	3,610
80	50	245	0,25	99	55	114,526	18,492	3,455
81	40	245	0,25	99	65	114,547	18,504	3,490
82	50	245	0,25	99	65	114,528	18,573	3,667
83	45	240	0,25	98	60	114,506	18,455	3,556
84	45	250	0,25	98	60	114,505	18,638	3,635
85	45	240	0,25	100	60	114,583	18,651	3,583
86	45	250	0,25	100	60	114,474	18,444	3,465
87	45	245	0,25	99	60	114,528	18,514	3,454
88	45	245	0,25	99	60	114,422	18,562	3,366
89	45	245	0,25	99	60	114,479	18,534	3,439
90	45	245	0,25	99	60	114,580	18,751	3,526
91	45	245	0,25	99	60	114,521	18,528	3,481
92	45	245	0,25	99	60	114,496	18,499	3,377

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b) ANOVA Analysis for RSM

The Analysis of Variance (ANOVA) was conducted to evaluate the statistical significance of the Response Surface Methodology (RSM) models for the three-dimensional responses: Length, Width, and Thickness. The results are summarized below:

- **Length**

The ANOVA analysis for the Length response revealed that the overall model was not statistically significant, as indicated by an F-test p-value of 0.917 (>0.05). None of the individual process parameters or their interaction terms showed significant effects on the length, with all p-values exceeding the conventional threshold of 0.05. Furthermore, the adjusted R-squared value was 0.00%, indicating that the model failed to explain any variability in the length measurements under the current experimental design.

- **Width**

Similarly, the ANOVA for the Width response also indicated that the RSM model was not statistically significant, with an F-test p-value of 0.901 (>0.05). No main effects or interaction terms were found to have a significant influence on the width, as all p-values were greater than 0.05. The adjusted R-squared value was also 0.00%, suggesting that the model did not capture any meaningful variation in the width response.

- **Thickness**

For the Thickness response, the ANOVA results showed that the overall model was again not statistically significant, with an F-test p-value of 0.193 (>0.05). Similar to the other responses, none of the process parameters or their interactions exhibited significant effects on thickness, as all p-values were above 0.05. The adjusted R-squared value was 0.00%, reinforcing the conclusion that the model lacked explanatory power for this response.

- **Summary**

In summary, the ANOVA analyses for all three-dimensional responses (Length, Width, and Thickness) consistently demonstrated that the RSM models were not statistically significant. None of the process parameters or their interactions showed meaningful influence on the responses, and the adjusted R-squared values were all 0.00%, indicating that the models failed to explain any variability in the data. These findings suggest that either the relationships between the process parameters and the dimensional responses are more complex than captured by the current model structure, or additional factors outside the scope of this study may be influencing the outcomes. Further investigation or refinement of the experimental design may be necessary to improve model performance and identify key influential parameters.

c) Response Optimization Analysis

In this study, response optimization was performed to determine the values of process parameters consisting of print speed, nozzle temperature, layer thickness, infill rate, and bed temperature. The composite desirability (D) is calculated as 0.2951, which indicates the overall performance of the system across all three responses. The current desirability (Cur) suggests that the current settings are close to the optimal conditions.

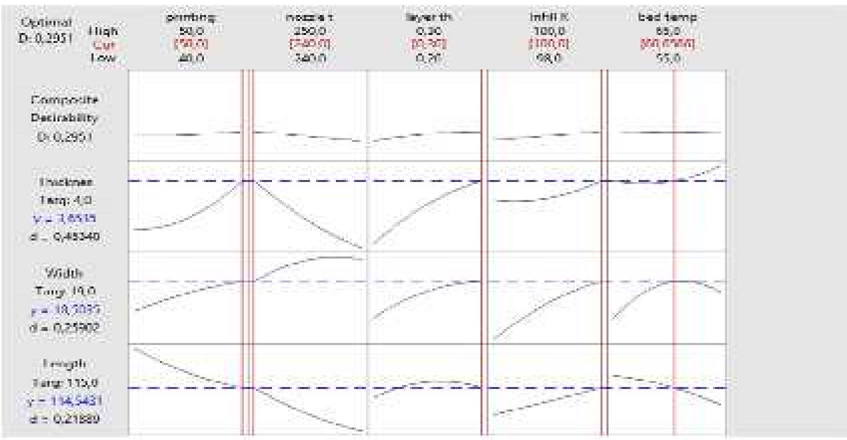

Figure 5: Response Optimization

Based on the Figure 5 response optimization graph, it shows that the response variables for the parameters of printing speed, nozzle temperature, layer thickness, infill rate, and bed temperature that are most optimal are 50 mm/s, 240°C, 0,30 mm, 100%, and 60,65°C.

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3. Grey Relational Analysis (GRA)

Based on GRA calculations for the Taguchi method, the Grey Relational Grade (GRG) value was obtained from two replications with a total of 27 experimental combinations in each replication. The GRG values show a fairly wide variation, with the GRG range in replication 1 between 0.389 and 0.942, while in replication 2 it ranges from 0.487 to 0.887.

Based on the GRA calculations for the RSM method, the Grey Relational Grade (GRG) values were obtained from two replications with a total of 92 experimental combinations in each replication. The GRG values showed considerable variation, ranging from 0.482 to 0.952 in the first replication and from 0.517 to 0.906 in the second replication.

4. Regression Analysis

In the Taguchi method regression results, the Taguchi method passed the multicollinearity test (VIF), autocorrelation test (Durbin Watson), normality test (Kolmogorov Smirnov), heteroscedasticity test (Glejser), multiple linear regression, F test, and coefficient of determination. In the hypothesis test (T-test), replication 1 had significant parameters, namely printing speed and bed temperature, while replication 2 had significant parameters, namely printing speed and layer thickness. Meanwhile, the RSM method passed the multicollinearity test (VIF), autocorrelation test (Durbin Watson), normality test (Kolmogorov-Smirnov), heteroscedasticity test (Glejser), multiple linear regression, hypothesis testing (T-test), and coefficient of determination, replication 1 and 2 had no significant effect or no effect on the dependent variable.

III.2. Discussion

The results of this study demonstrate that the Taguchi method successfully identified optimal parameters at a printing speed of 45 mm/s, nozzle temperature of 240°C, layer thickness of 0.30 mm, infill rate of 100%, and bed temperature of 55°C. In contrast, the RSM method yielded different optimal parameters: printing speed of 50 mm/s, nozzle temperature of 240°C, layer thickness of 0.30 mm, infill rate of 100%, and bed temperature of 60.65°C. In addition, (Nugraha & Wahyujati, 2022) Demonstrated that printing temperature and layer thickness significantly influence mechanical properties, which aligns with this study's finding that layer thickness notably affects dimensional accuracy, as confirmed by both the significant p-value (0.022) in the ANOVA results and the regression model of the Taguchi experiments.

The regression analysis performed on the RSM experimental data did not yield statistically significant results. None of the individual process parameters showed significant p-values, indicating that within the ranges investigated, no single factor had a dominant influence on dimensional accuracy. Additionally, the regression models generated from the RSM data exhibited low R^2 values, reflecting a poor fit between the predicted and actual measurements. This suggests that the selected parameter ranges or experimental design in RSM were insufficient to capture the underlying relationships influencing dimensional accuracy, ultimately limiting the model's predictive capability. This outcome supports (Alenezi et al., 2022), who emphasized that RSM requires homogeneous and stable data for effective modeling.

The study's limitations may have led to the low R^2 values in the RSM models. Future research should examine a broader range of parameters and include variables like cooling fan speed or nozzle diameter to build a better predictive model. Additionally, exploring other multi-response optimization methods, such as TOPSIS, could help assess their effectiveness compared to GRA in improving print quality.

IV. CONCLUSIONS

Based on research findings related to the effects of process parameters in 3D printing on dimensional accuracy through the application of the Taguchi method and Response Surface Methodology (RSM), the analysis shows that the optimal parameters in the Taguchi method are printing speed of 45 mm/s, nozzle temperature of 240°C, layer thickness of 0.30 mm, infill rate of 100%, and bed temperature of 55°C. Meanwhile, using the RSM method, the optimal parameters were obtained at a printing speed of 50 mm/s, nozzle temperature of 240°C, layer thickness of 0.30 mm, infill rate of 100%, and bed temperature of 60.65°C.

Based on regression analysis, in the Taguchi method, the variables that have a significant effect are printing speed, layer thickness, and bed temperature, while in the RSM method, there are no variables that have a

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significant effect.

This indicates that the Taguchi method is more robust against data variability and remains capable of producing a valid regression model, while the RSM method is more sensitive to data stability and the form of relationships between variables.

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The application of Lean Manufacturing at PT XYZ Packaging Unit with the Value Stream Mapping (VSM) Approach

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***Abstract*— The challenges of manufacturing companies in facing global market competition must be able to maintain the effectiveness and efficiency of operational processes that take place, including one strategy in getting good work productivity by focusing on eliminating waste that occurs in the operational process. In the packaging process, there are 14 activities classified into 9 operation activities, 3 transportation activities, 1 inspection activity, and 1 storage activity. Of all these activities are categorized as 50% value added activity with a time percentage of 62%, non-value-added activity, necessary activity of 36% with a time percentage of 29%, while 14% of activities are non-value-added activity with 9% percentage of 9%. Improvements are made by adding transfer conveyors from raw materials to the hopper, categorizing activities outside packaging as external activities, changing the number of operators and work schedules, and eliminating activities with pallet investment. The impact of the improvement is achieved by eliminating 14 activities and reducing them to 12 activities.**

Keywords: Lean Manufacturing, Non-Value-Added Activity, Value Added Activity, Value Stream Mapping

I. INTRODUCTION

The challenges faced in a manufacturing business are getting higher as economic and environmental pressures increase (Siti Zaenab Nur Hasanah dkk., 2023) .In competing in the global market, manufacturing companies must be able to properly maintain process efficiency and work effectiveness, especially in efforts to eliminate waste. The purpose of ensuring the process runs effectively and efficiently is to be able to produce products of good quality that satisfy customers. In addition to good quality, customer satisfaction is also determined by fast and on-time delivery. The demand for high productivity is one of the activities to maintain the continuity of meeting customer needs. Companies can focus on improving cycle time as a measure of work productivity, which can result in reducing processing and delivery times and improving product quality so that customer satisfaction can be met and even increased (Puji Priyono & Yuamita, 2022). Lean manufacturing is one of the company's strategic approaches in identifying and eliminating non-value-added activities so that the value of a product can be increased (Hafizh Alim & Suseno, 2022). Lean manufacturing, in addition to reducing waste, also aims to satisfy customers and improve operational performance (Firdaus & Wahyudin, 2023). Classify lean manufacturing methods into two categories. The first is an activity to identify all waste and eliminate the most significant ones that have a direct impact on the operational process. The goal is to improve quality and reduce costs. The second is to focus on leaner operational processes to eliminate constraints in operations (Reza & Santoso, 2022).

PT. XYZ is one of the "ID FOOD" companies that has a core business in 2 divisions, namely the production of raw material salt, commonly referred to as krosok salt, and the salt industry, which focuses on producing processed salt, both in the classification of consumer salt products and food industry salt products. PT XYZ has one plant in Sampang Regency that operates in the packaging of consumer salt products.

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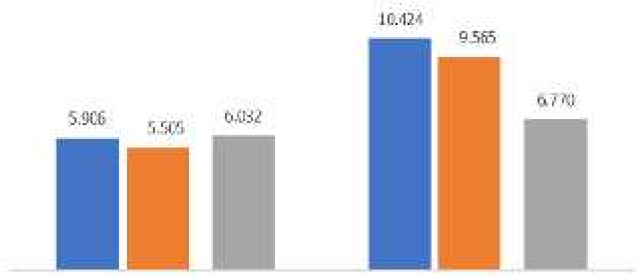
From Table 1, it can be seen that the low annual production achievement is in fine packaging products. As an effort to achieve the target, this study conducted an evaluation of the identification process and eliminated waste in order to obtain improvements in the operational process. This is being done in order to provide a lean operational process and have an impact on increasing productivity, so that production results can increase
.

Table 1. Annual production targets and achievements

Product	Annual Target	Realization 2023	Realization 2024
Rough Packaging	5.906	5.505	6.032
Smooth Packaging	10.424	9.565	6.770

■Annual target ■Realization 2023 ■Realization 2024



Rough Packaging Smooth Packaging
Figure 1: Production achievement graph

II. VALUE STREAM MAPPING

VSM can visualize the process flow in a packaging operation, which can then identify each activity included in value-added (VA) and non-value-added (NVA) that adds costs, processing time, and other time required to deliver products to customer. The VSM method is used to identify problems in the packaging process flow, as well as information based on direct observation of the production process (Meckel Rifaldo & Abryandoko, 2023). The data collected includes the production process flow, number of operators, production capacity, cycle time, and takt time. PAM is used in the process of identifying value-added and non-value-added in the production process (Ponda et al., 2022) . Furthermore, NVA will be categorized into two, namely necessary non-value-added activity (NNVA) and unnecessary non-value-added (NVA) (Rohani & Zahraee, 2015). To identify process activities, start by classifying each activity in the process into each activity category, namely operation, inspection, transportation, storage, and delay

Current state mapping is made based on the results of VSM and PAM. Current state mapping is used to analyze products and information flows comprehensively to find waste in each process. Waste is classified into seven types, namely over-production, transportation, motion, over-processing, defect, waiting time, and over-inventory (Agustin & Widjajati, 2024). The next step is to determine the most significant waste

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using the Pareto concept as the focus of improvement, then analyze the cause of the problem and design improvement activities to eliminate or reduce the waste, describe the proposed improvements in the future state mapping, and draw conclusions. (Prambudi & Giyanti, 2021).

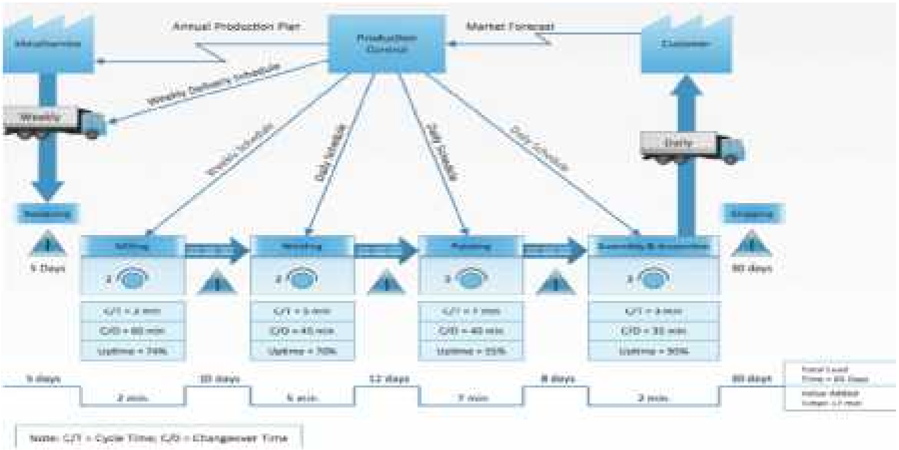

Figure 2. Value stream mapping process flow image

III. RESEARCH METHODS

This study focuses on improving the packaging process of the packaging machine, due to the low achievement of smooth packaging products processed through the packaging machine. The production process is carried out during one work shift with working hours of 07.00-16.00, eight working hours and one hour of rest. The initial step is to collect data related to the operation of the packaging machine, to calculate theoretically whether the capacity owned can have the potential to meet the annual target.

Table 2. Operational information on packaging machines.

Component	Magnitude	Unit
1 year working days	365	Day
Sunday	54	Day
National Holiday	16	Day
Machine Speed	35	ppm
Number of Machines	11	machine
Product Weight	200	gr
Effective working days	295	Day
Effective working hours	2.360	Hours

In theory, the calculation of engine capacity is obtained using the formula below:
Machine capacity = Effective working hours * Machine speed * Number of machines * Product weight
= 2.360 hours * 60 minute* 30 ppm * 11 machine * 200 gr
= 11.894.400.000 gr
= 11.894,4 ton

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Based on the theoretical calculations above, there is a non-achievement of 43.08%. Furthermore, process activity mapping is carried out on the packaging activity, which is then identified regarding the classification of VA and NVA.

IV. RESULTS AND DISCUSSION

The first step in the waste identification process is to observe the process flow and identify the details of the sequence of activities and the time needed to carry out these activities, including observing the number of workers in each activity. The approach from observation is to observe the material flow. The following is an example of a packaging activity table 3 Before carrying out mapping, it is necessary to calculate the takt time, which is the time needed to produce a product in certain units according to customer fulfillment needs (Perdana dkk., 2018). Takt time can be calculated using the equation below

:

Table 3 Packaging Activity

Activity	Time	Unit	Information	Operator	Activity Category	Activity category
Arrange raw materials sacks on pallets	600	second	Each 1 ton	A1, A2, A3	*Operation*	NNVA
Transfer to the hopper area	300	second	Each 1 ton	A1, A2, A3	*Transportation*	VA
Tear the sack seams	30	second	Each 50 kg	A1	*Operation*	NNVA
Pour into hopper	40	second	Each 50 kg	A2, A3	*Operation*	NNVA
Transfer screw conveyor	300	second	Each 50 kg	-	*Transportation*	VA
Product packaging	1,7	second	Each 200 gr	B1, B2, B3, B4, B5, B6, B7, B8	*Operation*	VA
Transfer conveyor machine output	4	second	Each 2.200 gr	-	*Operation*	VA
Extrabag packaging	30	second	Each 4 kg	C1, C2, C3, C4, C5, C6, C7, C8, C9	*Operation*	VA
Tape the extra bags	7	second	Each 4 kg	C1, C2, C3, C4, C5, C6, C7, C8, C9	*Operation*	VA
Arrange extra bags on the inner pallets.	5	second	Each 4 kg	C1, C2, C3, C4, C5, C6, C7, C8,	*Operation*	NVA
Arrange results from inner pallets to outer pallets.		second	Each 2,5 ton	C9		
Quality check (sampling)	1200	second	Each 2,5 ton	D1	*Operation*	NVA
	600	second	Each 2,5 ton	E1	*Inspection*	VA
Transfer to the warehouse.						
Arrange in the warehouse	600	second	Each 2,5 ton	F2	*Transportation*	NNVA

Before carrying out mapping, it is necessary to calculate the takt time, which is the time needed to produce a product in certain units according to customer fulfillment needs (Otsuka dkk., 2018).

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Takt time can be calculated using the equation below (Cagnetti dkk., 2021)

Takt time = Available working time / Demand
= (295-day x 8 hours x 60 minutes) / 10.424 ton
= 13.58 minutes.

Based on the process activity mapping above, the classification of activity categories and value-added categories is depicted in Figures 3 and 4.

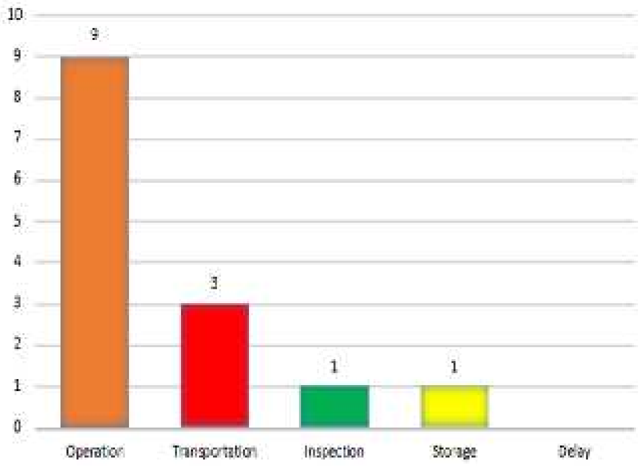

Figure 3. Activity Category Graph

In the Figure, it can be seen that 64.29% of the activities are in the operation category, the remaining 35.71% are outside the operation category, namely in the transportation, inspection, and storage categories. Of the 14 activities as illustrated in Figure 4, it is known that 50% are included in the value-added activity (VA), 36% are included in the necessary non-value-added activity (NNVA), and 14% are in the non-value-added activity (NVA) category.

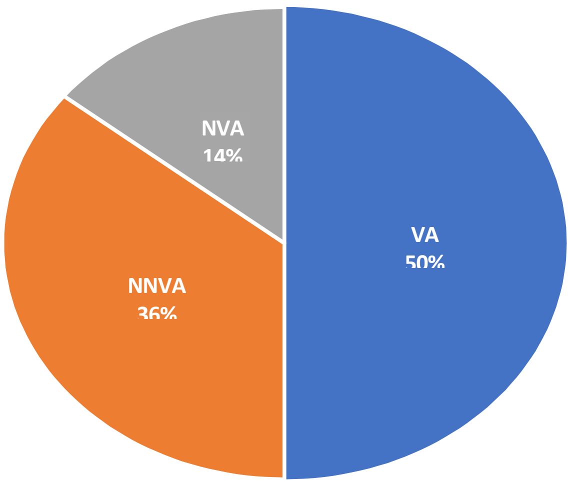

Figure 4. Graph of value-added activity categories

The next step is to calculate the cycle time of the natural packaging process in the same tonnage unit in the calculation of takt time. The goal is to compare the same work productivity assumptions based on current conditions and determine whether it can meet the takt time according to the calculations above.The following is information about cycle time in the packaging process in table 4.

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Table 4. Cycle time in the packaging process

Activity	Time	Unit	Information	Per unit tonnage	Activity category
Arrange raw materials sacks on pallets	600	second	Each 1 ton	600 second	NNVA
Transfer to the hopper area	300	second	Each 1 ton	300 second	VA
Tear the sack seams	30	second	Each 50 kg	600 second	NNVA
Pour into hopper	40	second	Each 50 kg	800 second	NNVA
Transfer screw conveyor	300	second	Each 50 kg	300 second	VA
Product packaging	1,7	second	Each 200 gr	773 second	VA
Transfer conveyor machine output	4	second	Each 2.200 gr	1.818 second	VA
Extrabag packaging		second	Each 4 kg	833 second	
	30				VA
Tape the extra bags		second	Each 4 kg	194 second	
	7				VA
Arrange extra bags on the inner pallets.		second	Each 4 kg	139 second	
	5				NVA
Arrange results from inner pallets to outer pallets.		second	Each 2,5 ton	480 second	
Quality check (sampling)	1200	second	Each 2,5 ton	240 second	NVA
Transfer to the warehouse.	600	second	Each 2,5 ton	240 second	VA
Arrange in the warehouse	600	second	Each 2,5 ton	480 second	NNVA
				7798 second	
				130 minutes	

Refereing to table 4 and the calculation of takt time in meeting the production target of 13.58 minutes. While in the mapping, the cycle time depicted is 130 minutes. It can be interpreted that there is still potential for not reaching the target fulfillment. So it is necessary to analyze in eliminating waste that occurs in the operational process by using current state mapping.

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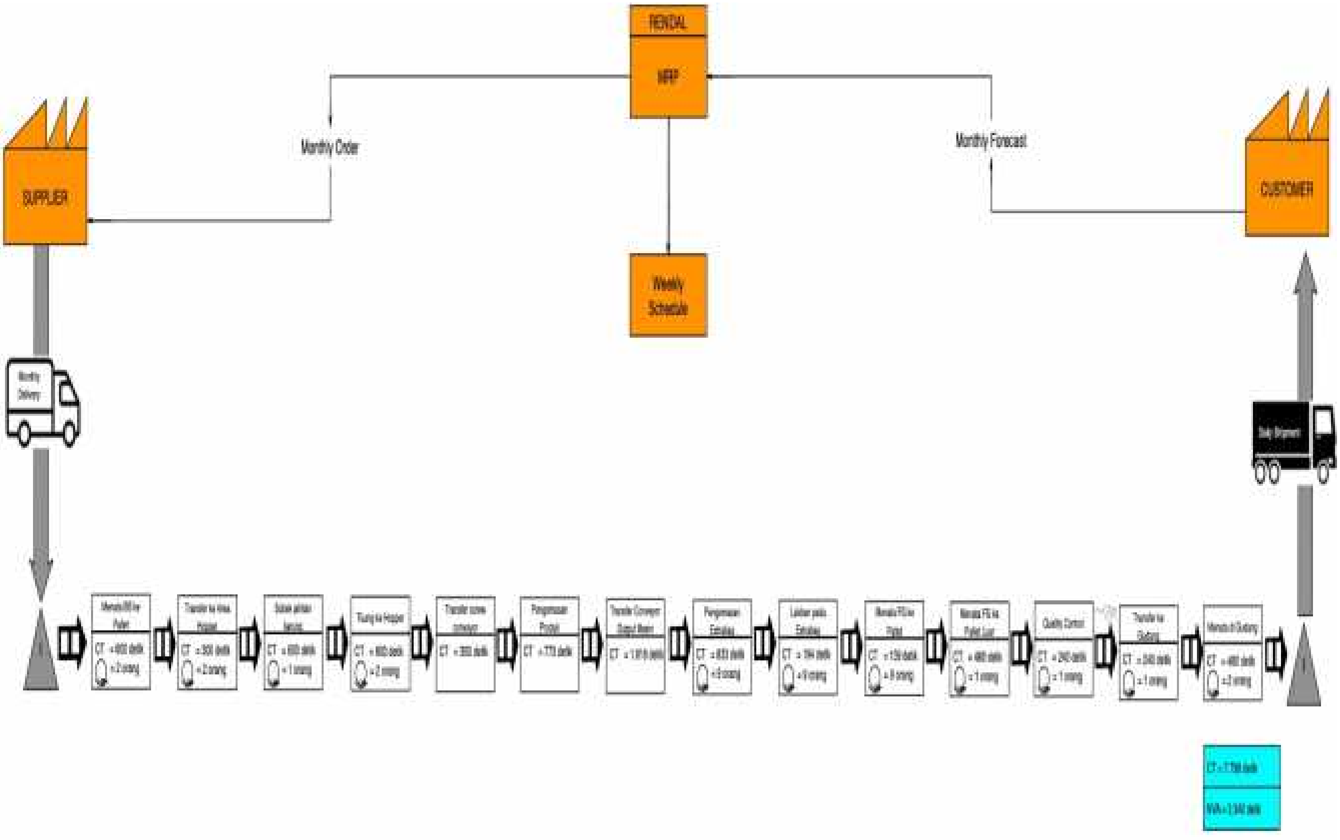

Figure 5. Current State Mapping

Referring to Table 4 and the calculation of takt time in meeting the production target of 13.58 minutes. While in the mapping, the cycle time depicted is 130 minutes. It can be interpreted that there is still potential for not re

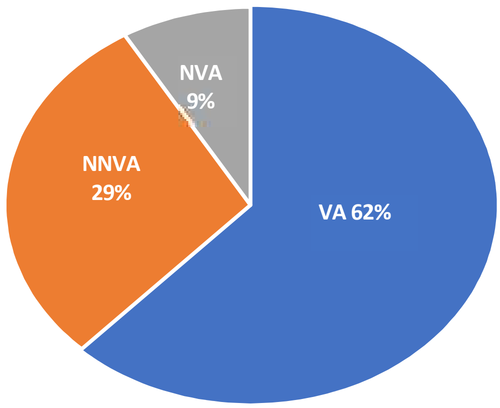

Figure 6. Time category graph of value-added

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Proposed Improvements

In the waste elimination process, based on the activity categories obtained in the previous process, efforts are Picture 5. Current State Mapping

Proposed Improvements

In the waste elimination process, based on the activity categories obtained in the previous process, efforts are made to eliminate activities related to NVA. If, in practice, there are obstacles, the next focus is on efforts to reduce time. Meanwhile, NNVA activities focus on reducing activities or time related to the process. It does not rule out the possibility of process improvement in activities in the VA category with the aim of getting faster process times. Based on the current time mapping, the percentage of activity category time is obtained in Figure 6.

For the figure 6, Proposed improvements for efforts to eliminate, reduce, and improve the process of packaging activities are carried out through a brainstorming process with respondents being teams related to operational processes, ranging from the operator position level to the general manager.

Table 5. Improvement porposal beased onactivity group

Activity	Activity Group	Improvement
Arrange raw materials on pallets	manual raw material transfer	
Transfer to the hopper area	manual raw material transfer	
Tear off sack seams	manual raw material transfer	
Pour into the hopper	manual raw material transfer	
Transfer screw conveyor	automatic raw material transfer	
Product packaging	Primary packaging	1. Adding a transfer conveyor from the raw material to the hopper 2. Categorizing activities outside of packaging as external activities
Transfer conveyor output machine	Primary packaging	3. Remapping operators according to workload
Extrabag packaging	Secondary packaging	4. Elimination of activities with a pallet investment
Duct tape on the extra bag	Secondary packaging	
Inner pallet Secondary packaging: Arrange results from inner pallet to outer pallet	Secondary packaging	
Transfer to the warehouse, Storage of Finished	Secondary packaging	
Quality checking (sampling)	Quality Control	
Transfer to the warehouse.	Storage of Finished Goods in Warehouse	
Arranging in the warehouse	Storage of Finished Goods in Warehouse	

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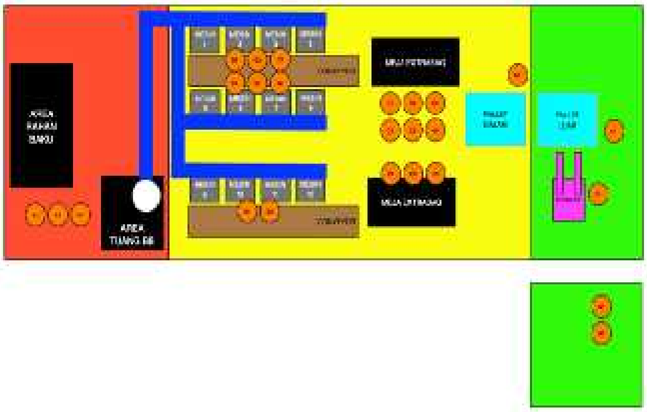

Figure 7. Layout and mapping of workers before improvement

After Improvement
Based on the proposed improvements in the next process, the first improvement is related to re-mapping the number of workers based on the results of the packaging machine. The goal is that the entire output of the packaging machine can be absorbed directly into the extrabag packaging process.

Table 6. Calculation of manpower in the secondary packaging process

Number of Machines	11	Machine
Machine Speed	35	Ppm
Product Weight	200	gr
Extrabag Packaging	30	Second/4 kg
Extrabag Tape	7	Second/4 kg
Machine Output per Hour	4.620	Kg
Manpower Planning	12	people

After the re-mapping process and the proposed addition of conveyors as a tool in the transfer process, and the addition of pallet investment in the warehouse, the classification of activities into two categories, namely external activity and internal activity, will have an impact on managing employee working hours. Below is a remapping process that illustrates future state mapping on Figure 8.

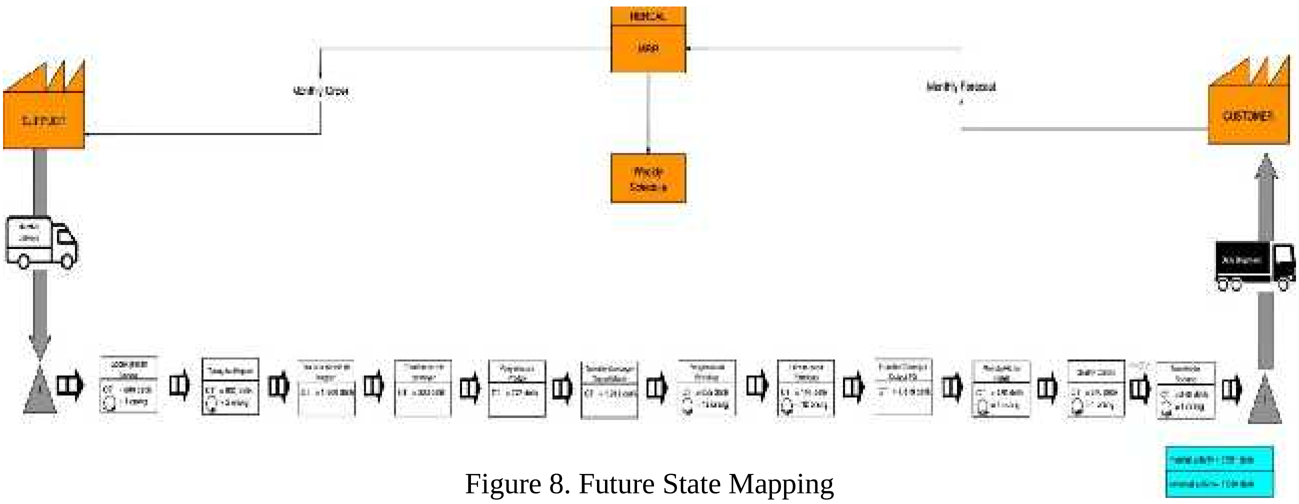

Figure 8. Future State Mapping

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Table 7. Calculation of manpower in the secondary packaging process

Activity	Group Activity	Activity External	Activity Internal	Unit
Tear the sack seam	Manual Raw Material Transfer	600		se
Pour into screw conveyor	Manual Raw Material Transfer	800		se
Transfer screw conveyor to hopper	Manual Raw material	1.800		se
Transfer screw conveyor	Manual Raw material	300		se
Product packaging	Primary Packaging		773	second
Transfer conveyor output machine	Primary Packaging		1.818	second
Extrabag packaging	Secondary packaging	625		second
Tape the extra bag	Secondary packaging	146		second
Transfer the conveyor to the outer pallet	Secondary packaging	1.818		second
Arrange finished goods on a pallet	Secondary packaging	480		second
Quality check (sampling)	Quality Control	240		second
Transfer to the warehouse	Storage of Finished Goods in Warehouse	240		second
		7.049	2.591	second

Based on Table 7, improvements were made to the arrangement of employee working hours based on activity groups from the packaging process depicted in Figure 8 and improvements to the layout in Figure 9.

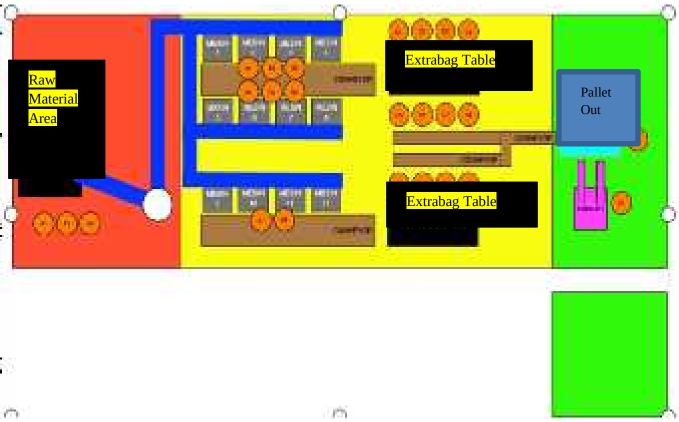

Figure 9. Layout and mapping of workers after improvement

The number of workers in the extrabag packaging process can be adjusted proportionally to the production capacity of the packaging machine. The production flow becomes more efficient and balanced, thus minimizing the waiting time between processes by replacing the forklift position. Potential congestion in the extrabag packaging area can be avoided. Labor productivity can be maximized, with a more targeted division of labor by replacing the forklift and pillet in position (Osho et al., 2024). Furthermore, by optimizing the layout and workflow, the reliance on manual handling and equipment repositioning is reduced. This not only enhances safety in the workplace but also contributes to a smoother and more continuous packaging operation (Attaqwa et al., 2021). The elimination of unnecessary movement and idle time leads to better synchronization between the packaging machine and the extrabag process, ensuring that materials are handled just in time.

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Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-V
PER UNIT TONNAGE	9	1390319	154480	1.90	(
Error	2	162450	81225		
Total	11	1552769			

In the ANOVA results F-Value = 1.90: This indicates the ratio of between-group variation to within-group variation (error) is low. P-Value = 0.392: This is well above the general thresold of significance (0.05), which means there is not enough statistical evidence to suggest that there is a real difference between groups. M Meaning of "Variation Caused by Random Factors or Measurement Error". (Gomaa, 2025). Since there is no significant difference:It is likely that the variation in per unit tonnage between groups is not due to differences in process conditions, equipment, labor, or work methods. Instead, the variation may be due to things such as: Natural fluctuations in the production process (e.g. slightly different raw material conditions). (Allo & Bhaskara, 2022). Measurement or recording errors during data collection. Uncontrolled factors (such as temperature, humidity, shift times, etc.). The sample size is too small, so the statistics are not robust enough to detect real differences. Mismatch of :

a) VSM Method with Real Field ConditionsVSM assumes a fairly stable and measurable process flow. If the production conditions in the field are very volatile or the process is not standardized, then the VSM results are not optimal or do not provide significant insight.

b) b) Resistance to Change Lean implementation usually involves changes in work culture and processes. c) If there is strong resistance from employees or management to change, the improvement process is difficult to run optimally.

d) Limited Scale of Implementation
If Lean and VSM are only applied to a small part of the process without involving the entire value chain, ththe impact can be small and insignificant. Improvements must be comprehensive for the results to be felt.

e)Lack of Training and Capacity Building
The team conducting VSM and Lean implementation needs to have adequate knowledge and skills.
Without sufficient training, the results obtained can be less than optimal.
f) No Follow-up and Monitoring After VSM
Mapping and analysis must be followed by concrete corrective actions and continuous monitoring. If it only stops at the mapping stage without real implementation, then there is no significant change.
g) External Factors and Changing Operational Conditions, Raw material supply disruptions, changes in market demand, or technical machine problems can also make Lean results less significant because these factors are difficult to control.

Contribution to sustainability for that case: Reducing NVA activities means lowering energy, fuel, and labor time consumption, which supports resource efficiency and lowers the carbon footprint of operations. And Appropriate and Efficient Use of Labor The table shows the number of operators per activity, for example: 8 operators (B1-B8) on “Product packaging”, 9 operators (C1-C9) on the activity “Tape on extrabags” This process observation and mapping allows for a more equitable and appropriate redistribution of workload. Improved labor welfare with a more balanced workload. Avoid excess labor, which impacts cost efficiency and long-term operational sustainability.Then, Material Flow Optimization Activities such as: "Transfer to hopper area", "Transfer screw conveyor" , "Transfer to warehouse" are identified as VA or NNVA, meaning they can be reviewed to see if they can be Automated. Simplified with a more efficient layoutBy classifying each activity into categories: Unnecessary activities, Excess transportation, Stacking of goods , Duplication of . operator tasks, Reducing NVA activities means lowering energy, fuel, and labor time consumption, which supports resource efficiency and lowers the carbon footprint of operations. This process observation and mapping allows for a more equitable and appropriate redistribution of workload. Encourages a lean and kaizen culture, which is at the core of operational sustainability. Reduces the risk of long-term waste due to decisions based on observation and analysis.

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Implementation Testing Based on Before & After Changes

A. Comparison of Total Process Time

From the Future State Mapping (Figure 8), we can compare the total time of Internal vs. External Activities:

Activity Type Total Time (seconds) : Internal 2,591, External 7,049 and Total 9,640 seconds. Then, Analysis Internal activities are activities that are actually performed during the main process. External activities are activities that can be performed outside of the core process time. By classifying activities and moving external activities outside of the core process time, total internal time can be minimized, thereby reducing effective lead time.

B. Layout Changes and Worker Mapping (Figure 9)

Previous: Many manual activities & material movement using forklifts After Improvement: Additional conveyors, Elimination of forklifts, Repositioning workers according to machine workload

Then, Implementation Results is Avoiding bottlenecks in the extrabag area, Reduced waiting time between processes, Reduced non-value-added activities (e.g., repetitive manual movements), Labor productivity increased due to clearer and more specific workflows

C. Workforce Planning

From Table 6: Machine output: 4,620 kg/hour, The extrabag process takes a total time (Tape + Packaging) of 37 seconds per 4 kg, Designed human capacity: 12 people → adjusted to accommodate machine output to prevent backlog. In Workforce planning based on actual machine capacity → prevents idle time or overload. Personnel efficiency achieved through a balanced division of labor.

Specifications Before Implementation and After Implementation Total process time: Not directly stated: 9,640 seconds total (with 2,591 seconds internal)

Manual activity: High (manual transfer, forklift) Reduced (conveyor, worker repositioning), Bottleneck: Existing in the extrabag process. Minimized through layout and labor. Human resource efficiency: Not optimal (12 people according to machine capacity). Occupational safety: Not optimal. Improved (minimized manual movement). Waste: High (movement, waiting time). Reduced through elimination of NVA and NNVA.

The solution to improve this research is Add a transfer conveyor from raw materials to the hopper. Manually transporting materials is time-consuming, causing bottlenecks and waste in transportation and waiting. Solution : Install an automatic conveyor with a level sensor to prevent empty or overflowing hoppers. Use a JIT system with small batches to ensure hoppers are always filled on time and reduce overstock (7 wastes: transportation & waiting). Trial the soft-launch conveyor, monitor OEE and cycle time for 2–4 weeks, then adjust the layout if necessary. Many activities are classified as "internal" because tey occur when the line is stopped, increasing downtime.

Solution: Perform Value Stream Mapping to identify internal vs. external activities, such as Move non-packaging activities—such as pallet preparation or material movement—to be performed while the line is running. Train staff cross-functionally to be ready to perform these tasks during non-stop packaging. Re-mapping operators according to workload.

This study describes the implementation of lean manufacturing in a salt packaging industry and derives some proposed improvements as a follow-up to efforts to eliminate process time. Some of the proposed improvements are described as follows:

1. Adding a transfer conveyor from raw materials to the hopper
2. Categorizing activities outside of packaging as external activities
3. Re-mapping operators according to the workload
4. Elimination of activities with a pallet investment
5. Change the number of operators and work schedule with details:

a. Raw material preparation operators: remaining 3 operators with working hours 07.00 - 16.00
b. Packer labor: from 9 people to 12 people with working hours 07.30 - 16.30
c. QC labor remains 1 person with working hours 07.50 - 16.50
d. Fixed forklift operator 1 person with working hours 08.00-17.00
e. Shift the function of the 1 operator from the work of arranging the results from the inner pallet to the outer pallet to the work of arranging the products from the output conveyor to the pallet.
f. Eliminate the function of arranging work in the warehouse with the number of operators, 2 people

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Application of the Analytic Hierarchy Process (AHP) in Strategic Site Selection for Software Development Branch Expansion in Indonesia

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***Abstract*— In an era where digital transformation dictates the survival of technology firms, selecting the optimal branch location is no longer a peripheral decision; it is a strategic imperative. This study offers a powerful yet practical application of the Analytic Hierarchy Process (AHP) to evaluate potential expansion sites for a mid-sized software development company in Indonesia. By integrating expert judgments with location-specific criteria such as talent availability, infrastructure reliability, ecosystem proximity, and cost efficiency, the AHP model provides a structured, transparent, and replicable framework for decision-making. The results clearly identify Location an urban tech hub near major IT universities as the most strategic choice, significantly outperforming other alternatives. More than just a location ranking, this model demonstrates how conventional decision-making in software enterprise expansion can be elevated through applied analytical thinking. The study also proves that even without high-end analytics platforms, decision models built in common tools like Excel can yield robust and scalable insights. These findings carry immediate relevance for technology firms, policy planners, and academic researchers who seek to align operational expansion with long-term innovation and productivity outcomes in knowledge-based industries.**

***Index Terms*— Analytic Hierarchy Process; Branch Location; Software Industry; Strategic Decision-Making**

I. Introduction

The convergence of digital transformation and global software demand has shifted how technology companies structure their growth strategies, particularly in expanding their operational footprint through new development hubs. For software development firms, especially in emerging economies like Indonesia, strategic branch location is no longer a secondary concern. It is a central determinant of project execution speed, developer retention, infrastructure reliability, and overall service quality. (Asawawibul et al., 2025; Mikalef et al., 2019; Pakurár et al., 2019). Unlike traditional industries, where logistics and material flow are central to location strategy, the software industry is governed by subtler variables such as access to digital talent, ecosystem maturity, regulatory certainty, and knowledge spillovers. The increasing reliance on distributed teams, hybrid collaboration models, and infrastructure-as-a-service has not diminished the importance of physical branch placement. Rather, it has complicated it. Locating a development branch in a region with robust digital infrastructure, proximity to universities or incubators, and favorable policy environments can enhance productivity in ways that are not immediately visible on a balance sheet but are eventually reflected in code quality, cycle time, and client satisfaction. These spatial dimensions of digital productivity require a structured approach to decision making that goes beyond intuition or informal benchmarking.

Multi-criteria decision-making (MCDM) tools provide a systematic framework to balance competing location priorities. Among the available methodologies, the Analytic Hierarchy Process (AHP) stands out for its ability to integrate qualitative judgments with quantitative outcomes through a transparent, repeatable mechanism (Dolatabad et al., 2022; Elkady et al., 2024; Pörtner et al., 2025). By translating expert pairwise comparisons into hierarchical weights, AHP facilitates location assessments that are not only consistent but also customizable to a firm's strategic goals. AHP has been applied in various fields, including healthcare, logistics, retail, and

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public planning (Apichonbancha et al., 2024; Duleba, 2020; Szabo et al., 2021). However, within the software development sector, its usage has been sporadic and largely confined to isolated decision problems rather than integrated strategic frameworks. The software characteristics of the software industry, its reliance on human capital, abstraction, and continuous iteration, are rarely reflected in existing AHP models, which often prioritize infrastructure and cost variables more suited to physical industries.

Furthermore, there has been limited exploration of how AHP-based location selection affects downstream productivity outcomes in the software domain. While many studies stop at ranking location alternatives based on static criteria, few attempt to link these choices to operational metrics such as sprint velocity, defect rates, or staff onboarding duration. This disconnect underscores a subtle yet critical limitation in current research, one that calls for contextualized, sector-specific applications of MCDM methodologies. Additionally, although the integration of AHP with Decision Support Systems (DSS) and Geographic Information Systems (GIS) has enhanced visualization and data interaction in other industries (Eldrandaly, 2011; Moradi et al., 2020; Pavani et al., 2024; Qureshi & Ghavami, 2024), such tools remain underutilized in the software industry. Particularly among small and mid-sized technology firms in Indonesia, decision-making processes still rely heavily on personal experience, peer imitation, or opportunistic expansion despite the availability of robust analytical tools.

This study responds to those conditions. It proposes a structured application of the AHP method for evaluating branch location alternatives within a software development firm, using criteria that reflect the unique operational contours of digital production. These include developer density, broadband stability, talent incubation presence, and regulatory ease. The model operates managerial intuition through systematic pairwise evaluation and computes consistency to ensure rational outcomes. While the AHP method itself is well established, this study diverges from conventional use by applying it to a context where location impacts are less visible but no less consequential. Rather than positioning itself as a methodological innovation, this research illustrates how a classical decision framework, when recalibrated to sectoral realities, can generate new value in decision quality and strategic alignment. In doing so, it strengthens the relevance of AHP not by changing its form, but by adjusting its function.

This effort is not only methodological. In a digital economy where talent distribution, infrastructure readiness, and ecosystem maturity vary significantly across regions, location strategy must be handled with the same analytical rigor as product development or financial forecasting. By grounding branch location planning in structured evaluation, this study offers practical utility for decision makers and opens the door for further integration of AHP-based models within digital DSS environments tailored for software firms. In summary, while the tools are not new, their application here is both timely and contextually necessary. The contribution of this work lies in how it reshapes an existing methodology to suit an under-addressed yet strategically vital domain branch expansion in the software development sector. It acknowledges that while software can be built anywhere, it cannot flourish everywhere equally.

II. METHODS

This study employs a structured multi-criteria decision-making approach using the Analytic Hierarchy Process (AHP) to determine the most appropriate location for the expansion of a software development company in Indonesia. Given the complexity of strategic spatial decisions in the digital sector, the AHP method was selected due to its ability to integrate both qualitative expert opinions and quantitative data into a logically consistent decision model. AHP has been widely applied in strategic location planning in various industries, including logistics, healthcare, and digital services, making it particularly relevant for this study.

2.1 Research Design

The research adopts a descriptive-analytical design to evaluate potential branch locations using structured managerial judgment and literature-based criteria. The approach involves identifying decision objectives, selecting relevant criteria and location alternatives, applying the AHP method to assess the importance of each criterion, and synthesizing the results to derive a recommended decision. This process emphasizes decision transparency, replicability, and practical relevance to the strategic context of software enterprise

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expansion.

2.2 Selection of Criteria and Alternatives

Four main criteria were identified for evaluating branch location alternatives:

a) Talent Availability: Refers to the accessibility and quality of human resources, particularly software developers and IT professionals, in the surrounding area.
b) Digital Infrastructure: Includes the reliability and speed of internet connectivity, access to power supply, and supporting digital utilities.
c) Operational Cost: Encompasses rental costs, utility expenses, and general affordability of setting up and maintaining a development office.
d) Innovation Ecosystem Proximity: Describes the level of integration with universities, tech incubators, startups, and government-supported digital initiatives.

These criteria were selected based on both recent academic literature and expert consultation within the company. They reflect the core strategic concerns of digital firms whose productivity depends on talent, technology access, collaboration potential, and cost efficiency.

Three location alternatives were evaluated:

a) Location A: An urban digital hub near two leading universities.
b) Location B: A suburban area with low operating costs but moderate infrastructure.
c) Location C: A creative-tech corridor with active startup communities and average internet quality.

2.3 Data Collection

Primary data were obtained through structured interviews and expert questionnaires administered to five internal decision-makers, including business development managers, project leaders, and the CTO. Participants were selected based on their involvement in strategic decision-making and their familiarity with operational expansion planning. Pairwise comparisons were used to capture the relative importance of each criterion and the preference among the location alternatives. Respondents were asked to compare criteria in pairs (e.g., “Which is more important: talent availability or operational cost?”) and to assess which locations better satisfied specific criteria (e.g., “Which location has better infrastructure?”). The responses were entered into a spreadsheet model developed in Microsoft Excel to ensure accessibility and reproducibility.

2.4 Application of the AHP Method

The AHP implementation consisted of the following steps:

a) Hierarchy Development: A three-tiered hierarchy was created, consisting of the goal (selecting the optimal location), the decision criteria, and the location alternatives.
b) Pairwise Comparison: Each criterion was compared with every other criterion to derive its relative importance. Likewise, each alternative was assessed in relation to each criterion.
c) Weight Calculation: The normalized weights for each criterion and each alternative were derived from the expert input.
d) Consistency Check: A consistency ratio (CR) was computed for each comparison matrix. A CR value below 0.10 was considered acceptable, ensuring that the judgments were logically consistent.
e) Result Synthesis: The final scores for each location were calculated by multiplying the weight of each criterion by the performance score of each alternative and then summing the results.

Excel was selected as the implementation platform due to its widespread use, transparency, and user-friendly nature. This choice also supports future use by the company’s internal teams without requiring specialized software or external consultants.

2.5 Practical Contribution

The methodological choice to apply AHP in this context offers more than theoretical clarity. It equips decision-makers with a structured yet adaptable tool to evaluate strategic alternatives under uncertainty. While the mathematical aspects of AHP are not emphasized in this report, the logic and transparency of the process are preserved, making the model practical for real-world applications. Moreover, this methodology enables the firm to align location selection with broader organizational goals such as increasing developer efficiency, improving collaboration environments, and supporting long-term scalability. The flexibility of the AHP model also allows for

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further integration into decision support systems (DSS) in the future.

III. Results and Discussion

This section presents the results of the AHP analysis conducted to evaluate and prioritize candidate locations for the branch expansion of a software development company. The analysis focuses on four main criteria: proximity to technology hubs (universities), digital infrastructure, cost of operation, and access to innovation ecosystems. These factors were selected based on interviews with stakeholders and aligned with recent findings in location strategy for digital enterprises (Brunetti, 2020; Hwabamungu & Shepherd, 2024; Kraus et al., 2023; Martínez-Peláez et al., 2023; Robertsone & Lapiņa, 2023). The AHP framework yielded a ranking of three location alternatives: Location A (urban tech hub), Location B (suburban business park), and Location C (startup-dense corridor). Pairwise comparison matrices were developed for each criterion and alternative. Experts used a 1–9 scale to assess the importance of each factor relative to the goal. Excel was utilized for calculations to maintain transparency and support reproducibility. After consistency checks, all comparison matrices returned to a Consistency Ratio (CR) below 0.1, indicating logical coherence in expert judgments.

The synthesized priority weights for the decision criteria were as follows:

a) Proximity to Universities and Talent: 0.41
b) Digital Infrastructure: 0.28
c) Operational Cost: 0.19
d) Innovation Ecosystem Access: 0.12

These weights highlight the overriding importance of human capital availability in the context of software productivity, consistent with studies emphasizing developer-centric site strategy. (Abassi et al., 2025; Berman et al., 2024; Chen et al., 2025; Crnogaj & Rus, 2023; Mainardi, 2025; Sharma et al., 2024; Tekman & Ordu, 2025). Location A achieved the highest overall score of 0.698, due to its strong proximity to major IT universities, high-quality broadband infrastructure, and ongoing government-sponsored tech programs. This indicates a favorable environment for talent recruitment and agile development processes, factors critical to maintaining competitiveness in the software industry. Location B followed with a score of 0.213, offering moderate infrastructure and lower cost but weaker access to tech talent. Location C ranked last at 0.089, despite a strong startup culture, due to lower scores in infrastructure and accessibility.

This prioritization supports the idea that while innovation networks matter, proximity to universities and stable digital infrastructure play a more immediate role in enabling scalable, productive operations. Similar conclusions were drawn in other empirical studies on digital service expansion. (Alenezi, 2023; Alghamdi, 2024; Esposito et al., 2025; Shen et al., 2023). The results further validate the AHP method's effectiveness in delivering nuanced, evidence-based decisions without requiring excessive computation or proprietary tools. As the company plans further regional scaling, this model provides a repeatable framework for evaluating future sites across different cities. It also enables firms to simulate "what-if" scenarios—e.g., how would results shift if operational cost becomes more critical than talent access?

From a managerial standpoint, the AHP analysis demonstrates that strategic location decisions should be grounded in structured criteria and consensus-building methods, not merely based on intuition. Additionally, using accessible tools like Excel makes this approach scalable for internal adoption by SMEs and startups that lack advanced decision-support infrastructure. While this study is limited to three alternatives and four criteria, the methodology allows for expansion and refinement. Future applications may incorporate dynamic inputs such as real-time job market analytics or infrastructure evolution forecasts, linking decision-making even more tightly with productivity outcomes and regional development trends.

IV. Conclusion

This study applied the Analytic Hierarchy Process (AHP) to support strategic decision-making in selecting a new branch location for a software development company in Indonesia. Through structured criteria including proximity to talent sources, digital infrastructure, operational costs, and innovation ecosystem access, this research demonstrated the effectiveness of AHP in synthesizing expert judgments into a reliable and replicable decision framework. The findings revealed that Location A emerged as the most favorable option, driven primarily by its strong proximity to top-tier IT universities and robust infrastructure. The quantitative weights assigned

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to each criterion reinforced the argument that talent accessibility and digital readiness significantly outweigh cost considerations in the context of software enterprise productivity. This result is consistent with contemporary trends in digital entrepreneurship and location optimization, where strategic access to human capital and enabling technologies is often prioritized over short-term financial efficiency.

Moreover, the use of a user-friendly tool such as Excel for model implementation validated the approach's accessibility and scalability, particularly for small to medium-sized enterprises (SMEs) operating without advanced analytics infrastructure. The method not only supported a clear decision but also encouraged internal consensus and managerial learning throughout the process. In sum, the application of AHP in this study does more than facilitate a single decision. It lays the foundation for an adaptable, transparent, and resource-efficient model for future location planning. As digital firms navigate an increasingly competitive and dynamic landscape, structured decision tools like AHP will be instrumental in aligning operational expansion with long-term strategic goals.

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Occupational Health and Safety Risk Assessment Application in Oil Refinery Using Hazard Identification, Risk Assessment and Risk Control (HIRARC)

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***Abstract* - This research aims to evaluate occupational safety and health (OHS) risks in the oil refinery unit of PT XYZ using the HIRARC (Hazard Identification, Risk Assessment, and Risk Control) method. This method involves three main stages: hazard identification, risk assessment, and risk control. The research was conducted descriptively and qualitatively through field observations, interviews, and the use of the HIRARC checklist. The identification results show that several work areas, such as the evaporator, separator, and stabilizer, have a Very High risk level due to extreme pressure and temperature, gas leakage, and the potential for explosion and fire. The risk assessment was conducted by considering the likelihood and consequences of each hazard. The risk control strategies analyzed include technical, administrative, and the use of personal protective equipment (PPE). However, most controls are still dominated by administrative approaches, while technical controls such as gas detection systems and shutdown automation have not been implemented optimally. The implementation of HIRARC has proven to be effective in systematically identifying and controlling risks and contributing to a safer, healthier, and more productive work environment in the oil and gas industry.**

***Keywords* – Accident Risk, HIRARC, Occupational safety, Refinery unit**

I. INTRODUCTION

The oil and gas industry is a strategic sector that not only supports the national economy but also holds high potential for workplace hazards (Hidayatullah et al., 2024). Operational activities such as chemical processing, heavy equipment operation, and extreme temperature and pressure control make this sector vulnerable to various types of workplace accidents (Nurjannah et al., 2025). Therefore, the systematic implementation of Occupational Safety and Health (OHS) is an urgent need to ensure the continuity of operations and the protection of the workforce.

PT XYZ is a company whose main task is to process crude oil from drilling into several ready-to-use products. The products produced include residue, diesel, and Pertasol. The crude oil production process in this company involves a heating stage, or what is known as atmospheric distillation. The Crude Distilling Atmospheric Unit (CDU) is one of the main units in crude oil processing at the refinery, which requires in-depth risk analysis due to the potential hazards that exist (Purwanto et al., 2024).

Oil refineries play an important role in supporting national energy security, especially in the midst of increasing fuel demand due to population and economic growth (Rahmansyah & Anggitasari, 2024). However, work in refinery units carries high OHS-related risks, given the complexity of operations involving high-tech equipment, hazardous chemicals, and extreme working conditions (Fadolly, 2021).

Common risks faced in an oil plant work environment include oil and gas leaks that can potentially cause fires, exposure to hazardous chemicals, high temperatures that can trigger burns, and machine noise that threatens workers' hearing health (Willy Afredo & Tarigan, 2021). In addition, high pressure in pipes and tanks is also a source of danger that needs to be mitigated. Such situations require special attention from the Industrial Hygiene unit to recommend corrective actions if hazardous conditions are found. This approach is especially important to avoid ergonomic hazards through effective job or work site design that is appropriate to the physical environment and task characteristics

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(Attaqwa et al., 2021).

Unfortunately, there are still many challenges faced in implementing the OHS system. Low labor awareness of the importance of using personal protective equipment (PPE), lack of continuous OHS training, and weak supervision of equipment maintenance are the main causes of the high number of work accidents in the oil and gas industry (Muhammad & Susilowati, 2021). Evaluation and improvement of the OHS system as a whole is important, and one approach that can be applied effectively is the Hazard Identification, Risk Assessment, and Risk Control (HIRARC) method (Umami et al., 2021).

Several studies on the application of HIRARC have proven effective in various sectors. For example, research conducted by Vikaliana & Melani (2024) shows the effectiveness of HIRARC in oil and gas warehouses in reducing logistics operational risks. Added with research conducted by Dewantari et al. (2022) shows the effectiveness of the HIRARC method in the construction sector, especially in the construction of the Business Center building at University Y. This method is proven to be able to identify potential hazards, assess risk levels, and establish appropriate controls to prevent work accidents (Allo, 2025).

This research aims to apply the HIRARC method to identify potential hazards in the oil and gas company's refinery unit, assess the level of risk of work accidents based on influential factors, and determine effective prevention efforts to minimize these risks. The scope of the research is focused on the work area of the Oil and Gas Company's refinery unit, which is at high risk of mechanical, chemical, and thermal hazards.

The benefits of this research are to provide scientific and practical contributions to the management of OHS in the oil and gas work environment, especially in oil and gas companies. In addition, this research is also expected to be a reference for educational institutions and job training in improving the quality of safety management systems in accordance with industry standards and applicable regulations.

II. THEORY REVIEW

A. *Occupational Safety and Health*

According to Surya & Ririh (2021), Occupational Safety and Health (K3) is an effort to create a work environment that is safe, comfortable, and free from the risk of accidents while working. In general, K3 aims to protect workers from various hazards that can threaten physical, mental, and emotional safety, as well as maintain the security of the company, community, and the surrounding environment. The implementation of OHS is also expected to create a sense of comfort and security for workers in carrying out their duties. Occupational safety and health play an important role in reducing the likelihood of occupational accidents in the workplace. In addition to direct factors such as exposure to physical and chemical hazards, the risk of accidents can also be influenced by operational planning aspects such as unbalanced workload distribution. Research by Pulansari et al. (2020) shows that the imbalance of production trajectories can create *bottlenecks* that have an impact on increasing work pressure at certain points, which in turn can increase the chances of work accident incidents.

B. *OHS Management System*

According to Surya & Ririh (2021) the OHS management system is a process that regulates all matters related to occupational safety and health within the company. The OHS management system acts as a system that manages various aspects of OHS, from planning, division of responsibilities, implementation, to managing the resources needed by the company to carry out occupational safety and health policies. The main objective of the OHS management system is to improve OHS protection in a targeted manner, prevent and reduce the risk of work accidents, and create a safe and comfortable working environment for workers.

C. *HIRARC*

According to Willy Afredo & Tarigan (2021), explains that HIRARC is a method used to minimize or prevent work accidents. HIRARC aims to identify

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hazards that may occur and to avoid work accidents. This method has several stages: the first stage is identifying hazards, the second is risk assessment, and the third is risk control.

D. *Risk Assessment*

According to Willy Afredo & Tarigan (2021), risk is the possibility of loss or even profit as a result of a certain event or action. Risk can be interpreted as a measure of potential hazards that considers how much loss may occur and how much chance the event has, according to the AS/NZS 4360: 2004 standard, risk is defined as the chance of an event that can have an impact, either directly or indirectly, on an object or system. Risk is usually calculated or assessed based on two main components, namely likelihood (the possibility of an event occurring) and consequence the impact or result of the event). The greater the chance of an event occurring and the more severe the impact, the higher the risk. The following description of risk assessment is presented in tabular form.

Table 1 Likelihood Scale

Level	Description	Description
1	Rare	Almost never happens
2	Unlikely	Rarely occurs
3	Possible	May occur occasionally
4	Likely	Frequent occurrence
5	Almost Certain	It may occur at any time

Table 2 Severity Scale

Level	Description	Detail
1	Negligible	No injury, small financial loss
2	Minor	Minor injury, medical treatment, and low financial loss
3	Moderate	Moderate injury, medical treatment required, major financial loss
4	Major	Severe injuries, heavy losses, up to 2 deaths
5	Catastrophic	More than two people died, and the impact was far-reaching, halting all activities.

Table 3
Risk Level Scale

Level of likelihood	Security Level				
	1	2	3	4	5
1	L	L	M	M	H
2	L	L	M	H	H
3	L	M	M	H	VH
4	M	M	H	H	VH
5	M	H	H	VH	VH

Table 4
Risk Level Category

Simbol	Level	Action
L	Low Risk	Monitoring to ensure control measures are working properly
M	Moderate Risk	Requires an assessment to determine if control measures are adequate
H	High Risk	Management's attention is required, and corrective action is required.
VH	Very High	Immediate corrective action is required

III. METHODS

This research uses a qualitative descriptive approach that aims to describe systematically, factually, and accurately the facts that occur in the field related to potential hazards and occupational safety and health risks in the refinery unit. This research also utilizes direct observation methods to obtain data related to hazard identification and occupational risk control, especially in the crude oil processing process. In addition to qualitative data, this research also utilizes quantitative data such as historical accident records and log data from monitoring instruments (e.g., temperature and pressure records). This is to support more objective analysis in the hazard risk assessment process.

Data in this study was collected using three main techniques, namely:

1. Field Observation
   Direct observations were made in various work units within the refinery, such as pumping units, furnaces, separators, and storage tanks, to identify potential hazards and working conditions.
2. Interviews
3. Unstructured interviews were conducted with field supervisors and operators to obtain in-depth information related to work procedures, potential accidents, and preventive measures implemented.
4. HIRARC Checklist
   Used to record potential hazards based on specific work activities and assist in assessing the level of risk based on the parameters of likelihood and consequence.

The data collection stages carried out by the research in the form of a flowchart are as follows:

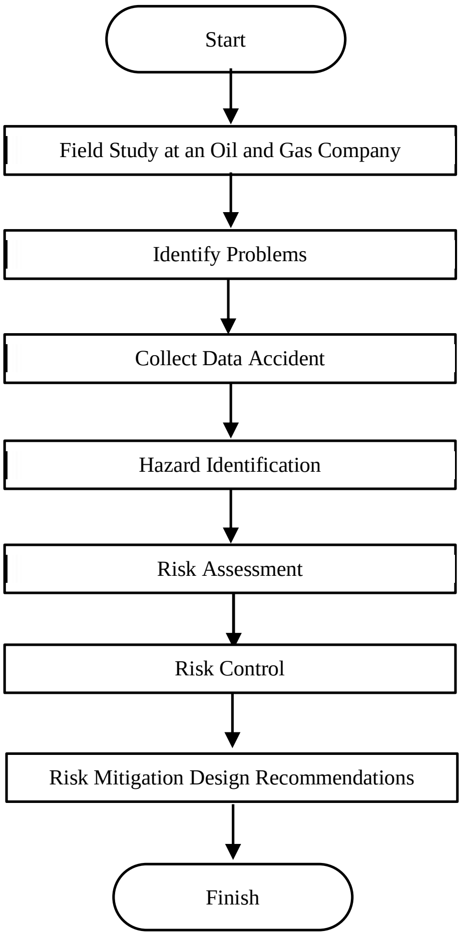

Figure 1: Flowchart of data collection work scheme

The analysis in this study was carried out using the HIRARC (Hazard Identification, Risk Assessment, and Risk Control) method with the following stages:

1. Hazard Identification
   Identify all potential hazards at the worksite based on the work area and activity, such as exposure to high temperature, high pressure, gas leakage, and noise hazards.
2. Risk Assessment
   Each potential hazard that has been identified is then assessed for its risk

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level by considering two main parameters, namely likelihood (the possibility of the event occurring) and consequence (the impact or result of the event).

3. Risk Control
   Determine appropriate control measures based on the level of risk, with reference to the risk control hierarchy, namely: elimination, substitution, engineering control, administrative control, and the use of Personal Protective Equipment (PPE).

IV. RESULT AND DISCUSSION

In the operational process of a company, especially those involving physical activity and the use of work equipment, the risk of work accidents is something that cannot be completely avoided. Based on work accident data for one year, 12 incidents were recorded. Indicating that the work environment still has a high risk to worker safety. This data becomes the basis for evaluating the potential hazards that exist in the work environment and helps companies design more effective preventive measures. The HIRARC (*Hazard identification, risk assessment, and risk control*) method is used in managing the risk of work accidents. The following is a recapitulation of data on work accident incidents in the PT XYZ refinery unit in a one-year period, presented in Table 5.

Table 5 Work accident data

No	Month	Number of Occurrences	Types of Work Accidents	
1	January	1	Scratched right hand while handling hot pipes	Minor Injuries
2	February	1	Eyes are splashed with hot steam during maintenance	Medium Injury
3	March	1	Sprained leg while lifting weights	Minor Injuries
4	April	1	Back bruised from slipping in the tank area	Medium Injury
5	May	1	Exposed to wood chips during welding	Minor Injuries
6	June	1	The hand was crushed in the door of the production area	Medium Injury
7	July	1	Eyes splashed with mild chemicals	Minor Injuries
8	August	1	Falling down the stairs during inspection	Minor Injuries
9	September	1	Scrapes caused by contact with machinery	Minor Injuries
10	October	1	Electrocution during installation or repair	Medium Injury
11	November	1	Hands are crushed by materials when arranging goods	Minor Injuries
12	December	1	Neck hit by iron fragments during pipe repair	Medium Injury

Based on Table 5, a total of 12 work accidents were recorded at the PT XYZ refinery unit over a one-year period, with one incident each month. The second quarter (April–June) showed the highest frequency, accounting for 3 incidents (25%), which may indicate increased operational intensity or maintenance activities during that period. In terms of severity, 7 incidents (58.3%) were classified as minor injuries, such as scratches, mild burns, and chemical splashes, while 5 incidents (41.7%) were categorized as moderate injuries, including electrocution and back bruises.

The most common causes of accidents were contact with hot surfaces or steam (4 cases), exposure to chemicals (2 cases), and slips or mechanical hazards. These patterns highlight the presence of recurring hazards related to thermal and chemical exposure, reinforcing the importance of proactive risk identification and mitigation strategies. The consistency in the type of incidents across different months also suggests potential systemic gaps in safety procedures or protective measures that require further evaluation.

Based on the results of observations and analysis in the field, it shows that the PT XYZ refinery unit has several hazard risks spread across various work areas, such as the pump, stabilizer, and separator units. The hazards found are mostly related to the physical and chemical properties of the materials used and extreme working conditions, such as high pressure and heat. An example in the pump work area with identified hazard sources is leakage, identification of slipping hazards, and environmental pollution. For more details, the hazard risks are presented in the table below.

Table 6 Risk Identification

Work Area	Hazards Source Identification	Hazard Risk Identification
Pump	Leaks	Slipping, environmental pollution
Heat Exchanger	Smoke from the heating process	Exposure to noxious fumes, respiratory distress
	Shell leakage	Pollution
	Heat from the shell	Burns
Stabilizer	High pressure and temperature	Explosion, fire
	Crude oil leak	Fire, explosion, pollution
Furnance	Hot area temperature	Burns
	Noise	Hearing impairment
	Cube leakage	Explosion, fire
Evaporator	Oil/vapor leakage	Fire, explosion, chemical exposure
	High pressure and temperature	Explosion, fire
Condenser	High pressure	Explosion, leakage
Cooler	Coolant/oil leakage	Environmental pollution
	Pipeline pressure and temperature	Explosion, fire, equipment damage
Separator	Pressurized oil and water	Explosion, pollution
	Gas leak	Explosion, fire, gas poisoning

Each identified hazard risk is then assessed using a semi-quantitative approach, where each risk is evaluated based on the *likelihood* and *consequence* values, then classified into risk categories (*risk levels*) such as *Low*, *Moderate*, *High*, and *Very High*. These results form the basis for prioritizing risk mitigation measures to ensure occupational safety and sustainability of the operational environment.

From the results of data processing, it is known that some work areas at PT XYZ, such as Separator, Evaporator, and Stabilizer, have a risk level classified as *Very High* (VH), especially those related to leakage, high pressure, and the potential for explosion and fire. Meanwhile, areas such as the Cooler and Furnace show *Moderate* to *High* risk levels, depending on the identified hazard sources. Table 7 below presents the results of the risk assessment analysis based on the identification of hazard sources, risk types, likelihood of occurrence, impacts, and risk categories in each work area at the industrial facilities studied.

Table 7 Risk Assessment

Work Area	Hazard Source Identification	Hazard Risk Identification	Hazard Identification					
			Possibilities		Impact		Risk	
			Value	Category	Value	Category	Value	Category
Pump	Leaks	Slipping, environmental pollution	4	*Likely*	3	*Major*	12	H
Heat Exchanger	Smoke from the heating process	Exposure to noxious fumes, respiratory distress	3	*Possible*	3	*Moderate*	9	M
	Shell leakage	Pollution	4	*Likely*	3	*Moderate*	12	H
	Heat from the shell	Burns	2	*Unlikely*	2	*Minor*	4	L
Stabilizer	High pressure and temperature	Explosion, fire	3	*Possible*	5	*Catastrophic*	15	VH
	Crude oil leak	Fire, explosion, pollution	4	*Likely*	4	*Major*	16	VH
Furnance	Hot area temperature Kebisingan	Burns	2	*Unlikely*	3	*Moderate*	6	M
	Noise	Hearing impairment	3	*Possible*	2	*Minor*	6	M
	Cube leakage	Explosion, fire	3	*Possible*	4	*Major*	12	H
Evaporator	Oil/vapor leakage	Fire, explosion, chemical exposure	4	*Likely*	5	*Catastrophic*	20	VH
Condenser	High pressure	Explosion, leakage	3	*Possible*	4	*Major*	12	H
Cooler	Coolant/oil	Environmental pollution	4	*Likely*	4	*Major*	16	VH

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	leakage							
	Pipeline pressure and temperature	Explosion, fire, equipment damage	3	*Possible*	4	*Major*	12	H
Separator	Pressurized oil and water	Explosion, pollution	4	*Likely*	5	*Catastrophic*	20	VH
	Gas leak	Explosion, fire, gas poisoning	4	*Likely*	5	*Catastrophic*	20	VH

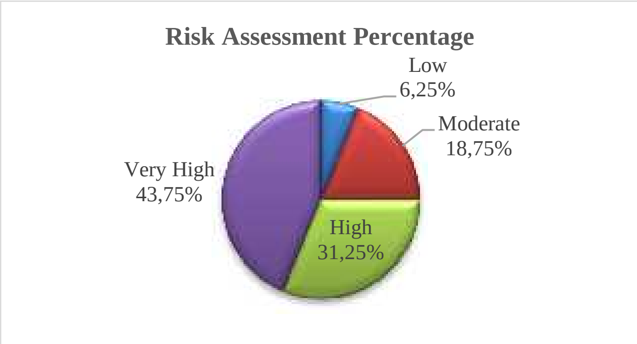

Figure 2: Risk Percentage

Based on the pie chart, it can be seen that most of the risks are in the Very High category (43,75%), followed by High (31.25%), Moderate (18.75%), and Low (6.25%). This information provides an overview of the level of risk faced and can be the basis for determining risk handling priorities.

After identifying and assessing the risks in each work area, the next step is to determine the appropriate form of risk control to minimize potential hazards and their impact on work safety and the environment. Based on field observations and the previous risk analysis, the control strategy focuses on a combination of technical and administrative measures, as well as the use of personal protective equipment (PPE). Although administrative controls such as SOPs, safety training, and PPE usage form an essential part of the risk mitigation strategy, the refinery unit has also implemented a number of engineering and technical controls to directly reduce hazards at the source. These include the installation of automated pressure and temperature alarm systems, routine equipment inspections, and maintenance protocols designed to detect wear and failure risks before incidents occur. Additionally, operational areas are equipped with monitoring instruments that enable early detection of unsafe conditions, particularly in high-risk units like the evaporator and separator. These technical measures demonstrate that the risk control efforts are not limited to procedural compliance but are backed by practical, system-based interventions that improve real-time responsiveness and enhance overall safety integrity.

Therefore, it can be concluded that the approach to risk control in this study adopts a balanced combination of administrative and engineering strategies, aligning with best practices in industrial safety management and fulfilling the multi-layered protection principle in high-hazard environments. Technical controls such as ventilation systems, temperature/pressure alarms, and gas detection equipment are used to prevent hazardous events early on. Meanwhile, administrative controls in the form of periodic inspections, emergency procedures, worker training, and the implementation of SOPs are also an important part of maintaining operational safety.

Some high-risk areas, such as Separator, Evaporator, and Stabilizer, require stricter controls, including the installation of alarm systems, maintenance of piping systems, and complete use of PPE. Areas such as Pumps and Coolers emphasize routine inspections and periodic repairs to prevent leaks and system damage. With proper and consistent control, the level of risk can be minimized so as to support the creation of a safe, healthy, and productive work environment. Several

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technology-based hazard detection systems are relevant for risk assessment in the oil and gas industry. These include Internet of Things (IoT) sensors, which can continuously monitor parameters such as pressure, temperature, and gas concentration in real time; SCADA (Supervisory Control and Data Acquisition) systems, which allow centralized monitoring and automated responses to critical deviations; and predictive maintenance systems, which use data analytics to forecast equipment failure before it happens. These technologies are increasingly applied in high-risk industrial environments to enhance safety and reduce the reliance on manual supervision. Table 8 below presents the risk control efforts organized by source of hazard, type of risk identified, and preventive and mitigating actions that can be taken.

Table 8 Risk Control

Work Area	Hazard Source Identification	Hazard Risk Identification	Risk Control
Pump	Leaks	Slipping, environmental pollution	Routine inspection, periodic maintenance, leak repair, and fire extinguisher
Heat Exchanger	Smoke from the heating process	Exposure to noxious fumes, respiratory distress	Ventilation system, PPE (mask, respirator), closed system maintenance
	Shell leakage	Pollution	Periodic pressure checks, immediate repair of leaks
	Heat from the shell	Burns	Warning signs, PPE (heat-resistant gloves)
Stabilizer	High pressure and temperature	Explosion, fire	Temperature/pressure alarm, emergency procedures
	Crude oil leak	Fire, explosion, pollution	Periodic inspections, operator training on emergency procedures
Furnance	Hot area temperature	Burns	Heat insulation, PPE
	Kebisingan		Use of earplugs/earmuffs
	Noise	Hearing impairment	Regular pressure checks, periodic maintenance
Evaporator	Cube leakage	Explosion, fire	Routine inspection, pipeline maintenance
	Oil/vapor Leakage	Fire, explosion, chemical exposure	Temperature/pressure alarm, emergency procedures
Kondensor	High pressure	Explosion, leakage	Automatic pressure control, maintenance
Cooler	Coolant/oil leakage	Environmental pollution	Regular check-ups, periodic maintenance
	Pipeline pressure and temperature	Explosion, fire, equipment damage	Pressure & temperature monitoring, system alarms, operating SOPs
Separator	Pressurized oil and water	Explosion, pollution	Safety valve, periodic inspection, pipe maintenance
	Gas leak	Explosion, fire, gas poisoning	Leak alarms, complete use of PPE

Based on the results of the HIRARC analysis, it can be concluded that the PT XYZ refinery unit faces significant risks, especially in activities involving high temperature and pressure. As stated by Fadolly (2021), work in the oil refinery sector requires extra attention to OHS due to the complexity of the process and the involvement of hazardous materials.

Awareness of the importance of using PPE and implementing safe work procedures is one important aspect in minimizing the potential for work accidents (Muhammad & Susilowati, 2021). In addition, the use of automatic gas detection devices and emergency shutdown systems is a technical measure that is increasingly needed in dealing with the threat of explosion or leakage.

In addition to the safety aspect, the efficiency of the production process also affects the level of occupational risk in the field. Research conducted by Pulansari & Sulaiman (2020) states that the imbalance of production lines can reduce company efficiency and cause bottlenecks, which in turn increases the potential for work backlogs and accident risks at certain points in the operational process. This shows that efficient work planning not only impacts production output but is also an important factor in creating a safer and more controllable work environment.

This research also shows that the HIRARC method is effective in providing a comprehensive overview of potential hazards, risk assessment, and control solutions in a structured and logical manner. The application of this method not only helps reduce work accidents but also increases workers' awareness of a safe and productive work environment.

From the analysis, the activity in the evaporator area is the activity with the highest

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risk level (risk value = 20, very high category). This risk mainly comes from the possibility of an explosion due to high pressure and open flames. Followed by the separator with the risk of gas leakage, which is also in the very high category. This result is in line with the view of Kurniati & Sulaiman (2023), which emphasizes that a decline in equipment performance due to undetected degradation can increase the risk of extreme damage, so it is important to set a reliability threshold as an indicator of the timing of preventive maintenance.

Evaluation of existing controls shows that most controls are still administrative in nature, and the use of PPE. Meanwhile, engineering and substitution controls have not been fully implemented optimally, especially in terms of equipment modernization, sensor systems, and emergency *shutdown* automation.

V. CONCLUSIONS AND SUGGESTIONS

The application of the *Hazard Identification, Risk Assessment, and Risk Control* (HIRARC) method in the PT XYZ refinery unit shows that the work environment in the oil processing sector has various potential hazards with varying levels of risk. Based on the results of identification and analysis, it was found that the evaporator and separator areas are the areas with the highest risk, each having a *very high* category risk score of 20.

Some of the dominant risk factors include explosions due to high pressure, exposure to extreme temperatures, gas leaks, and chemical vapors. Currently, the risk controls implemented still rely heavily on administrative controls and the use of Personal Protective Equipment (PPE), while controls through engineering and substitution have not been implemented thoroughly.

Overall, the HIRARC method proved effective in identifying potential hazards, assessing risk levels, and designing appropriate control strategies according to the control hierarchy. These results indicate that the HIRARC approach is highly relevant to support the Occupational Health and Safety (OHS) management system in the oil and gas industry.

With further research that is more in-depth and uses varied methods, it is hoped that the OHS system in the oil and gas sector can further develop and be able to create a safe, productive, and sustainable work environment.

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Development Value Stream Mapping to Identify 8 Types of Waste

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***Abstract*—This study proposes an Extended Value Stream Mapping (Extended VSM) framework to address the limitations of traditional VSM in identifying all eight types of waste (Muda), particularly those associated with human factors, environmental conditions, and material movement. While conventional VSM effectively maps value-added and non-value-added activities, it often fails to detect motion waste, transportation inefficiencies, and underutilized human potential. The proposed framework integrates time measurement using Stopwatch Time Study (STS), workflow analysis through the Operation Process Chart (OPC), ergonomic risk evaluation with the Rapid Entire Body Assessment (REBA), mental workload assessment via NASA Task Load Index (NASA-TLX), and environmental condition indicators such as lighting, temperature, and noise. Designed for labor-intensive production systems, EVSM offers a multidimensional mapping tool capable of supporting continuous improvement initiatives. Although this research does not include a real-case implementation, the framework is designed to be practically applicable and empirically validated in future studies.**

***Index Terms*—About; Eight Waste; Lean Manufacturing; Muda Waste; Value Stream Mapping.**

I. INTRODUCTION

Value Stream Mapping (VSM) is one of the main tools in the implementation of lean manufacturing, which serves to map, analyze, and improve the flow of production processes with a focus on value-added activities and the identification of waste (non-value-added) activities. (Rother & Shook, 1999). However, in practice, traditional VSM generally only identifies some types of waste, such as waiting time, overprocessing, and inventory (Roosen & Pons, 2013; Suhardi, Hermas Putri K.S, & Jauhari, 2020). Other wastes such as transportation, motion, and defects, especially those related to operator activities and material movement, are often overlooked because VSM is not designed to capture these aspects in depth. (Carrim & Gupta, 2024; Fatma, Ponda, & Sutisna, 2022) In fact, the eight types of waste known as Muda Waste, namely overproduction, waiting, transportation, overprocessing, inventory, motion, defect, and non-utilized talent, are all interconnected and significantly contribute to the inefficiency of the production system (Liker & Hoseus, 2008; Ohno & Bodek, 1988). Therefore, there is a need to expand the scope of VSM to be able to comprehensively identify all of these types of waste.

In response to these limitations, various developments of VSM have been carried out, such as Ergonomic VSM (Ergo-VSM), which integrates aspects of work posture, physical load, and mental workload into the value stream. (Domínguez, Mendoza, Montoya, Vargas-Bernal, & Jacobo-Galicia, 2023; Jarebrant, Winkel, Johansson Hanse, Mathiassen, & Öjmertz, 2016), as well as Environmental VSM (Environment-VSM), which adds sustainability indicators such as energy consumption and the quality of the work environment (Garza-Reyes, Torres Romero, Govindan, Cherrafi, & Ramanathan, 2018). Nevertheless, both approaches still have limitations, such as Ergo-VSM being qualitative and not fully integrated with work time measurement (Suryoputro, Sari, Burhanudin, & Sugarindra, 2017), while Environment-VSM emphasizes environmental impacts more than pure operational efficiency aspects (Garza-Reyes et al., 2018)

To address these various limitations, several supporting tools can be used to enhance the

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effectiveness of waste mapping. Tools like the Rapid Entire Body Assessment (REBA) are used to assess the risk of work posture quantitatively (Hignett & McAtamney, 2000), the NASA Task Load Index (NASA-TLX) to measure mental workload (Hart & Staveland, 1988), and Stopwatch Time Study (STS) to objectively identify time wastage and overprocessing (Hadad, Keren, & Hanani, 2014). Environmental allowances based on ILO (International Labour Organization) standards are used as a reference in assessing additional working time due to non-ideal working conditions, thus providing a more accurate picture of non-productive activities that arise due to environmental factors (Lukodono & Ulfa, 2018). Considering the limitations of traditional VSM as well as the potential for integration with other methods, the development of an Extended VSM is necessary. The Extended VSM is expected to not only map value streams and waste from an operational perspective but also to integrate aspects of ergonomics, human factors, the work environment, and material movement as important elements in the production system.

II. METHODS

This research method is structured in several stages for developing Extended VSM, which aims to identify the eight types of waste (Muda). The stages begin with a literature study to examine the limitations of traditional VSM, followed by the identification of relevant additional aspects, the selection of appropriate measurement tools, and the design of a visual structure for the Extended VSM based on the integration of operational, ergonomic, and working environment aspects.

A. Determining the Identification of Waste in Extended VSM

Extended VSM was developed with the aim of being able to identify the eight types of waste (Muda) more comprehensively, namely: overproduction, waiting, transportation, overprocessing, inventory, motion, defects, and non-utilized talent. Each waste is indicated by a specific indicator and measurements, thus facilitating the mapping and analysis process. The determination of the type of waste to be mapped is done by referring to the limitations of traditional VSM and the need for cross-aspect integration in the production system (Liker & Hoseus, 2008; Ohno & Bodek, 1988).

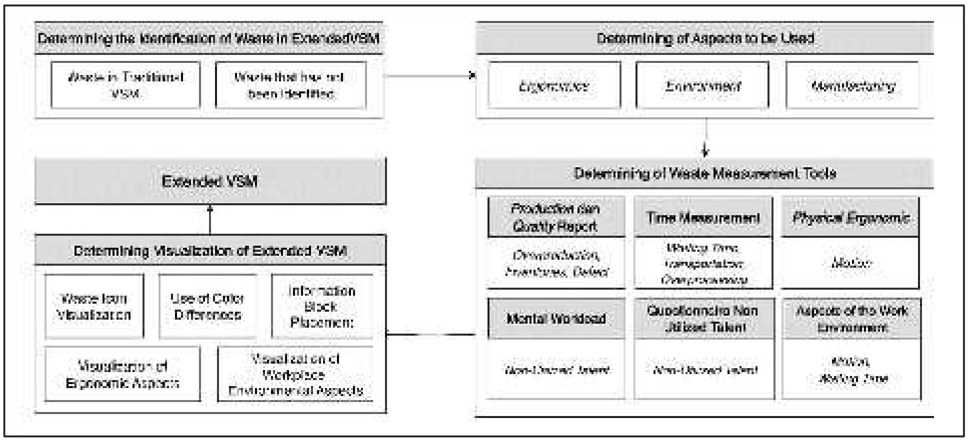

Figure 1: Flowchart of Methodology

B. Determining the Aspect

The aspects involved in the design of Extended VSM include manufacturing aspects adapted from traditional VSM, ergonomic aspects adapted from Ergo-VSM, and environmental aspects adapted from Environment-VSM. These three types of VSM serve as the foundation for determining waste measurement tools, which are derived from the production and quality reports of an industry, observations, and questionnaires. The eight types of waste measured in the development of Extended-VSM include:

1. Manufacturing system metrics derived from production and quality reports are indicators of the existence of waste, such as overproduction, inventories, and defects. Additionally, work time measurements serve

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as indicators of waste from waiting time, transportation, and overprocessing.

2. Ergonomic aspects, consisting of physical ergonomics, mental workload, and non-utilized talent questionnaires, as indicators of waste from motion and non-utilized talent.

Environmental aspects, including noise, temperature, and lighting, are used as considerations.

C. Determining Visualization of Extended VSM

Visualization in the development of Extended VSM is designed to enrich the value stream map display with more comprehensive information. This visualization includes several additional elements, such as waste icons to directly represent types of waste at each activity, as well as the use of symbols and colors to distinguish between categories of activities and their risk levels.

First, special icons are used to represent each of the eight types of Muda Waste, such as symbols for waiting, overprocessing, or motion, which are placed directly on the relevant process flow. This adopts the visual concept of Service-VSM that uses thematic icons to clarify the types of waste (Bonaccorsi, Carmignani, & Zammori, 2011).

Second, visualization is enhanced through the use of colors and symbols that distinguish between value-added activities, non-value-added activities, and activities with high risks. This principle refers to the design of Cost-Based VSM, where variations in the color of lines or arrows illustrate differences in the intensity of activities or cost risks (Gunduz & Fahmi Naser, 2017). Colors are also used to mark processes with high ergonomic risks, exposure to extreme environments, or excessive mental workloads.

Third, ergonomic data is presented in a structured manner within each process block. The physical ergonomic score results will be visualized in the form of work posture risk values, while mental demand will be shown through total mental workload scores. This integration follows the visual structure of Ergo-VSM, which places ergonomic indicators under cycle time information (Jarebrant et al., 2016).

Fourth, the work environment aspects are visualized based on parameters such as temperature, lighting, and noise. These values will be compared with the recommended work allowances by the ILO to indicate whether the conditions may lead to wasted motion due to disruptions in work comfort (Garza-Reyes et al., 2018). Finally, all process data, such as cycle times and activity categories, will be summarized in one information panel for each work process. With this integrated visualization, Extended VSM is expected to provide a comprehensive overview of waste from the perspectives of operations, ergonomics, and the work environment.

III. Result and discussion

The proposed framework of Extended Value Stream Mapping (EVSM) aims to expand the analytical capability of traditional VSM by integrating human factors and ergonomic assessments into the value stream analysis. The following sections outline the design strategy, implementation steps, and visualization components of the proposed framework.

A. Extended Value Stream Mapping Strategy

In the development of Extended Value Stream Mapping (Extended VSM), the design strategy begins with identifying the limitations of conventional Value Stream Mapping (VSM) methods, particularly in detecting non-operational waste such as non-ergonomic work postures, mental workload, and low labor utilization. Extended VSM is designed to address the need for a more comprehensive value stream mapping by integrating measurement elements from physical ergonomics (through REBA), mental workload (through NASA-TLX), and cycle time data (with Stopwatch Time Study). The addition of these aspects allows Extended VSM to not only identify non-value-added activities but also to explain the root causes of waste based on objective data. This strategy aligns with a human-centered lean approach, where the improvement process is not only focused on material and time efficiency but also considers the well-being of workers in the system.

Waste related to defects and overproduction is identified through analysis of production quality reports and output data. Defect waste is quantified by calculating the number and types of rejected, reworked, or failed products recorded over a given period. These quality records are used to trace back defective outputs to specific processes, operators, or environmental conditions. On the other hand, overproduction waste is detected by comparing actual production volumes against customer demand or takt time targets, highlighting

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areas where excessive production occurs due to poor scheduling, large batch sizes, or misaligned production planning. Additionally, inventory waste is identified through process observation and material flow documentation, especially when raw materials, work-in-progress (WIP), or finished goods accumulate without corresponding throughput.

B. Integration of Time Measurement with Stopwatch Time Study (STS)

The initial step begins with the preparation of a value stream map using the traditional VSM approach. At this stage, the flow of materials and information from the beginning to the end of the production process is mapped using standard VSM symbols (Rother & Shook, 1999). The purpose of this mapping is to identify value-added activities (Value Added / VA) and non-value-added activities (Non-Value Added / NVA). The information collected includes cycle time, waiting time, the number of workers, stock quantities, and information flow such as production schedules (Rother & Shook, 1999). Meanwhile, environmental factors contributing to indirect waste, such as high temperature, poor lighting, and excessive noise, are monitored using direct workplace measurements and compared with standard thresholds set by the International Labour Organization (ILO) to evaluate ergonomic environmental conditions.

C. Mapping of Traditional Value Streams

The second stage involves collecting work time data using the Stopwatch Time Study method to accurately determine cycle time, process time, and wait time. The results of this STS are used to measure process efficiency and identify waste types such as waiting, overprocessing, and transportation. STS is considered more accurate compared to subjective estimates because it is based on the actual amount of work activity in the field, including adjustments for allowance factors [23].

To further improve the identification of transportation waste, this research also incorporates the Flow Process Chart (FPC). FPC is used to visually document each step in the workflow, including movements and inspections, enabling the detection of non-value-added transport activities between operations. When used in conjunction with STS, FPC helps pinpoint excessive or unnecessary material and operator movements that contribute to inefficiencies in the production system (Wignjosoebroto, 2008). This integration of STS and FPC strengthens the diagnostic capability of Extended VSM in capturing time-based and movement-related waste more comprehensively.

D. Physical Ergonomic Evaluation with Rapid Entire Body Assessment

To capture the dimensions of waste from the aspect of motion waste and the potential for musculoskeletal disorders, an assessment of work posture was conducted using the Rapid Entire Body Assessment (REBA) method. REBA allows for a quantitative assessment of body positions while working (neck, back, arms, legs) and assigns risk scores to each activity (Hignett & McAtamney, 2000). The integration of REBA in the value stream map provides an overview of which activities pose high risks and have the potential to reduce productivity and increase physical workload (Suryoputro et al., 2017).

E. Measurement of Mental Workload and Workforce Engagement (Non-Utilized Talent)

The measurement of cognitive aspects is carried out using the NASA Task Load Index (NASA-TLX), which assesses six dimensions of mental load, namely mental demand, physical demand, temporal demand, performance, effort, and frustration(Hart & Staveland, 1988). These dimensions describe the extent of the subjective load felt by operators in carrying out their tasks. In addition, a measurement of potential non-utilized talent wastage is conducted through a questionnaire designed to identify whether the ideas, skills, or potential of operators have been utilized optimally.

F. Measurement Extended Value Stream Mapping Visualization Design

The design of Extended Value Stream Mapping (Extended VSM) visualization is an important stage in ensuring readability and effective communication between functions in the production system. A good Extended VSM design must be able to integrate information from various dimensions, including material flow, information flow, processing time, as well as ergonomic and cognitive data, into a single map that is easy to understand and used as a decision-making tool.

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Green	Corrective action is not required.
Yellow	Requires further evaluation.
Red	The evaluation must be conducted immediately.

Figure 2: Visualization of Action Levels with Color

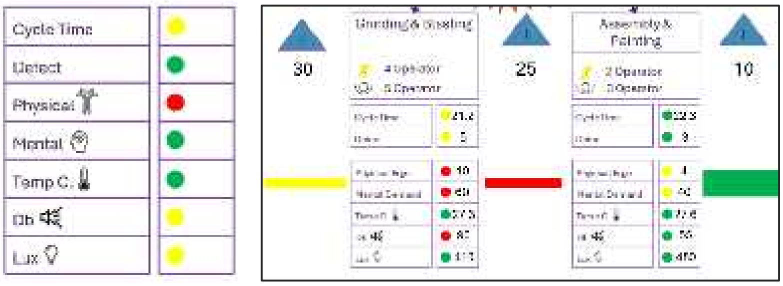

Figure 3: Visualization of Information Block and Material Flow

1. *Integration of VSM Standards Symbols with Additional Indicators and Color*
   Essentially, the main structure of Extended VSM still refers to the standard symbol format of traditional VSM as proposed by Rother & Shook (1999), such as process box, data box, information arrows, and inventory symbols. This aims to maintain readability and visual consistency for lean practitioners who are familiar with conventional value stream maps. The Extended VSM framework leverages color-coded indicators to provide a comprehensive yet accessible map of production processes. However, to reflect the broader dimension of wastefulness, these symbols are enhanced with additional indicators in the form of:
   - The REBA score (Rapid Entire Body Assessment) is displayed in the form of numerical labels under each work activity. This score indicates the level of ergonomic risk from the operator's working posture and is color-coded: green (low risk), yellow (medium), red (high) (Hignett & McAtamney, 2000).
   - The NASA-TLX index is displayed as a mini bar graph below the process information path, reflecting the operator's perception of mental workload (Hart & Staveland, 1988).
   - Special symbols for Non-Utilized Talent, such as a yellow silhouette icon of a person, to indicate work areas with workers' cognitive potential that is not utilized.

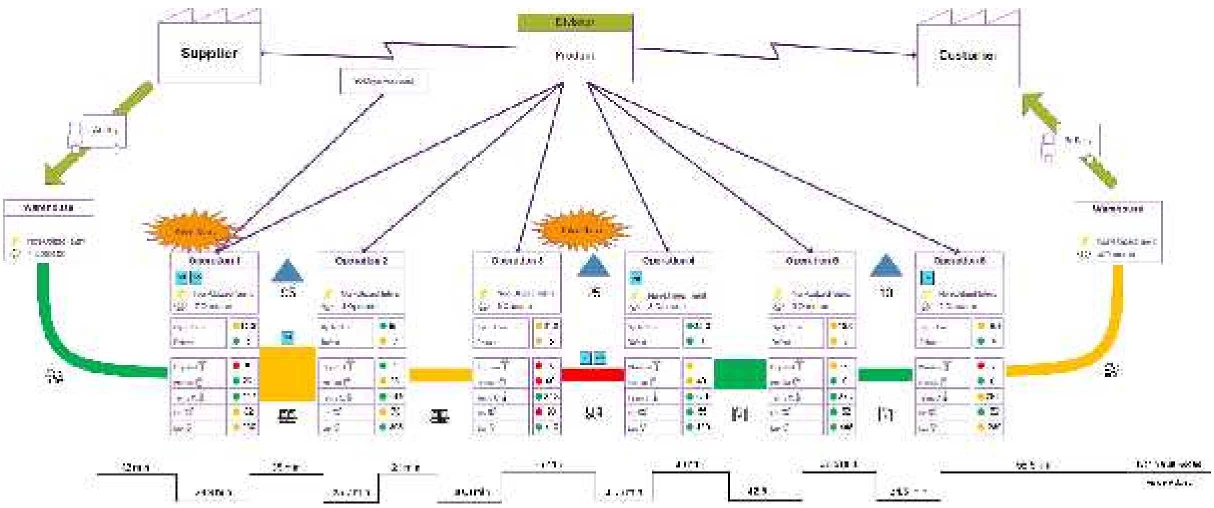

Figure 4: Extended-Value Stream Mapping

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The internal reference to this structure refers to the visualization approach developed by Ergo-VSM (Jarebrant et al., 2016), which adds an ergonomics column below the process data box, as well as E-VSM (Garza-Reyes et al., 2018), which adds a workplace environment layer into the production symbol.

2. *Multilayer Design: Time Flow, Material Flow, and Ergonomic Flow*
   Extended VSM is designed in a multilayer structure as shown by the Sankey-VSM approach (Nuss, Blengini, & Mayer, 2017), where material flow is depicted using thick arrows that indicate the intensity or frequency of movement. Meanwhile, workload and ergonomics data are added as a layer beneath the process box.
   - The flow of time is depicted with a horizontal timeline, maintaining the format of lead time and cycle time.
   - The flow of material is visualized through arrow paths that vary in thickness, indicating the amount or frequency of material movement.
3. *New Symbols and Icons for Human Factor and Environmental Aspects*
   In order to expand the scope of analysis regarding waste in the production system, the Extended VSM visualization design developed in this research integrates additional symbols and icons to represent aspects of human factors and the work environment. To mark activities that have a high level of ergonomic risk based on assessment results using the REBA method, human body posture icons in red or orange are used as visual indicators. This symbol provides early warnings about activities that may lead to musculoskeletal disorders, as well as facilitating the process of identifying work areas that require ergonomic interventions. In addition, a brain-shaped icon or cognition symbol is inserted into the workflow processes that have high scores based on the NASA Task Load Index (NASA-TLX), to indicate excessive mental workload that can disrupt concentration, trigger stress, and reduce operator performance (Hart & Staveland, 1988). The placement of this icon not only provides quantitative information from the psychosocial aspects of work but also encourages data-driven decision-making regarding training needs, job rotation, or task load adjustments. In order to encompass ergonomic aspects of the environment, Extended VSM also includes specific icons such as a sound symbol (for noise), a thermometer (for working temperature), and a light bulb (for lighting), which refer to physical factors in the work environment that can affect operator comfort and productivity (Garza-Reyes et al., 2018).

IV. Conclussion

This study proposed an Extended Value Stream Mapping (Extended VSM) framework that enhances conventional VSM by integrating ergonomic and cognitive assessments, enabling a more comprehensive identification of the eight types of waste in lean manufacturing. Through the incorporation of Stopwatch Time Study (STS), Rapid Entire Body Assessment (REBA), and NASA-TLX, the Extended VSM effectively maps not only operational wastes such as overproduction, waiting, transportation, overprocessing, and inventory, but also human-centered wastes including motion, defects, and non-utilized talent. The visual representation of Extended VSM integrates standard VSM symbols with ergonomic risk scores, mental workload indicators, and intuitive icons, providing a multidimensional diagnostic tool. This approach supports both efficiency improvement and worker well-being, offering significant value for labor-intensive manufacturing environments aiming for sustainable lean transformation.

V. Recommendation

Although the proposed Extended Value Stream Mapping (EVSM) framework successfully integrates time analysis, ergonomic assessments, mental workload evaluation, and environmental condition monitoring to comprehensively identify the eight types of waste, further research and development are recommended to enhance its applicability and effectiveness in industrial settings.

First, the integration of digital tools such as motion tracking sensors, wearable devices, and real-time data acquisition systems could significantly improve the objectivity and

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automation of data collection. Combining Extended VSM with Industry 4.0 technologies may lead to the development of smart VSM systems that allow for continuous monitoring and instant feedback for waste elimination. Second, while this study incorporated human factors and environmental ergonomics, future improvements could include psychosocial aspects of labor, such as motivation, stress levels, and team dynamics, which also influence performance and potential waste. Lastly, it is advisable to develop standardized visual notations for displaying ergonomic and environmental indicators within VSM to support consistency, comprehension, and cross-functional communication across different departments and stakeholders.

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Community Perceptions and Preference on The Condition of Temu Traditional Market Facilities and Infrastructure

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***Abstract*—The market is a place where producers and consumers meet to interact in buying and selling daily necessities. This interaction activity certainly requires adequate support for facilities and infrastructure. The traditional market of Temu Market, located in Sidoarjo Regency, is managed by the government with an operational system by the Sidoarjo Regency Market Service. The purpose of this study was to determine the condition of the facilities and infrastructure of the Temu Traditional Market, to determine the perception and preferences of the community towards the facilities and infrastructure of the traditional market, and the development strategy of the temu Traditional Market based on community perceptions and preferences. The data analysis method used is the analysis of interest performance analysis (IPA). The results of the analysis of the condition of the facilities and infrastructure of the temu Traditional market, out of 13 indicators there are 10 facilities and infrastructure that are appropriate, namely Shops, kiosks, stalls, parking areas, loading and unloading areas, management offices, toilets, places of worship, drainage, trash cans, road access and clean water. The results of the analysis of community perceptions and preferences regarding the Temu Market are the main priorities that need attention: the security post and waste management. The performance that needs to be maintained because it has received good appreciation from the community is the toilet/bathroom, loading and unloading area, management office, and place of worship.**

***Index Terms*—About; Community Participation; Traditional Market; infrastructure.**

I. INTRODUCTION

In global development, the pace of socio-economic conditions of society and changes in the value system have brought about changes. Changes to the pattern of life and the needs of the community. To fulfil the wants and needs of the community, various shopping facilities have emerged. The market is one of the shopping facilities that has been integrated over the years and has a very important place in people's lives to fulfil their needs. For the community, the market is not just a meeting place for sellers and buyers; the market is also a place of social interaction and representation of traditional values. Traditional markets are places where sellers and buyers meet and are characterised by the process of bargaining transactions between sellers and buyers directly. The building usually consists of stalls or outlets, lots, and open ground. In addition to the advantages that traditional markets have, it cannot be denied that, in general, traditional markets also have weaknesses that are now increasingly seen as chaotic (Widyastuty 2012).

Traditional Markets based on the Regulation of the Minister of Home Affairs No.20 of 2012 concerning Regulations and Empowerment of Traditional markets which reads "a place of business that is built, arranged and managed by the Regional Government, Private, State-Owned Enterprises, and Regional-Owned Enterprises, including cooperation with the private sector with business premises in the form of Shops, Stalls, Los, and Tents owned or managed by small, medium, self-help traders or cooperatives with small-scale businesses, small capital and the process of buying and selling merchandise by bargaining (Menteri Dalam Negeri 2012)

The role of the market in an area is influenced by the availability of facilities and infrastructure that drives market activity. The existence of traditional markets, which should be a pillar of people's

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economic development, has been neglected and mismanaged. The management of traditional markets has many problems that give negative perceptions to the community, the main problem is problematic management so that traditional markets cannot run optimally, for example markets that should have funds for market maintenance but the funds are minimal, facilities and infrastructure are lacking, market space is narrow, so many people choose to shop at modern markets.(Rosni, Arif, and Herdi 2017)

Market facilities and infrastructure are all types of equipment, work equipment and facilities that function as the main or auxiliary tools in the implementation as well as in the context of interests that are related to the organisation of work in the market, to increase the development of market activities, therefore facilities and infrastructure are important, because the availability of market facilities and infrastructure can support the economic activities of the community, economic activity will be hampered if market facilities and infrastructure are not adequate.

Facilities and infrastructure must be provided by the government, namely the Market Office, to support the smooth running of activities in a market. According to the Regulation of the Minister of Home Affairs of the Republic of Indonesia (Mendagri RI) No. 20 of 2012 concerning Regulations and Empowerment of Traditional markets that market supporting facilities include: management offices, parking areas, toilets, landfills, drainage, hydrants (firefighting water sources), security posts, places of worship, kiosks, los, loading and unloading areas, and transportation (Menteri Dalam Negeri 2012).

Meanwhile, market infrastructure includes road access, electrical installations, health services, and clean water. In accordance with the regulations of the Minister of Home Affairs, market facilities and infrastructure are important elements in market services to the community. The condition of road access in a good market is a very important capital in serving population mobility and the distribution of goods.

The market in terms of its activities is divided into 2, namely traditional markets and modern markets. The Traditional Market is a place of transaction between sellers and buyers directly. The seller's place is composed of stalls or outlets, lots, and open grounds opened by the seller or the market manager. Markets generally sell daily necessities, such as foodstuffs, vegetables, eggs, meat, traditional snacks, fruit, and religious items. The transaction system used in traditional markets is a bargaining process with direct interaction between sellers and buyers to determine the appropriate price and amount agreed upon. The modern market is a place for transactions between sellers and buyers indirectly. In the modern market, buyers serve their own needs by taking their needs to a place that has been arranged beforehand. Then the price of the goods has also been listed on the label on the shelf / where the goods are placed, and the price is a fixed price, which cannot be negotiated (Legi, Pangemanan, and Waeorundeng 2023)

The market in terms of merchandise is divided into 2, namely the general market and specialised market. General markets are markets that sell or offer more than one type of merchandise. The merchandise offered is covering daily needs, and the special market is a market that sells or offers a kind or some of its merchandise along with its completeness (Alverina 2020)

Markets based on their service radius are divided into 4 service scales, namely City-scale (regional) markets, Sub-city-scale markets, Local-scale markets, and neighbourhood-scale markets. City-scale markets (regional) are markets located in the city centre with a radius of service scope that reaches the entire city area and is located on the city's regional road access. Sub-city markets are markets located in the city centre area and are close to the main road with a service radius of 1600-2000m. Local Market is a market located in the centre of the region with a service area of 500-700 m and population mobility ranging from 40,000-60,000 people. Neighbourhood Market is a market located within the radius of housing or certain neighbourhoods with a service area of 200-400 m.(Manoppo, Timboeleng, and Supardjo 2018).

Some types and functions of space within the market are stalls and los, market office or management office, and public facilities. Kiosks and los are used as a place for trading activities. Kiosks and los are divided into three parts, namely, for wet, semi-wet, and dry shopping. Serves as a place to display and hold merchandise for traders and as a place for transactions between traders and visitors or buyers (Wirasmoyo, Ratriningsih, and Haryanti 2020).

A market office or management office is needed as a place for market management. Serves as a space or container for market managers to accommodate or

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support the performance of market managers (Winda 2014).

Public facilities are available to support market activities. The provision of supporting facilities includes parking spaces, security posts, clinics, toilets, loading and unloading, and warehouses. Serves to support or assist managers, traders, or buyers in carrying out activities in the market (Rasyid 2018).

Prambon Sub-district is one of the sub-districts in Sidoarjo Regency, which has an area of 34.23 km2, with a population of 84,095 people. There is one traditional market to fulfil the daily needs of the community or residents in Prambon Sub-district, namely Temu Market. The market is located in Temu Village, where the market is managed by the government with an operational system by the Sidoarjo Regency market office. Stalls are used with a rental system, where traders pay rent every month to the market office for the traditional market area Temu has an area of around 2,197 m2, with a total of 72 stalls, 32 units of stands/tables, and 19 units of stalls. Some of the existing market facilities include drainage, parking area, toilets, and market infrastructure such as road access, communication, and health services.

This research will analyse the condition of existing facilities and infrastructure based on the Regulation of the Minister of Home Affairs of the Republic of Indonesia No. 20 of 2012, and to find out people's perceptions and preferences for traditional markets. Many factors influence the development and the number of consumers who will visit the market. In research conducted by Maulana dan Saino (Maulana and Saino 2016),

it shows that the factor that most influences purchasing decisions in traditional markets (study on Progo Market, Tropodo Village, Waru-Sidoarjo) is the physiological needs factor consisting of physiological needs, comfort, service quality, product diversity and also the condition and condition of the facilities and infrastructure available relatively affect people's desire to shop.

Based on the problems that exist in the Temu Traditional Market, the research is interested in giving the title ‘Perceptions and Community Preferences for Traditional Market Facilities and Infrastructure Temu Prambon District Sidoarjo Regency’. The study aims to determine the perceptions and preferences of the community towards Traditional Market facilities and infrastructure Temu.

II. RESEARCH METHOD

The method used in this research on Perceptions and Preferences of the community towards the traditional market of Temu Prambon District is to use the evaluative Qualitative Descriptive analysis method and analysis of perceptions and preferences.

Determination of the population in this study is based on the population of the village, which is the location of the Temu traditional market, namely Temu Village, with a population of 3,575 people/person. The sample for this study was 97 respondents who were divided into the community and visitors in the Temu traditional market.

Evaluative Qualitative descriptive analysis is used to determine the existing condition of the facilities and infrastructure of the Traditional Market Temu Prambon sub-district, which includes the physical condition of the building, market support facilities, and market commodities with Permendagri No. 20 of 2021 on Traditional Market Management and Empowerment.

Importance performance analysis is an analysis method that combines aspects of the level of importance and assessment of the quality or condition of an object in a 2-dimensional form. The aspects assessed are aspects of road access, health services, clean water, shops, stalls, los, parking areas, loading and unloading areas, management offices, toilets/bathrooms, worship, security posts, firefighters, drainage, and waste.

The weighting of community perceptions or assessments uses a Likert scale from 1 - 5 (very poor to very good), while the weighting of preferences or interests expected by the community uses a Likert scale of 1 - 5 (very unimportant to very important) (Table 1).

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Table 1. Perception and Preference Weight of Each Attribute

X-axis (Perception)	**Weight**	**Y-axis (Preference)**	**Weight**
Very good	5	Very Important	5
Good	4	Important	4
Fair	3	Average	3
Less	2	Unimportant	2
Very Less	1	Very Unimportant	1

Source: Analysis, 2023

$$\overline{Xi} = \frac{\sum_{i=1}^{k} Xi}{n} \quad (1)$$

$$\overline{\overline{Yi}} = \frac{\sum_{i=1}^{k} \overline{Yi}}{n} \quad (2)$$

Description:
Xi: Weighted average level of assessment of the performance of the i-th attribute.
Yi: Weighted average level of assessment of the importance of the i-th performance attribute.
n: Number of respondents.

The level of these elements will be described and divided into 4 parts in a diagram, as in Figure 1.

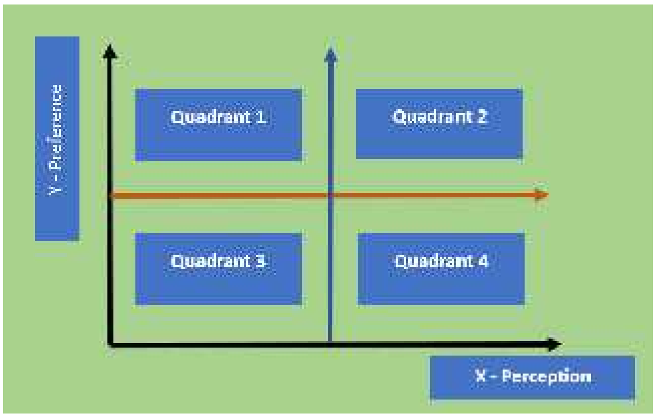

Figure 1. Cartesian Diagram

The explanation of Figure 1 is Quadrant 1 top priority, showing important attributes but low performance; Quadrant 2 priority maintain, showing important attributes and good performance; Quadrant 3 low priority, showing less important attributes and low performance; Quadrant 4 excessive, showing less important attributes but good performance.

III. RESULT AND DISCUSSION

Environmental land use conditions around the research location in Pasar Temu are surrounded by settlements and service trade..

A. Condition of facilities and infrastructure of Temu Traditional Market

Access road is a connection to, from, inside or outside the market building that is provided for all people, including people with disabilities and vehicles. Pasar Temu itself is located on Jalan Raya Temu, so it is easily accessible and reachable by anyone. As for road access in the market or corridor/gangway, which functions as a separator between stalls/clos and as a movement space, it is quite good because the road conditions are paved, so that the impression of a shabby and muddy market is not visible. Number equations consecutively with equation numbers in parentheses flush. First, use the equation editor to create the equation. Use the table format as shown below:

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Health service facilities such as health posts that provide first aid in accidents to cope with emergencies, and disinfectant rooms to clean transport facilities and equipment used for poultry. Existing health services at Temu Traditional Market, such as health posts and disinfecting rooms, are still missing.

Clean water is one type of resource that is usually used by humans for consumption or in carrying out their daily activities, including sanitation. Clean water in the temu traditional market is available on an ongoing basis and a water reservoir has also been provided in the form of a reservoir so that water can flow.

A shop/kiosk is a trading place that has a dividing wall, while a los is a fixed and open trading space that can be equipped with a table. For the traditional market area, Temu has an area of around 2,197 m2, with a total of 72 stalls, 34 units of stands/tables, and 15 units of stalls.

An area that functions as a vehicle facility for visitors, both four-wheeled and two-wheeled. At the traditional market location, Temu already has a parking area located on the north side and east side of the market. In the parking area on the north side of the market, the parking area uses the shoulder of the road, which can cause congestion.

The loading and unloading area are areas that function as a facility that facilitates the supply of logistics to and from the market. In the market, there is already a loading and unloading area located on the east side of the market.

The management office serves as a facility for market management activities. In Temu market, there is already a management office.

Toilets are sanitary places for large and small water disposal. In Temu Market, there are already 3 toilets available, and the condition of the toilets in Temu Market is not clean. The room is used for worship. In Temu market, there is already a mosque which is usually used by visitors or traders to worship. Facilities used by security officers to maintain or secure the market. In Temu market, there is already a security post, but the condition of the post is not feasible, and it also looks dirty.

Fire-fighting facilities include fire extinguishers, hydrants, and PMK wells. In Temu market itself, there is still no firefighting facility. The natural or artificial removal of water from the surface or subsurface of a place. Drainage in the study area is closed and leads to the river to the west of the market. The shape of the drainage in Pasar Temu is rectangular and has dimensions of 40 cm deep and 50 cm wide. Waste bins are a facility needed to accommodate waste so that they do not scatter and do not make the area look slum-like. The waste system in Temu Market is quite good because a place has been provided and the processing system is in place.

The following table analyses the facilities and infrastructure of the traditional market temu sidoarjo (Table 2).

Table 2: Qualitative descriptive analysis of Facilities and Infrastructure Evaluation.

No	Indicators	Permendagri No. 20 of 2021	Existing conditions	Evaluation analysis	Figure
1	Facilities	Shop, Kiosk, Stalls	There are 72 units of kiosks, 34 units of stands/ tables, and 15 units of stalls.	Appropriate	 Fig. 2 Kiosks, stands, and stalls
2		Parking Area	Parking lots in Temu market are available, but not so wide, and you still use the shoulder of the road for parking.	Appropriate	

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No	**Indicators**	**Permendagri No. 20 of 2021**	**Existing conditions**	**Evaluation analysis**	**Figure**
					Fig. 3 Parking area in Temu Market
3		The loading and unloading area	Loading and unloading areas are available, and the conditions are still sufficient with pavement from the ground.	Appropriate	 Fig. 4 The loading and unloading area
4		The management office	There is already a management office located on the west side of the market.	Appropriate	 Fig. 5: The management office
5		Toilets	2 toilets/bathrooms are available for women and men.	Appropriate	 Fig. 6: toilet facilities
6		security post	Not available	Not Appropriate	 Fig. 7 Security post
7		The room used for worship	There is one place of worship, namely, the mosque.	Appropriate	
8		Fire-fighting facility	Not available	Not Appropriate	

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No	Indicators	Permendagri No. 20 of 2021	Existing conditions	Evaluation analysis	Figure
9		Drainage	There is already drainage with a depth of 40 cm and a width of 50 cm.	Appropriate	 Fig. 8 drainage
10		Waste management	There are already provided landfills, and the processing system is burned	Appropriate	 Fig. 9 Waste management
11	Infrastructure	Road Accessibility	Access roads inside and outside the market can be accessed easily and widely.	Appropriate	
12		Health Facilities	Not available	Not Appropriate	
13		Clean water availability	Clean water facilities are in the form of reservoirs.	Appropriate	

Sumber: Analisis 2023

B. erception and Preference Analysis

Perception and preference analysis is an analysis that seeks an assessment and level of importance from visitors according to the number of samples or respondents determined. In this analysis, we also used indicators that determine the assessment of traditional market facilities and infrastructure temu. Through these indicators will assess aspects that have been determined, namely, the management office, parking area, toilets, landfills, drainage, hydrants (fire-fighting water sources), security posts, places of worship, stalls, loading and unloading areas, road access, health services, and clean water.

1. Shops, kiosks/stalls.
   For the results of the analysis of perceptions and preferences of shops, kiosks, stalls seen from 4 aspects (cleanliness, health, comfort, and accessibility), namely, 1.185 for the results of perceptions and 1.854 for the results of preferences. For more details, see Table 3

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Table 3: Perceptions and preferences weights of shops, kosks/stalls.

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	225	Very Important	1.625
Good	228	Important	160
Fair	480	Average	69
Less	252	Unimportant	0
Very Less	0	Very Unimportant	0
Total/Σ Xi	1.185	Total/Σ Yi	1.854

2. Parking Areas
For the results of the analysis of perceptions and preferences of parking areas, seen from 4 aspects (availability, marking, comfort, and accessibility), namely, 1.216 for perceptions results and 1.834 for preferences results. For more details, see Table 4.

Table 4: Perceptions and preferences weights of Parking areas.

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	325	Very Important	1.525
Good	468	Important	240
Fair	312	Average	69
Less	18	Unimportant	0
Very Less	93	Very Unimportant	0
Total/Σ Xi	1.216	Total/Σ Yi	1.834

3. Loading and Unloading area
For the results of the analysis of perceptions and preferences of loading and unloading areas seen from 5 aspects (availability, marking, comfort, accessibility, and cleanliness), namely, 1.508 for perception results and 2.272 for preferences results. For more details, see Table 5.

Table 5: Perceptions and preferences weights of loading and unloading areas.

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	3885	Very Important	1.855
Good	428	Important	312
Fair	558	Average	99
Less	44	Unimportant	6
Very Less	93	Very Unimportant	0
Total/Σ Xi	1.508	Total/Σ Yi	2.272

4. Office management
For the results of the analysis of perceptions and preferences of the management office seen from 5 aspects (availability, marking, comfort, accessibility, and cleanliness), namely, 1.818 for the results of perceptions and 2.267 for the results of preferences. For more details, see Table 6.

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Table 6: Perceptions and preferences weights of office management

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	465	Very Important	1.825
Good	744	Important	328
Fair	597	Average	114
Less	10	Unimportant	0
Very Less	2	Very Unimportant	0
Total/Σ Xi	1.818	Total/Σ Yi	2.267

5. Toilet/bathrooms
   For the results of the analysis of perceptions and preferences of the toilet/bathroom seen from 5 aspects (availability, lighting, comfort, safety, and cleanliness), namely, 1.514 for perceptions results and 2.336 for preferences results. For more details, see Table 7

Table 7: Perceptions and preferences weights of toilets/bathrooms

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	25	Very Important	2.085
Good	468	Important	188
Fair	891	Average	63
Less	128	Unimportant	0
Very Less	2	Very Unimportant	0
Total/Σ Xi	1.514	Total/Σ Yi	2.336

6. Worship
   For the results of the analysis of perceptions and preferences of places of worship seen from 5 aspects (availability, lighting, comfort, security, and cleanliness), namely, 1.837 for the results of perceptions and 2.254 for the results of preferences. For more details, see Table 8.

Table 8: Perceptions and preferences weights of worship facilities

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	20	Very Important	1.730
Good	728	Important	440
Fair	873	Average	84
Less	16	Unimportant	0
Very Less	0	Very Unimportant	0
Total/Σ Xi	1.637	Total/Σ Yi	2.254

7. Security posts.
   For the results of the analysis of perceptions and preferences of security posts seen from 5 aspects (availability, lighting, comfort, security, and cleanliness), namely, 485 for the results of perceptions and 2.425 for the results of preferences. For more details, see Table 9.

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Table 9: Perceptions and preferences weights of security posts

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	0	Very Important	2.425
Good	0	Important	0
Fair	0	Average	0
Less	0	Unimportant	0
Very Less	485	Very Unimportant	0
Total/Σ Xi	485	Total/Σ Yi	2.425

8. Fire-fighters
   For the results of the analysis of perceptions and preferences of fire-fighters seen from 3 aspects (fire extinguishers, hydrants, firefighters), namely, 291 for perception results and 1.455 for preferences results. For more details, see Table 10.

Table 10: Perceptions and preferences weights of fire-fighters

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	0	Very Important	1.455
Good	0	Important	0
Fair	0	Average	0
Less	0	Unimportant	0
Very Less	291	Very Unimportant	0
Total/Σ Xi		Total/Σ Yi	1.455

9. Drainase
   For the results of the analysis of perceptions and preferences for drainage seen from 4 aspects (availability, slope, no buildings on it, and cleanliness), namely, 1.347 for the results of perceptions and 1.851 for the results of preferences. For more details, see Table 11.

Table 11: Perceptions and preferences weights of Drainage

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	280	Very Important	1.630
Good	248	Important	140
Fair	687	Average	81
Less	32	Unimportant	0
Very Less	0	Very Unimportant	0
Total/Σ Xi	1.347	Total/Σ Yi	1.851

10. Waste management
    For the results of the perception and preferences analysis of solid waste seen from 4 aspects (availability, transport equipment, temporary waste disposal sites, and waste management), namely, 966 for perception results and 1920 for preferences results. For more details, see Table 12.

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Table 12: Perceptions and preferences of waste management

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	0	Very Important	1.865
Good	148	Important	40
Fair	609	Average	15
Less	122	Unimportant	0
Very Less	87	Very Unimportant	0
Total/Σ Xi	966	Total/Σ Yi	1.920

11. Road Access
    For the results of the analysis of perceptions and preferences for road access seen from 3 aspects (cleanliness, corridor/gangway, and accessibility), namely, 1.064 for the results of perceptions and 1.268 for the results of preferences. For more details, see Table 13.

Table 13: Perceptions and preferences weights of road access

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	195	Very Important	760
Good	468	Important	364
Fair	393	Average	144
Less	8	Unimportant	0
Very Less	0	Very Unimportant	0
Total/Σ Xi	1.064	Total/Σ Yi	1.268

12. Health services.
    For the results of the analysis of perceptions and preferences for health services seen from 3 aspects (health posts, disinfectant rooms, and first aid in accidents), namely, 291 for the results of perception and 1.455 for the results of preferences. For more details, see Table 14.

Table 14: Perceptions and preferences weights of Health services

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	0	Very Important	1.455
Good	0	Important	0
Fair	0	Average	0
Less	0	Unimportant	0
Very Less	291	Very Unimportant	0
Total/Σ Xi	291	Total/Σ Yi	1.455

13. Clean water/sanitation
    For the results of the analysis of perception and preference for clean water/sanitation seen for 3 aspects (availability, reservoirs, and water quality), namely 1056 for perception results and 1426 for preference results. For more details, see Table 15.

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Table 15: Perceptions and preferences weights of clean water/sanitation

X-axis (Perception)	Total Value	Y-axis (preference)	Total Value
Very good	20	Very Important	1.315
Good	700	Important	108
Fair	336	Average	3
Less	0	Unimportant	0
Very Less	0	Very Unimportant	0
Total/Σ Xi	1.056	Total/Σ Yi	1.426

This gap analysis by calculating the average level of performance/perceptions and level of importance/preferences for all attributes will be further described in Table 16.

Table 16: The Gap Analysis

No	Attributes	$\overline{X}$	$\overline{Y}$
1	Shops, Kiosks, stalls	12,21	19,11
2	Parking Areas	12,53	18,90
3	Loading and Unloading Areas	15.54	23,43
4	Management office	18,40	23,30
5	Toilet/bathrooms	15,60	24,08
6	Worship	16,87	23,23
7	Security posts	5,00	25,00
8	Fire-fighters	3,00	15,00
9	Drainage	13,88	19,08
10	Waste management	9,96	19,79
11	Road Access	10,97	13,07
12	Health services	3,00	15,00
13	Clean water / Sanitation	10,88	14,70
	Total	147,84	253,69
	$\overline{X}$ and $\overline{Y}$	11,37	19,51

Based on table 16, it explains that the results of the calculation of the gap analysis on all attributes obtained the value of $\overline{X}$ is 11,37, while the value of $\overline{Y}$ is 19,51.

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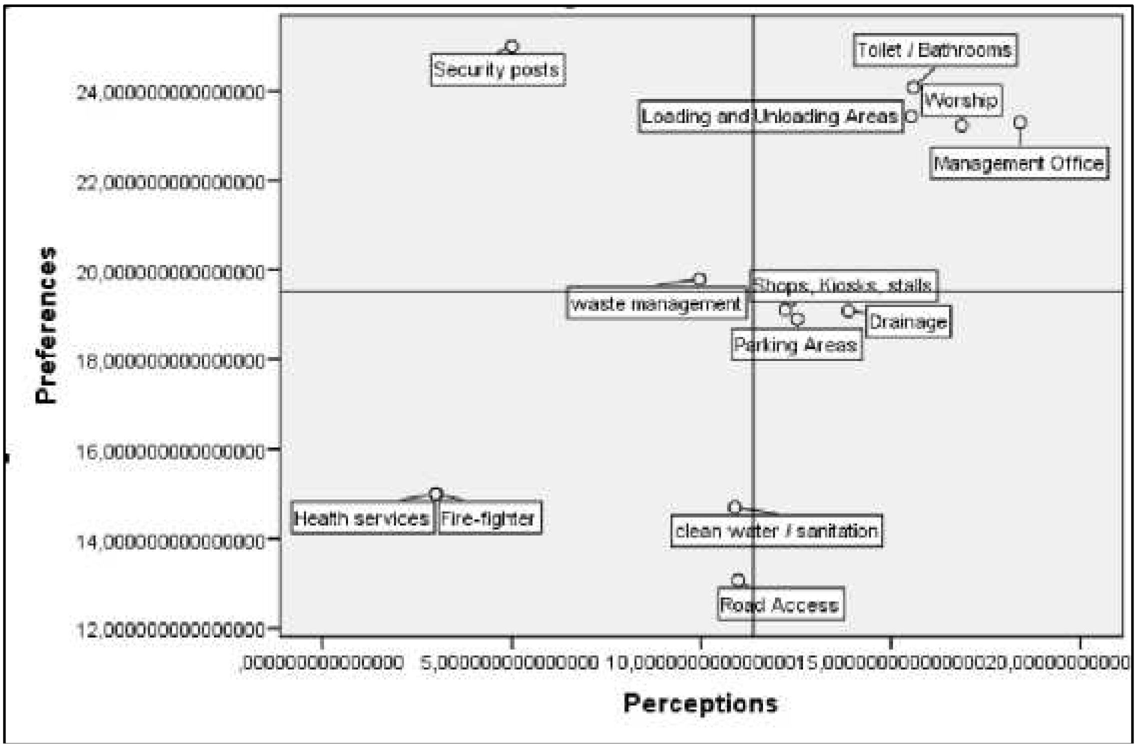

Fig. 10 Cartesian diagram of perceptions and preferences

Two indicators are included in quadrant I, namely, security posts and waste. Quadrant I is located on the top left. This quadrant contains indicators that are considered important by the community, but in reality, these indicators are not as expected. Thus, security posts and waste are prioritised for development so that what is expected is realized.

Four indicators are included in quadrant II, namely, toilets/bathrooms, loading and unloading areas, management offices, and places of worship. Quadrant II is located on the top right. According to people's perceptions and preferences, it is good and has met the needs, so it only needs to be maintained by caring, so that quality is maintained.

Four indicators included in quadrant III are health services, firefighting, clean water, and road access. According to the perceptions and preferences of the community, it is considered less important, and the service is not too special, but it is felt that there is a need for the development of these facilities.

Three indicators included in quadrant IV, namely, shops, kiosks, los, drainage, and parking areas. According to people's perceptions and preferences, these facilities are excessive, so they are sufficient.

IV. CONCLUSION

Existing conditions of Temu traditional market facilities and inftrastructure, from 13 indicators there are 10 facilities and infrastructure that are in accordance with the regulation of the Minister of Home Affairs no. 20 of 2012 concerning Management and Empowerment of Traditional Markets, namely Shops, stalls, lots, parking areas, loading and unloading areas, management office, toilets/bathrooms. Places of worship, Drainage, waste management, access roads, and clean water/sanitation. While there are three facilities and infrastructure that are not suitable, namely security posts, fire-fighters, and health services.

The results of the analysis of community perceptions and preferences regarding the Temu Market are the main priorities that need attention: the security post and waste management. The performance that needs to be maintained because it has received good appreciation from the community is the toilet/bathroom, loading and unloading area, management office, and place of worship.

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Development of a Framework for Lean Education Implementation in Vocational High Schools

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Abstract— ***Lean, which aims to eliminate waste, has been applied to manufacturing and non-manufacturing operations. Some studies reported that lean applications improve operations in universities and high schools. This study aims to develop a framework for implementing Lean Education for vocational high schools (SMK). This research is motivated by various forms of waste in SMK operations, such as long waiting times. A combination of an exploratory qualitative approach, literature review, and expert validation is utilized to construct a context-specific framework. The proposed framework consists of three main stages: pre-implementation, implementation, and post-implementation, each comprising key activities such as waste identification, staff training, process mapping, lean strategy execution, and continuous improvement. This framework is expected to support SMK in minimizing waste and aligning vocational education more closely with industry needs, thereby enhancing the quality of its graduates.***

Index Terms—About; **Lean Education, vocational schools, waste reduction, practical learning, implementation framework**

I. Introduction

Vocational High Schools (SMK) are formal educational institutions that strategically prepare graduates to be competent and ready to enter the workforce according to industry needs. However, in practice, vocational learning at SMKs, particularly in hands-on activities like using lathe machines, often encounter various forms of waste that negatively affect the effectiveness and efficiency of the teaching and learning process. Types of waste commonly found in SMKs include long waiting times due to limited access to practical equipment (waiting), excessive use of practice materials (excess inventory), work results that do not meet industrial specifications (defects), and time lost during equipment setup processes (setup time). These issues hinder students from achieving the required competencies, increasing teachers' workloads, and creating a disconnect between the educational process and industry demands. The concept of Lean Thinking, which originated in the manufacturing sector, has been widely adopted in various service sectors, including education. Lean Education aims to identify and eliminate non-value-added activities in educational processes to create a more efficient and sustainable learning system [6]. However, most lean applications in education have focused on higher education and general senior high schools, while implementation at the vocational high school level—especially in hands-on vocational training—remains very limited. Several previous studies have proposed frameworks for implementing lean education, such as the dynamic model by Anvari et al (2011), the application of lean principles in business schools by Emiliani (2004), and the integration of Value Stream Mapping (VSM) in educational laboratories by Manos & Almeida (2024). Nevertheless, no framework has been specifically designed and validated for the context of secondary-level vocational education, such as SMKs in Indonesia. Based on this background, this study aims to develop a framework for implementing lean education that can help SMKs design and manage practical learning activities more efficiently and effectively. By integrating findings from literature reviews and validation by vocational education experts, this framework is expected to serve as a

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practical reference for schools to minimize waste and improve the quality of vocational education delivery.

II. LITERATURE REVIEW

Waste is any activity, process, or resource that fails to contribute value to a production system and should therefore be minimized or eliminated [9]. Research by Mulyana et al (2022) proposes 8 waste categories of 46 waste in the Higher Education setting (Table 1).

Table 1 Waste in Higher Education Institution [9]

No.	Category of Waste	Form of Waste in Higher Education Institution
1	Defects	The lecturer failed to find the document. Going to the wrong classroom. The lecturer did not inform of the absence/cancellation of the class on the due class schedule. Lecturers change the lecture schedule. Lecturers make mistakes when inputting grades in the academic information system. The lecturer re-examines students. The lecturer encountered inaccessible documents. The lecturer has encountered teaching material media that cannot be opened. Human error in typing Lecturers have made mistakes in typing learning preparation and teaching materials. The lecturer found the projector connecting cable unusable. Lecturers have experienced a shortage of exam scripts.
2	Overproduction	Lecturers print documents/exam questions/journals/handouts in excess. The teaching load every semester is excessive. Lecturers add lecture hours outside the predetermined schedule. There is excessive dissemination of information/announcements. There are too many lecturers in the department. Lecturers do administrative tasks outside of working hours
3	Waiting	Lecturers reply to messages/questions from students for quite a long time. The delay of the lecturer in collecting reports from a predetermined time. Lecturer delay in attending meetings. Lecturers wait for class when the class to change. Repair of campus facilities has taken a long time. The lecturer is waiting for the meeting to determine the results of the teaching task. Lecturers wait for students to attend lectures. The lecturer waits for students to collect answers to the exam. Students are late in submitting assignments.
4	Non-Utilized Talent	Lecturers get jobs/assignments that are not in accordance with their scientific field. Lecturers do not conduct research every semester. Lecturers do not do community service every semester.
5	Transportation	Lecturers make mistakes in sending documents/files between work units.
6	Inventory	The lecturer keeps the email on the draft. The lecturer keeps the previous year's exam questions.

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6	Inventory	Lecturers keep a large number of documents (for example: teaching materials/handouts/exam questions/journals). Lecturers keep large amounts of Office Stationery. Class facilities that are owned are not used during operating hours.
7	Motion	The distance between the classroom and the office/work space is quite far. The lecturer workspace is always in an untidy condition. Lecturers look for documents/files/journals for a long time.
8	Extra Processing	Lecturers input student scores more than once in different systems. Receiving information through more than one information channel (WhatsApp, email, hard copy, etc.). The posting of the same information/announcement repeatedly. The lecturer checks/corrects the same files (exam answers, theses, correspondence, etc.) repeatedly. The lecturer checks the teaching material repeatedly. The lecturer teaches the same material over and over. Lecturers attend/make meetings repeatedly with the same discussion.

A summary of literature review of various studies on lean education can be seen in Table 2.

Table 2 Studies on Lean Education Implementation

Author	**Journal Title**	**Tools**	**Research Object**	**Lean Implementation Framework**
[8]	Towards Lean Teaching: Non-Value-Added Issues in Education	Lean Thinking, Value Stream Mapping (VSM), Lean Tools	Leaning Education at University Level	Planning, Implementation, Evaluation, Follow-up
[4]	Lean Education Analysis to Minimize Waste in High School Chemistry Learning	VSM, Failure Mode and Effects Analysis (FMEA), Fishbone Diagram	Leaning Education in Chemistry Learning at High School	Problem identification (Define), Mapping current state using VSM, collecting data and calculating lead time and cycle time (Measure), Waste analysis (Analyze), Designing Future State VSM (Improve), Monitoring implementation results (Control)
[11]	Improving Teaching and Learning Process by Applying Lean Thinking	Lean Thinking, 5S Methodology, Visual Management	Lean Education in Engineering Laboratory at the University of Novi Sad, Serbia	Identification of value-added and non-value-added activities, Current state mapping using VSM, Waste identification and

Author	**Journal Title**	**Tools**	**Research Object**	**Lean Implementation Framework**
				analysis, Designing Future State VSM, Evaluation
[10]	The Application of Lean Management Method in Optimizing Administrative Efficiency in Schools	Lean Management (5S, VSM, Kaizen)	Lean Management in School of Administration in Indonesia	Identification of administrative processes, Current process mapping using VSM, Waste identification, Root cause analysis, designing improvement proposals, Change implementation, Evaluation, and continuous improvement (Kaizen)
[5]	Improving Business School Course by Applying Lean Principles and Practices	Lean Principles (VSM, Kaizen, Voice of Customer, PDCA, Customer Value Model)	Lean Education in Business Schools	Waste identification, VSM implementation, Continuous improvement through PDCA, Monitoring and evaluation of student satisfaction
[7]	Quality Assessment of Laboratory Activities in Professional Education Institutions Based on Lean Thinking	Learn Thinking (VSM, KPI)	Lean Education in Laboratory of Educational Institutions	Planning and formation of functional teams, Process mapping using VSM, Implementation of improvement strategies, Lean culture adoption
[2]	A Proposed Dynamic Model for a Lean Roadmap	Lean (VSM, PDCA, Lean Self-Assessment Tool)	Lean Framework in Manufacturing Industry	Preparation, Design, Implementation
[6]	A New Method in Education: Lean	Lean Education (VSM, 5S, Kaizen, Root Cause Analysis, Visual Management)	Lean Education in Technical Higher Education in Ghana	Value identification, VSM mapping, Creating flow, Student needs analysis, Continuous improvement (Kaizen)
[3]	Service Value Stream Management (SVSM)	Lean Service (VSM, Lean Principles)	Lean Service in Public Service	Service process identification, Current state mapping (SVSM), Waste analysis, Future state design,

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Author	Journal Title	Tools	Research Object	Lean Implementation Framework
			Organizations in Sweden	Improvement implementation (Kaizen), Monitoring and evaluation, Standardization and dissemination

III. RESEARCH METHODOLOGY

This study employs a qualitative exploratory method by reviewing previous research literature to identify lean implementation frameworks that can be adapted to lean education. The lean education framework is developed based on a comprehensive review of relevant literature and supported by the results of interviews and Focus Group Discussions (FGDs) with experts in the field. Once the proposed framework is constructed, it is subsequently validated by experts to ensure its relevance and applicability within the context of vocational education.

IV. RESULT AND DISCUSSION

A Lean Framework typically serves as a roadmap, guiding organizations on how to implement lean manufacturing by outlining the sequence of lean tools to be introduced within the organization [1]. The following are several lean frameworks from previous studies that have been adapted to the field of education:

1. [2] This study proposed a generic framework for applying lean in education that can adapt to different vocational high school settings. The framework consists of three main stages:

   a. **Preparation Stage** – Includes strategic planning, forming an implementation team, and providing lean training.
   b. **Design Stage** – Involves mapping using *Value Stream Mapping (VSM)*, conducting business analysis, and planning for change.
   c. **Implementation Stage** – Includes pilot projects, evaluating results, and expanding lean implementation throughout the system.

2. [5] proposed a lean framework by integrating Value Stream Mapping (VSM) as a lean management tool to analyze and improve the flow of materials and information in laboratory learning processes. The stages of this framework are as follows:

- Step 1: Planning and Cross-Functional Team Formation – Establishing a team consisting of educators, administrators, and quality assurance experts.
- Step 2: Value Stream Mapping (VSM) – Mapping the current state, identifying inefficiencies, and designing a more optimal future state.
- Step 3: Improvement Strategy Implementation – Identifying improvement opportunities, developing an action plan, implementing changes, and monitoring the results.
- Step 4: Lean Culture Adoption – Embedding a culture of continuous improvement within the institution.

The results of this study show that the model is capable of identifying waste in laboratory activities, improving efficiency, and assisting institutions in enhancing student learning outcomes.

3. [7] proposed a framework for applying Lean Principles and Practices to improve the quality of courses in business schools. The proposed framework includes:
   a. Identifying waste in teaching, such as ineffective teaching methods, redundant content, and inadequate assessments.
   b. Applying the Value Stream Mapping (VSM) concept to analyze and improve the efficiency of the learning process.
   c. Continuous improvement through the PDCA (Plan-Do-Check-Act) cycle.

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d. Focusing on student satisfaction as the primary customer by redesigning the curriculum and teaching methods to respond more to their needs.

Based on the results of the literature review, the main stages of lean implementation across various fields can be categorized into pre-implementation, implementation, and post-implementation phases. The following stages of lean framework development, as can be seen in Table 4 are validated by experts, are adopted from previous studies:

Table 4 Framework of Lean Education Stages in Vocational High School (SMK) Learning

Step	Details Steps	Reference
Pre Implementasi	Identifying problems or waste	[2], [6]
	Staff training and lean introduction	[3], [5]
	Initial process mapping	[2], [7]
	User needs analysis	[2], [5]
	Formation of lean improvement team	[5], [6]
Implementasi	Executing process mapping results in identifying and eliminate waste	[2], [3]
	Solution development	[2], [6]
	Use of lean tools	[5], [6]
	Active stakeholder involvement	[5], [7]
	Pilot Project	[6], [7]
Post Implementasi	Evaluation of implementation results	[6], [7]
	Continuous Improvement	[2], [5]
	Documentation of results and dissemination of best practices	[5], [7]
	Strategy adjustments	[5]
	Model replication to other programs or units	[5]

V. CONCLUSION

This study has produced an implementation framework for lean education specifically designed for practical learning activities in Vocational High Schools (SMK). The framework consists of three main stages—pre-implementation, implementation, and post-implementation—each comprising sub-stages such as waste identification, staff training, initial process mapping, lean strategy execution, and continuous evaluation and improvement. The framework was developed through an in-depth literature review and validated by experts in vocational education and lean methodology. The results of this study are expected to provide a tangible contribution to improving the efficiency and effectiveness of practical learning in SMKs, and to serve as a strategic reference for schools in reducing waste commonly found in the learning process. Furthermore, this framework can serve as a starting point for the development of a more industry-responsive vocational education system. A suggestion for future research is to conduct empirical testing of this framework across various vocational high schools (SMKs) with different characteristics, and to integrate a quantitative approach to measure the effectiveness of the framework's implementation more objectively and measurably.

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Applying Production Capacity Planning Analysis to Enhance Operational Efficiency in the Garment Industry

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***Abstract*—Rira Clothing Convection is a business engaged in the convection of Muslim clothes for girls. The demand to continually adjust to the development of fashion trends regularly demonstrates the company's awareness of the importance of adapting to an ever-changing market. The existence of these fluctuations certainly affects the production process, which includes the target number of clothes that must be produced, the determination of the number and schedule for ordering raw materials, the production process time, the number of machines needed, and others. The purpose of this study is to minimize the cost of raw material inventory with the Material Requirement Planning (MRP) Method and plan the optimal production capacity so that production runs effectively and efficiently with the Capacity Requirement Planning (CRP) Method. The results of the study showed that the calculation of the minimum inventory used the Material Requirement Planning (MRP) method with the Economic Order Quantity (EOQ) technique. The total inventory cost for the main raw materials is Diamond Crepe fabric with four orders of 427.5 meters/order and Rayon Stretch fabric with three orders of 745.5 meters/order of Rp 1,400,000. The optimal production capacity planning is the number of working days at the pattern making, cutting, and sewing stations, as many as four days in five periods and 4.5 days in one period, while in the bundling, packing, and finishing stations as many as four days in six periods.**

***Index Terms*—Capacity Planning; Garment Industry; MRP; CRP**

I. INTRODUCTION

The industrial sector in Indonesia is experiencing significant growth, and products are becoming increasingly complex, leading to heightened competition within the industry. This trend is evidenced by the diverse range of products marketed by various companies (Ulfah et al., 2018). To navigate this competitive landscape, it is crucial to focus on consumer loyalty. Companies that provide high-quality services and products and meet demand in a timely manner are more likely to achieve consumer loyalty. The key to a company's success lies in understanding consumer desires. When a company accurately identifies and meets consumer needs with the right products at the right time, it can enhance overall customer satisfaction. Timely understanding of consumer needs also enables companies to maintain optimal product inventory, ensuring smooth production and distribution processes without undesirable shortages or surpluses. Metrics such as timeliness and optimal product inventory are vital in evaluating the efficiency and success of an industry (Syam et al., 2022).

In this context, it is essential to manage all company resources effectively, particularly within the production process, to maintain a competitive position. A well-executed production process requires thorough planning and control to avoid obstacles that could disrupt the production flow and hinder the ability to meet customer demand adequately (Purnomo, 2019). Proper planning and control of production are necessary not only to avoid impediments but also to ensure that the inputs and outputs of the business are well-managed. These inputs include efficient costs and raw materials, as well as an effective workforce.

The production process at Rira Clothing Convention is primarily manual, utilizing several machines such as sewing machines. In garment production, it is crucial to consider market demand to meet consumer needs and remain competitive. However, Rira Clothing Convention frequently faces challenges due to fluctuating market demand, especially in the months leading up to significant Islamic holidays like Idul Fitri, when demand surges dramatically compared to other months, making it difficult to predict demand

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accurately. These fluctuations inevitably affect the production process, including targets for the number of garments to be produced, determining the quantity and schedule of raw material orders, production time, the number of machines required, and other factors. The following is the data on demand for girls' Muslim clothing at Rira Clothing Convention over the past two years (Yuliawati et al., 2023).

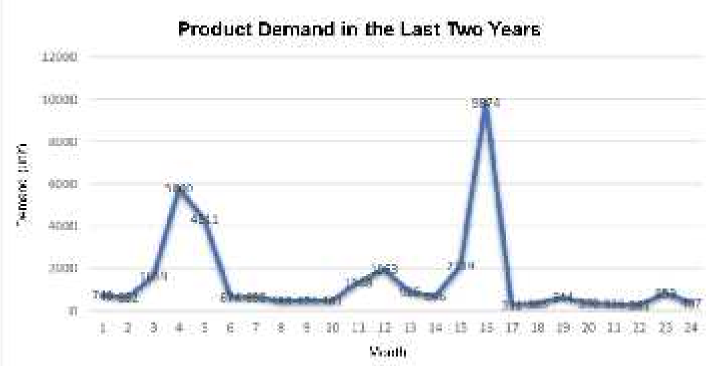

Figure 1: Demand Data for Girls' Muslim Clothing in 2021 to 2022

Raw material inventory is crucial for the company. A shortage of inventory can disrupt the production process and hinder the ability to meet customer demand. Conversely, excess inventory increases storage costs, risk of damage or obsolescence, and can impede the production flow (Gulo et al., 2023). One method that can be applied to effectively plan raw material inventory is Material Requirement Planning (MRP), which allows companies to predict raw material needs more accurately (Daroini & Himawan, 2022).

Material Requirement Planning (MRP) is a systematic method for scheduling the raw materials required in the production process, considering inventory costs within a single cycle. The primary objective of MRP is to determine and establish the quantity and procurement of raw materials based on the Bill of Materials (BOM) and projected demand forecasts as outlined in the Master Production Schedule (MPS). MRP ensures that raw materials are received precisely when needed for the production process (Ibrahim et al., 2018).

Both capacity shortages and surpluses in a company can have severe consequences. A capacity shortage can disrupt production and delivery processes, resulting in delays and even failure to meet production targets. This can damage the company’s reputation as customer trust in its ability to meet their needs is compromised. Conversely, excess capacity also poses significant risks by increasing production costs and resulting in low resource utilization, making it difficult for products to remain competitive in the market. Additionally, excess capacity can lead to decreased profits and loss of market share due to intense competition (Makhmudah et al., 2022).

Capacity Requirement Planning (CRP) is a method that can be applied for planning production capacity needs based on the established production plan. CRP helps companies ensure that the required production capacity is available at the right time to meet the production schedule (Putriani & Rahmalita, 2023). CRP is an advanced planning and control process that follows Material Requirement Planning (MRP) and is concerned with the availability of production capacity. The objective of CRP analysis is to balance the demand with the available processing capacity (Yasmin Firiza, 2020). By using both MRP and CRP methods, this study aims to optimize the production process so that Rira Clothing Convection can meet customer demand in line with market needs, thereby sustaining its business in the garment industry.

Based on the aforementioned background, it is evident that production planning and control are necessary for the girls' Muslim clothing at Rira Clothing Convention. This research will involve creating a Master Production Schedule (MPS) based on the forecasting results, followed by data processing using the Material Requirement Planning (MRP) method and the Capacity Requirement Planning (CRP) method. This study is crucial to ensure that the production process operates optimally, with the expectation that planning and control of raw materials and

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production capacity will be effectively managed.

II. METHOD

A. Design, Location, and Research Period

The object of this research is the production process at Rira Clothing Convention, located at Jl. Rungkut Barata VI No.18, Rungkut Menanggal, Gunung Anyar District, Surabaya, East Java. The focus of this study is to plan and control the raw material inventory and production capacity for the One Set model of girls' Muslim clothing required by Rira Clothing Convention. The data processing stage is carried out based on the sequential steps in the research methodology. The processing steps begin with forecasting the demand for the One Set model of girls' Muslim clothing, determining the Master Production Schedule (MPS), planning raw material requirements using the Material Requirement Planning (MRP) method, calculating inventory costs, and concluding with planning production capacity using the Capacity Requirement Planning (CRP) method.

B. Forecasting

Demand forecasting is conducted to estimate the number of requests for the upcoming period. The forecasting methods used are moving average, exponential smoothing, and multiplicative decomposition (seasonal) with the assistance of POM-QM software. Each forecasting method has an error measurement. The forecasting method with the smallest error measurement will be used as the basis for the master production schedule.

C. Bill Of Material (BOM)

The table contents should be typed in single spacing, 8-point size, Times New Roman.

The Bill of Material (BOM) lists all components required to create a product or assembly (Ginting et al., 2019). BOM plays a crucial role in coordinating and managing the supply chain and production processes. It details how the components are arranged or assembled to form the final product, providing clear instructions to operators or workers on how to assemble or combine these components during the production process.

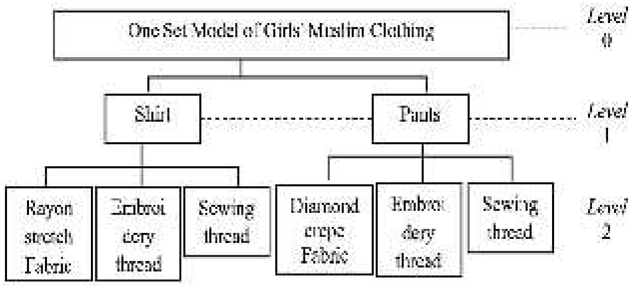

Figure 2: Bill Of Materials (BOM) for One Set Model of Girls' Muslim Clothing

D. Material Requirement Planning (MRP)

The basic components of Material Requirement Planning (MRP) consist of the Master Production Schedule (MPS), product structure over time, and inventory data (Kahfi et al., 2020). The information from the master production schedule provides other relevant details such as demand quantity, inventory status, and the timing for ordering materials or assembling necessary components. There are four stages or steps involved in the MRP preparation: netting (net requirements), lotting, offsetting (planned order release), and exploding (Handoko & Puspitasari, 2021).

Table 1 MRP Calculation Tables

Lead Time:	Time Periods				
	1	2	3	4	5
GR					
SR					
POH					
NR					
POR					
PORel					

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In the calculation of MRP, two techniques are used: the Lot For Lot (LFL) technique and the Economic Order Quantity (EOQ) technique. In the Lot For Lot method, the lot size or order quantity is set so that the inventory ordered matches exactly the net requirements for that period. The fundamental principle of EOQ is to find the point where the total inventory holding cost and setup cost are at their lowest.

$$Q = \sqrt{\frac{2DS}{H}} \quad (1)$$

E. *Capacity Requirement Planning (CRP)*

Capacity Requirement Planning (CRP) is a method for planning capacity needs, focusing on managing and regulating the use of equipment, machinery, labor, and other resources required in the detailed process. The steps in Capacity Requirement Planning (CRP) include calculating the capacity of work centers, determining the load, and balancing capacity and load. Capacity planning can be performed through analysis and reporting using the CRP method as follows (Sandy Wicaksono & Siti Mundari, 2022): Receiving information related to Planned Order Release from MRP.

1. Receiving information related to Standard Time per unit and Standard Setup Time per lot size.
   Operation Time = Run Time + Set Up Time (2)
2. Calculating the capacity at each work center
   Available Capacity Time = Number of working hours x Utilization x Efficiency (3)
   $$\text{Utilization} = \frac{\text{Actual working hours}}{/\text{A} \quad \text{w} \quad \text{h}} \times 100\% \quad (4)$$
   $$\text{Efficiency} = \frac{\text{Standard working hours}}{/\text{Available working hours}} \quad (5)$$

III. RESULTS AND DISCUSSIONS

A. *Forecasting Results*

The following are the comparison results of the three forecasting methods.

Table 2 Comparison of Data Processing Results using POM-QM Software

Error Measurement	Forecasting Methods		
	Moving Average	Exponential Smoothing	Multiplicative Decomposition (Seasonal)
MAD	166.9	143.937	87.017
MSE	55.829,65	40.704,03	17.548,81
MAPE	264.172	223.046	229.448
Standard Error	180.00%	155.36%	118.57%

Based on the table above, it is shown that the method with the smallest error measurement is the Multiplicative Decomposition (Seasonal) method, with a Mean Absolute Deviation (MAD) of 87.017, Mean Squared Error (MSE) of 17,548.81, Mean Absolute Percentage Error (MAPE) of 229.448, and a standard error of 118.57%. Therefore, this method is used to forecast demand for subsequent periods and determine the master production schedule.

Table 3 Master Production Schedule (MPS)

No	Period	Forecasting Results	JIP
1.	13	16.841	17
2.	14	50.97	51
3.	15	14.695	15
4.	16	20.211	21
5.	17	9.775	10
6.	18	9.457	10
7.	19	22.051	23
8.	20	140.395	141
9.	21	132.722	133
10.	22	321.945	322

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No	Period	Forecasting Results	JIP
11.	23	51.61	52
12.	24	33.081	34
13.	25	60.943	61
14.	26	331.76	332

B. MRP Calculation Results

MRP calculations using the Lot For Lot technique and the EOQ technique show results as in the following tabl

Table 4 MRP for Rayon Stretch Fabric using LFL Technique

Lead Time: 1 Month	Period														
Rayon Stretch Fabric (Meter)	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
GR		17	51	15	21	10	10	23	141	133	322	52	34	61	332
SR															
POH		0	0	0	0	0	0	0	0	0	0	0	0	0	0
NR		17	51	15	21	10	10	23	141	133	322	52	34	61	332
PORec		17	51	15	21	10	10	23	141	133	322	52	34	61	332
PoRel	17	51	15	21	10	10	23	141	133	322	52	34	61	332	

Table 5 MRP for Diamond Crepe Fabric using LFL Technique

Lead Time: 1 Month	Period														
Diamond Crepe Fabric (Meter)	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
GR		25.5	76.5	22.5	31.5	15	15	34.5	211.5	199.5	483	78	51	91.5	498
SR															
POH		0	0	0	0	0	0	0	0	0	0	0	0	0	0
NR		25.5	76.5	22.5	31.5	15	15	34.5	211.5	199.5	483	78	51	91.5	498
PORec		25.5	76.5	22.5	31.5	15	15	34.5	211.5	199.5	483	78	51	91.5	498
PoRel	25.5	76.5	22.5	31.5	15	15	34.5	211.5	199.5	483	78	51	91.5	498	

Table 6 MRP for Rayon Stretch Fabric using EOQ Technique

Lead Time: 1 Month	Period														
Rayon Stretch Fabric (Meter)	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
GR		215	0	0	0	0	0	0	215	0	215	215	0	215	215
SR															
POH		0	212.5	212.5	212.5	212.5	212.5	212.5	212.5	425	425	210	422.5	422.5	207.5
NR		215	0	0	0	0	0	0	2.5	0	0	5			7.5
PORec		427.5							427.5			427.5			427.5
PoRel	427.5							427.5			427.5			427.5	

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Table 7 MRP for Diamond Crepe Fabric using EOQ Technique

Lead Time: 1 Month	Period														
Diamond Crepe Fabric	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
GR		322.5	0	0	0	0	0	0	322.5	0	322.5	322.5	0	322.5	322.5
SR															
POH		0	423	423	423	423	423	423	423	100.5	100.5	523	200.5	200.5	623.5
NR		322.5	0	0	0	0	0	0	0	0	222.5	0	0	122	
PORec		745.5									745.5			745.5	
PoRel	745.5									745.5			745.5		

Table 8 Inventory Cost using LFL and EOQ Technique

No.	Technique	Raw Materials	Ordering Cost (Rp)	Holding Cost (Rp)	Total Inventory Cost (Rp)
1.	LFL Technique	Rayon Stretch Fabric	700.000	9.380	709.380
		Diamond Crepe Fabric	700.000	4.620	704.620
TOTAL			1.400.000	14.000	1.414.000
2.	EOQ Technique	Rayon Stretch Fabric	200.000	2.680	202.680
		Diamond Crepe Fabric	150.000	990	150.990
TOTAL			350.000	3.670	353.670

The inventory costs associated with using the Lot For Lot (LFL) technique amount to Rp 1,414,000, with ordering costs of Rp 1,400,000 and holding costs of Rp 14,000. In contrast, the inventory costs associated with using the Economic Order Quantity (EOQ) technique amount to Rp 353,670, with ordering costs of Rp 350,000 and holding costs of Rp 3,670. The comparison between the two techniques indicates that the inventory costs with the EOQ technique are lower than those with the LFL technique. Therefore, planning raw material orders using the EOQ technique is recommended to minimize the inventory costs incurred.

C. CRP Calculation Results

The Capacity Requirement Planning (CRP) calculation is performed to balance the load with the available capacity, ensuring that the production process runs optimally. The CRP results indicate that the pattern-making station (WC 1), cutting station (WC 2), and sewing station have the same excess and shortage of capacity. Whereas, the bundling station (WC 3) has the same capacity balance as the finishing and packing station (WC 5).

Table 9 CRP WC 1,2, and 4

Description	Period						Total
WC 1, 2, and 4	12	19	21	22	24	25	
Available Time (Minutes)	12.480	12.480	12.480	12.480	12.480	12.480	74.880
Utilization Rate	0.98	0.98	0.98	0.98	0.98	0.98	5.88
Efficiency Rate	1	1	1	1	1	1	6

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Description	Period						Total
WC 1, 2, and 4	12	19	21	22	24	25	
Available Capacity	12.231	12.231	12.231	12.231	12.231	12.231	73.386
Actual Demand	1.720	1.720	1.720	1.720	1.720	1.720	10.320
Excess/Shortage	10.511	10.511	10.511	10.511	10.511	10.511	63.066

Table 10 CRP WC CRP WC 3 and WC 5

Description	Period						Total
WC 3 dan 5	12	19	21	22	24	25	
Available Time (Minutes)	12.480	12.480	12.480	12.480	12.480	12.480	74.880
Utilization Rate	0.99	0.99	0.99	0.99	0.99	0.99	5.94
Efficiency Rate	1	1	1	1	1	1	6
Available Capacity	12.356	12.356	12.356	12.356	12.356	12.356	74.136
Actual Demand	1.720	1.720	1.720	1.720	1.720	1.720	10.320
Excess/Shortage	10.636	10.636	10.636	10.636	10.636	10.636	63.816

The table above indicates that balancing the capacity and load across all workstations is necessary to make the production system more effective and efficient. Balancing is achieved for Work Centers (WC) 1, 2, and 4 by changing the working days from 26 days (8 hours/day) to 4 days across all periods, except for period 21, which requires 4.5 days. For Work Centers 3 and 5, balancing results in 4 days across all periods.

Table 11 CRP Adjustment for WC 1, 2, and 4

Description	Period						Total
WC 1, 2, and 4	12	19	21	22	24	25	
Available Time (Minutes)	1.920	1.680	1.920	1.680	1.680	1.680	10.560
Utilization Rate	0.98	0.98	0.98	0.98	0.98	0.98	5.88
Efficiency Rate	1	1	1	1	1	1	6
Available Capacity	1.882	1.647	1.882	1.647	1.647	1.647	10.352
Actual Demand	1.720	1.720	1.720	1.720	1.720	1.720	10.320
Excess/Shortage	162	-73	162	-73	-73	-73	32

Table 12
CRP Adjustment for WC 3 and 5

Description	Period						Total
WC 3 dan 5	12	19	21	22	24	25	
Available Time (Minutes)	1.920	1.920	1.920	1.920	1.920	1.920	11.520
Utilization Rate	0.99	0.99	0.99	0.99	0.99	0.99	5.88
Efficiency Rate	1	1	1	1	1	1	6
Available Capacity	1.901	1.664	1.901	1.664	1.664	1.664	10.458
Actual Demand	1.720	1.720	1.720	1.720	1.720	1.720	10.320
Excess/Shortage	181	-56	181	-56	-56	-56	138

IV. CONCLUSIONS

The raw material ordering plan for the One Set model of children's Muslim clothing at Rira Clothing Convection is carried out using the EOQ technique within the MRP method. Rayon Stretch raw material is ordered four times at 427.5 meters per order, and Diamond Crepe raw material is ordered three times at 745.5 meters per order.

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Thus, the total ordering cost for both raw materials is Rp 1,400,000, and the total holding cost is Rp 14,000, resulting in a total inventory cost of Rp 1,414,000.

Using the Capacity Requirement Planning method, optimal production capacity planning for the One Set model of children's Muslim clothing at Rira Clothing Convection is as follows: 4 working days (8 hours/day) at all Work Centers 1 (pattern-making), 2 (cutting), 3 (bundling), 4 (sewing), 5 (packing and finishing) in period 12 and period 21, which requires 3.5 days or 3 days (8 hours/day) plus 1 day (4 hours/day) in period 19, 22, 24 and 25.

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Quality Control of Glass Bottle Drinking Water Products Using the Six Sigma Method

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***Abstract*— This study aims to enhance production performance and product quality, thereby achieving various financial and strategic objectives, including market share, competitiveness, and profitability. The problem faced by this company is in product quality control, where there are still defective products that arise during the production process. Therefore, this study uses Six Sigma with the concept of Define, Measure, Analyze, Improve, and Control (DMAIC) as a step to optimize production procedures at UD. NUSAQU, whose product is bottled drinking water. The focus of this study is on the visual of product defects in the form of cups, which are divided into two grades, namely Grade A and Grade B, which are distinguished based on the plastic cup material used. The results of data testing show that in Grade A and Grade B, slanted lid damage has the highest level of damage, but in Grade B, the results are the same as those of leaking cups. The DPMO value produced in Grade A is 62,633.914, while in Grade B it is 130,961.47. The smaller the DPMO value, the better the product quality. The average value of Six-Sigma for Grade A is 3.03, while Grade B is 2.63. Based on these values, it can be concluded that Grade A has better quality than Grade B, but both require improvement and enhancement efforts to achieve 6 sigma.**

***Keyword*: defect, quality control, six-sigma**

I. INTRODUCTION

One of the primary needs of society is water, which is a very important source of energy for the survival of society. This makes many entrepreneurs take advantage of opportunities in their businesses and efforts, such as making practical and healthy packaged mineral water products. However, the vast opportunities that exist create tight and sharp competition in the packaged mineral water business both in the local and national markets. Tight competition requires entrepreneurs to provide good products and in accordance with consumer desires in terms of quality, starting from raw materials, labor, machine tools used, packaging, and finished products.

Several industries are dedicated to improving production performance and product quality to achieve various financial and strategic goals, such as market share, competitiveness, and profitability (Fersini, 2019; Aytekin et al., 2023; Samanta et al., 2023). To achieve this, Lean Six Sigma (LSS) applies the DMAIC framework, which consists of five stages: 1) Define; 2) Measure; 3) Analyze; 4) Improve; and Control [4]. In addition to its strategic advantages, LSS seeks to clarify manufacturing processes by identifying opportunities for waste reduction, process variability reduction, and problem solving (Mandal, 2012; Chen et al., 2023).

Several previous studies have stated that in quality control, DMAIC still needs to be applied more adequately (Hakimi, 2018; Tsarouhas & Sidiropoulou, 2024). In this study, Pareto analysis is used to determine the process in production that causes the most defects, and to evaluate by identifying the part of the production process that is a significant cause of defects, among many other causes (Kartika, 2020; Can et al., 2021).

The case study chosen in this study is Glass Bottle UD. Nasaqu, which has been operating since 2019 in Pegantenan District, Pamekasan Regency, East Java, especially for 240 ml glass packaging. This company often produces defective products in large quantities, which are generally caused by factors such as raw materials for its glass packaging, human error, and the machines used. The Six-Sigma method is used to identify and eliminate defects in the production process, thereby improving the quality of the final product. With this research, it is hoped that business owners will get sufficient guidelines and knowledge in implementing effective and efficient production by reducing product defects that occur.

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II. METHOD

This study uses the DMAIC methodology, which is the basis of the Six Sigma process improvement initiative (Sajjaad et al., 2021; Elnaby et al., 2023). The following procedures describe a problem-solving methodology in which specific tools are used to transform practical problems into statistical formats, build solutions based on statistical models, and transform those solutions into practical solutions (Orbak et al., 2023).

Several stages in this study are as follows (Chen et al, 2023):

a. ***Define***

At this stage, significant causes of failures that occur during the production process are determined, and the methods used are:

1) Defining the problem of quality standards in producing products that have been determined by the company.
2) Defining the action plan that must be carried out based on the results of observations and research analysis.
3) Determining the targets and objectives for improving Six Sigma quality based on the results of observations.

b. ***Measure***

At this stage, the accuracy and feasibility of the measurement system or data collection system must be verified. The measurement phase identifies problems that require resolution through statistical graphs, such as a Pareto chart. Because the data studied is attribute data, the following stages are carried out in its measurement:

1) Analysis with a P-chart control diagram with the following steps:
   a) Data collection used for P-chart analysis, namely, the amount of production and the number of defective products produced.
   b) Calculating the mean product nonconformity with the equation:

   $$\bar{p} = \frac{np}{n} \quad (1)$$

   Where p‾ is the average nonconformity, n indicates the number of samples, and np is the number of defective products.
2) Determining the control limit for supervision is carried out by calculating the UCL (Upper Control Limit) value as the upper limit, LCL (Lower Control Limit) as the lower limit, and CL (Control Limit) as the linear limit. The equation is as follows:

$$C = \bar{p} = \frac{\sum np}{\sum n} \quad (2)$$

$$U = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \quad (3)$$

$$L = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \quad (4)$$

3) Calculating Sigma Capability, by:
   a) Determining the number of units to be measured
   b) Identifying Opportunities
   c) Calculating the number of defects
   d) Calculating the sigma capability value (baseline process)
   This capability value calculation uses DPMO measurement units to determine the sigma level.

c. ***Analyze***

At this stage, an analysis of the causes of quality problems is carried out using:

1) Pareto Diagram
In this study, after obtaining product failure information data. An analysis of the causes or dominant factors that cause the failure of a product is carried out by sorting the possibility of defects based on the type of failure from the largest to the smallest.
2) Cause-Effect Diagram
After the dominant cause of the defect is known, an analysis of the relationship between an effect and a number of causes that may result in the occurrence of product failure is carried out. This is done by determining five problem areas, namely methods, materials, machines, environments, and workers.

d. ***Improve***

After identifying the root cause, conducting measurements (looking at opportunities, damage, current capability processes), reviewing recommendations for improvement, analyzing, and then taking corrective actions. In this phase, solutions to eliminate the causes of variation are developed, verified, and standardized. This phase consists of:

1) Design-based solutions.
2) Assessing the accuracy of the proposed solution.

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3) Risk assessment and mitigation strategies

e. *Control*

During this phase, it is critical to maintain process control through error checking. This phase immediately identifies the root cause of any out-of-control process and restores the level of process control. At this phase, Statistical Quality Control (SQC) is critical to monitor and assess process performance and stability. To maintain good results, it is critical to stabilize the process that has been improved during the previous phase.

III. RESULTS AND DISCUSSION

1. Control Chart Analysis Stage (P-Chart)

Data taken from UD AMDK Nusaqu, namely, quality control measured by the number of final products. Measurements were carried out using statistical quality control type P-Chart on final products from September 2023 to August 2024, namely a sample size of 12. The type of product that will be used in this study is Bottled Drinking Water.

The amount of glass bottled drinking water produced during September 2023 to August 2024 was 374,400 glasses, and it was found that products suspected of being defective, originating from three main causes of defects, were 7813 glasses.

The amount of glass bottle drinking water produced during September 2023 to August 2024 was 374,400 glasses, and it was found that the products suspected of being defective, originating from three main causes of defects, were 7813 glasses. The following is a measurement sheet for taking samples from September 2023 to December 2023 to determine the LCL (Upper Control Limit) and LCL (Lower Control Limit) values. UD AMDK Nusaqu Packaged Drinking Water. The calculation of CL, UCL, and LCL Grade A values is shown in Table 1.

Table 1. Determining CL, UCL, LCL Grade A value

Period	Number of products	Number of defects	Proportion	CL	UCL	LCL
1	30.000	698	0.02327	0.02087	0.02334	0.01839
2	28.800	611	0.02122	0.02087	0.02339	0.01834
3	32.400	676	0.02086	0.02087	0.02325	0.01849
4	31.200	586	0.01878	0.02087	0.0233	0.01844
5	31.200	654	0.02096	0.02087	0.0233	0.01844
6	31.200	701	0.02247	0.02087	0.0233	0.01844
7	32.400	689	0.02127	0.02087	0.02325	0.01849
8	31.200	597	0.01913	0.02087	0.0233	0.01844
9	31.200	638	0.02045	0.02087	0.0233	0.01844
10	31.200	688	0.02205	0.02087	0.0233	0.01844
11	31.200	620	0.01987	0.02087	0.0233	0.01844
12	32.400	655	0.02023	0.02087	0.02325	0.01849
Total	374.400	7813				
$\bar{p}$	0,0208681					
1-$\bar{p}$	0.9791319					

As a rule of thumb (Prawirosentono, 2002), the following criteria are used:

a. If P < LCL, it means that all samples are in the acceptance area (LCL), then check the cause.
b. If LCL < P > UCL, it means that all samples are in the acceptance area, called normal behavior samples or good process capability.
c. If P > UCL, it means that the sample jumps up outside the acceptance (UCL), or it can be said that the process capability is low; then, check the cause and take corrective action by

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improving performance in the production process activities. The P-Chart Grade A control chart is shown in Figure 3.

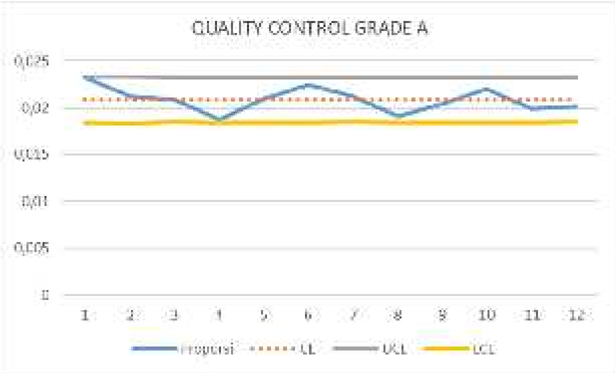

Figure 1: P-Chart Control of Grade A

From Fig. 3, it can be seen that not all lines cross the upper limit of the UCL, but from all there are still defects caused by machine factors that are not in accordance with the machine temperature settings that have been determined by the company. Human Error also greatly affects the quality of glass bottles, starting from packaging to the removal of products that are thrown, so that the product packaging is torn.

Table 2. Determining CL, UCL, LCL Grade B value

Period	Number of products	Number of defects	Proportion	CL	UCL	LCL
1	30.000	1200	0.04	0.04365	0.04719	0.04011
2	28.800	1152	0.04	0.04365	0.04726	0.04004
3	32.400	1296	0.04	0.04365	0.04706	0.04025
4	31.200	1134	0.0635	0.04365	0.04712	0.04018
5	31.200	1456	0.04667	0.04365	0.04712	0.04018
6	31.200	1346	0.04314	0.04365	0.04712	0.04018
7	32.400	1296	0.04	0.04365	0.04706	0.04025
8	31.200	1948	0.06244	0.04365	0.04712	0.04018
9	31.200	1256	0.040226	0.04365	0.04712	0.04018
10	31.200	1425	0.04567	0.04365	0.04712	0.04018
11	31.200	1567	0.05022	0.04365	0.04712	0.04018
12	32.400	1267	0.0391	0.04365	0.04706	0.04025
Total	374.400	16343				
$\bar{p}$	0.0436512					
1-$\bar{p}$	0.9563488					

The P-Chart Grade B image is shown in Figure 4. From Figure 4, it can be seen that there is still a line that passes the upper limit of UCL in August and also in November 2023 which is caused by the improper setting of the machine temperature so that many defective products such as leaking Cups with tilted Lids and also when the packaging of the goods is thrown which causes the product packaging to tear.

2. Sigma and Defect Level Measurement Stage

The Sigma and Defect per Million Opportunities (DPMO) measurement stage, as well as Grade A sampling from September 2023 to August 2024, can be seen in Table 3.

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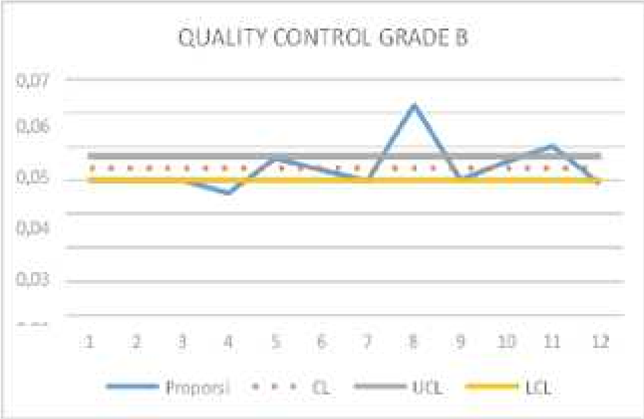

Figure 2: P-Chart Control of Grade B

Based on the sigma level measurement above, the DPMO pattern of the failure of bottled drinking water products (glasses) and the inconsistent sigma achievement still vary up and down throughout the 2023 period. It is known that the sigma level from September 2023 to August 2024 has exceeded the average sigma value in Indonesia, and an average DPMO value of 62633.914 was found with an average sigma level of 3.03. The Sigma Level Measurement Stage and Defects Per Million Opportunities Grade B from September 2023 to December 2023 can be seen in Table 4.

Table 3. Calculation of Sigma and DPMO Grade A

Period	Number of products	Number of defects	CTQ	DPO	DPMO	Six Sigma
1	30.000	698	3	0.0698	69.800	2.98
2	28.800	611	3	0,063645833	63.645.833	3.02
3	32.400	676	3	0.062592593	62.592.593	3.03
4	31.200	586	3	0.056346154	56346.154	3.09
5	31.200	654	3	0.062884615	62884.615	3.03
6	31.200	701	3	0.067403846	67403.846	3
7	32.400	689	3	0.063796296	63796.296	3.02
8	31.200	597	3	0.057403846	57403.846	3.08
9	31.200	638	3	0.061346154	61346.154	3.04
10	31.200	688	3	0.066153846	66153.846	3.01
11	31.200	620	3	0.059615385	59.615.385	3.06
12	32.400	655	3	0.060648148	60.648.148	3.05
sum	374.400	7813	3	0.062604167	62.604.167	3.03
average					62.633.914	3.03

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Table 4. Calculation of Sigma and DPMO Grade B

Period	Number of products	Number of defects	CTQ	DPO	DPMO	Six Sigma
1	30.000	1200	3	0.12	120.000	2..67
2	28.800	1152	3	0.12	120.000	2.67
3	32.400	1296	3	0.12	120.000	2.67
4	31.200	1134	3	0.109038462	109.038.46	2.73
5	31.200	1456	3	0.14	140.000	2.58
6	31.200	1346	3	0.29423077	129.423.08	2.63
7	32.400	1296	3	0.12	120.000	2.67
8	31.200	1948	3	0.187307692	187.307.69	2.39
9	31.200	1256	3	0.120769231	120.769.23	2.67
10	31.200	1425	3	0.137019231	137.019.23	2.59
11	31.200	1567	3	0.150673077	150.673.08	2.53
12	32.400	1267	3	0.117314815	117.314.81	2.69
sum	374.400	16343	3	0.130953526	130.953.53	2.62
average					130.961.47	2.63

Based on the sigma level measurements above, the DPMO pattern of the failure of packaged drinking water products (glasses) and the achievement of the sigma level is still inconsistent, fluctuating throughout the 2023 period. It is known that the sigma level from September 2023 to December 2023 that occurred included the average sigma value for Indonesia, which found an average DPMO value of 130961.47 with an average sigma level of 2.63.

3. Analysis of Causes of Poor Quality AMDK

Analyze is a stage for improving quality by clarifying the causes of damage, namely with a Pareto diagram and a cause-effect diagram. Damage to Grade A is explained in Table 5. The Pareto Diagram of Grade A glass is shown in Figure 5 in the following section.

Table 5. Level of Grade A Product Defect

Type of defect	Total	Percentage	Cumulative Percentage
Slanted Lid	3.173	41%	41%
Packaging	2.936	38%	78%
Leaking Cup	1.704	22%	100%
Total	7.813	100%	

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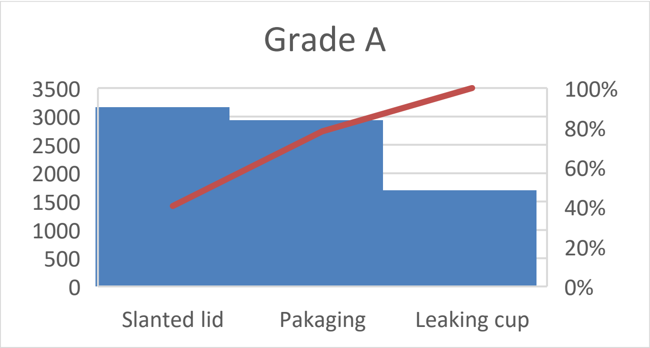

Figure 3: Pareto Diagram of Grade A

As for the amount of damage to glass bottled water products, the Grade B category can be explained in Table 6.

Table 6. Level of Grade B Product Defect

Type of damage	Total	Percentage	Cumulative Percentage
Slanted Lid	6.095	37%	37%
Packaging	6.019	37%	74%
Leaking Cup	4.229	26%	100%
Total	16.343	100%	

Next, the Pareto diagram for the product of glass mineral water packaging with Grade B quality is shown in Figure 6 as follows.

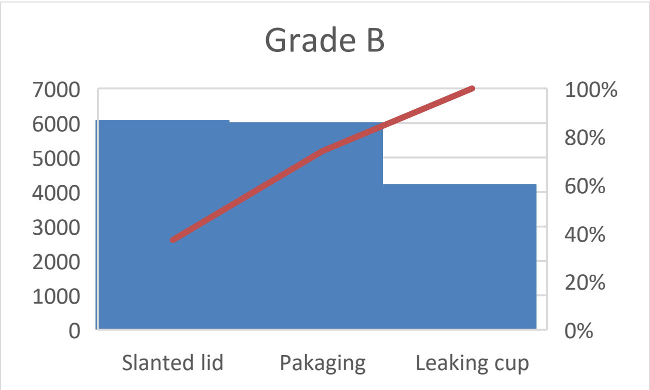

Figure 4: Pareto Diagram of Grade B

4. Cause-and-Effect Diagram

A cause-effect diagram is useful for showing factors that influence quality and have an impact on the problem we are studying. In addition, we can also see more detailed factors that influence and have an impact on the main factor, which we can see from the arrows in the shape of fishbones in the fishbone diagram.

Based on sample data, histograms, and Pareto diagrams, it can be seen that the number of broken cup defects, tilted lids, and packaging for cup products are still outside the standard, and the most dominant is the broken cup defect. The factors causing the broken cup defect can be described using a cause-and-effect diagram. The cause-and-effect diagram of the broken cup defect can be seen in Figure 5.

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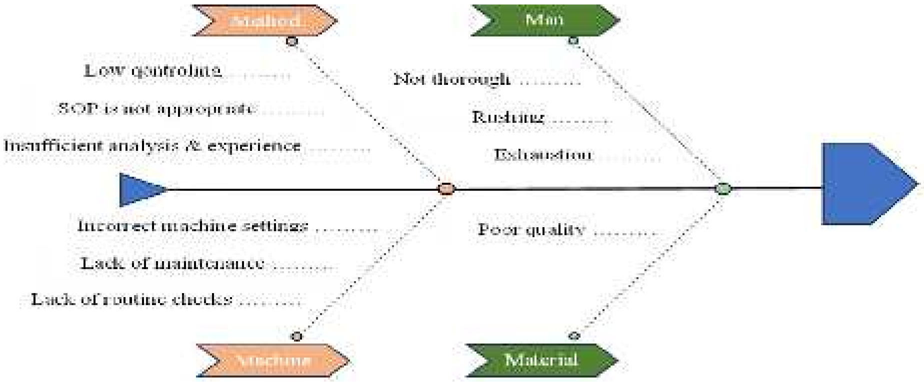

Figure 5: Fish Bone Diagram

Based on the observation results above, the main product defects are caused by raw materials, humans, machines, and methods as follows:

a. Machines, imperfect machine settings in adjusting the thickness of raw materials and machine temperature, lack of machine temperature maintenance, lack of machine temperature maintenance and machine elements, namely molds, compressors, cooling towers, loose panbelts resulting in products that are not in accordance, and lack of routine checks before production so that the machine is damaged during the production process causing a lack of machines
b. Humans, fatigue of thermoforming machine operators due to the large workload given, lack of concentration, lack of thoroughness, being in a hurry when working, and chasing targets, resulting in the production process not running optimally.
c. Methods, lack of analysis and operator experience in machine settings, lack of supervision of performance, incomplete and poorly adhered SOPs, and lack of training for machine operators, causing inconsistencies in machine settings.
d. Materials, poor quality raw materials due to limited raw materials, and raw materials that do not comply with raw material standards, which cause several product defects.

5. Improvement

Some actions in the measurement process that can be taken are:

a. Opportunities: Reduce the number of defective products by implementing more precise Control.
b. Damage: Of the 374,400 products produced from September 2023 to December 2024, there were 7,813 defective products.

Grade A and Grade B capability processes. The Six Sigma Values in Grade A and Grade B are explained in Table 7.

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Table 7. Value of Six Sigma Grade A and Grade B

Periode	Grade A		Grade B	
	DPMO	*Six Sigma*	DPMO	*Six Sigma*
1	69.800,00	2.977	120.000,00	2.67
2	63.645,83	3.025	120.000,00	2.67
3	62.592,59	3.033	120.000,00	2.67
4	56.346,15	3.086	109.038,46	2.73
5	62.884,62	3.031	140.000,00	2.58
6	67.403,85	2.995	129.423,08	2.63
7	63.796,30	3.024	120.000,00	2.67
8	57.403,85	3.077	187.307,69	2.39
9	61.346,15	3.044	120.769,23	2.67
10	66.153,85	3.005	137.019,23	2.59
11	59.615,38	3.058	150.673,08	2.53
12	60.648,15	3.049	117.314,81	2.69
Average value	**62.604,17**	**3.033**	**130.961,47**	**2.63**

The results of the comparison of production process data for grade A and grade B can be seen in Figure 8. From the figure, it can be seen that the comparison of production process data for grade A and grade B shows more damage to grade B, so the production process (quality control) that must be paid more attention to is grade B,wherealldamageisreduced.

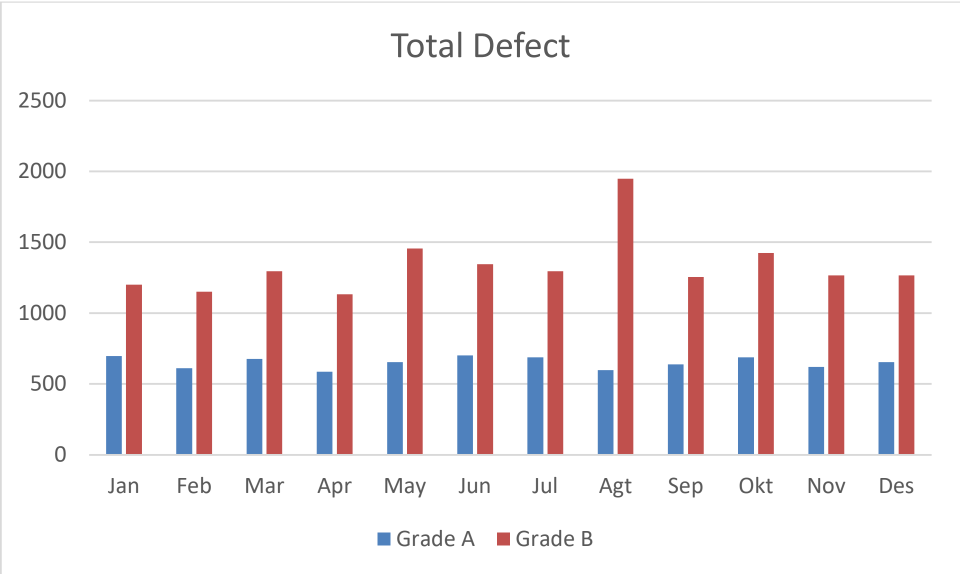

Figure 6: Data Comparison of Grade A and Grade B Production

IV. Conclusion

Based on the results of the research and discussion, several conclusions can be drawn as follows.

1. The application of the Six Sigma method can improve performance and reduce the possibility of errors. And in the end, the Six Sigma method is able to improve the quality of its production to be better and can increase profits for the AMDK NUSAQU company.
2. The selection of Cup Grade A raw materials is more recommended than Cup Grade B, given the fewer defective products. Cup Grade A is recommended because the percentage value of Cup Grade A damage reaches 22%. While the

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percentage value of Cup Grade B reaches 37%. The Six Sigma value of Cup Grade A reaches 3.033. While the Six Sigma value of Cup Grade B reaches 2.63. So, Cup Grade A was chosen because its value is better than the value of Cup Grade B

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Implementation of the Age Replacement Method for Moulding Machine Maintenance at PT. KMI

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***Abstract*— The rapid development of the industrial world has caused the manufacturing industry to think hard to survive the fierce competition. PT. KMI is a company engaged in industrial furniture, oriented to the best quality in its products and supported by sophisticated technology in the production process. The problem that occurs is unexpected machine damage, causing the production process to stop. The way to overcome this is to schedule the replacement of components that are susceptible to damage, especially sensors, bearings, and roller trans. Determination of critical components using the ABC method and the age replacement method. The selection of damage distribution, at this stage, is based on the goodness of fit value. One way to increase productivity is to schedule the replacement of components that are susceptible to damage, especially sensors, bearings, and roller trans. The recommended replacement time is 128 days for sensors with a cost reduction of IDR 1.848.097 for replacement of sensor components, 261 days for bearing components with a cost reduction of IDR 1.301.553 and 251 days for roller trans components with a cost reduction of IDR 1.646.870. by using the ABC method, 3 critical components can be found, namely sensors and bearings with a percentage value of 42.80% for sensors, 20.95% for bearings, and 14.03% for Roller trans. The most optimal time interval for the three components is the sensor component, 128 days, with downtime cost savings of IDR 1.848.097. The bearing component is 261 days with downtime cost savings of IDR 1.301.553. The roller trans component 251 days with downtime cost savings of IDR 1.646.870.**

Key Words: age replacement, bearing, component, roller, sensor

I. Introduction

The development of the global market in the industrial sector has triggered increasingly intense competition. Companies are required to carry out processes and produce high-quality products, both based on consumer and company standards. Industry acts as a source that produces and provides products or services needed by the wider community. (Srirahayu, 2021). Industries that are increasingly dependent on machines in producing goods. The machines used are physical aspects that require maintenance so that the company remains productive. Maintenance is defined as an activity carried out to it can restore or maintain the machine in optimal condition to be able to operate. (Ardiansyah & Widjajati, 2021).

(Ar-Royyan & Mukhtar, 2023) Put forward another definition of maintenance as a series of activities or actions carried out continuously with the aim of keeping the equipment in good and optimal condition.

The production process in the manufacturing industry uses machines, and the continuous use of machines to achieve production targets that sometimes exceed capacity can reduce machine performance, shorten machine life, and result in the need to replace damaged components. (Pardiyono & Suryani, 2020)

The Age replacement method is a preventive maintenance method that can estimate the replacement of components that have reached a certain age, based on damage data. (Dio et al., 2023). Virana Putra et al. (2022) Conducted a study using the age replacement method. The results obtained were that the rate of component damage increased according to increased usage, equipment that had had component replacement

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would return to its original condition, and there were no problems in component inventory.

Age Replacement is a replacement model where the component replacement time interval is carried out by taking into account the service life of the component, so that it can avoid the occurrence of equipment that has just been

installed being replaced in a relatively short time (Jardine & Tsang, 2013)
(Chien et al., 2014) Conducted a study on the age replacement method with the condition that if the tool is damaged before the specified time, then the component replacement process will be carried out when the component reaches its optimal age. This is calculated from the date of component replacement, so that it can save maintenance costs.

PT. KMI has various production machines. The molding machine is one of the mandatory machines, because all production processes go through the molding machine. Therefore, special attention is needed in the maintenance of the molding machine. The type of reactive maintenance is to repair if there is damage or breakdown. (Ali M & Kusuma, 2019).
The proposed machine maintenance scheduling at PT. KMI is in the form of component replacement time and component inspection time for critical components on critical machines, so that the proposed preventive maintenance scheduling will also result in a decrease in downtime, a decrease in maintenance costs, an increase in availability, and an increase in the reliability of critical machines.

II. METHOD

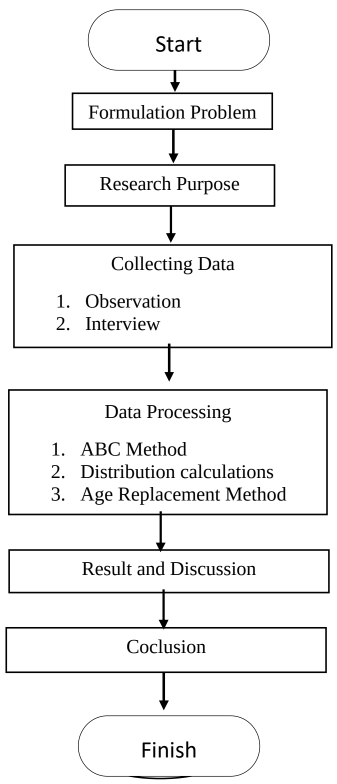

Figure 1: Research Design

a. Formulation Problem
In this discussion, the problem is formulated using the Age Replacement method.
b. Research Purpose
Benefits of the Research, for the company, for the author, for the university, and the purpose of the research, identifying damage that occurs to machine components, and determining the optimal time interval for critical molding machine components that need to be replaced.
Collecting Data
Data collection is a step to obtaining the data needed for the study.
d. Data Processing

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Carrying out the processing of what has been collected based on the theory derived from the literature study. Data processing produces the most optimal time interval for using machine components, optimal annual maintenance on the machine, and minimizing costs for machine maintenance.

e. Results and Discussion

This stage contains a discussion using the Age Replacement method.

f. Conclusions

Conclusions are made to find out the results of the research that has been carried out, in order to find out whether a study is successful or not. After making a conclusion, the next step is to determine suggestions in the form of input to the company and subsequent researchers.

The research variables studied are Downtime Damage to Molding Machine, Maintenance Time on Each Machine Component, Cost of Loss During Downtime, Machine Maintenance Cost, Machine Maintenance Cost.

Data Analysis Methods

According to (Praharsi et al., 2015), 2015 the steps in calculating the Age Replacement method are as follows:

1. Determine critical components of critical machines based on machine failure data, using the Pereto diagram to determine critical components.
2. Performing calculations and analysis of component damage data, by calculating the Time to failure (TTF) and Time to repair (TTR) of critical components. TTF calculations are performed by calculating the time difference between the first damage is completed and the time of the next damage and TTR calculations are performed by calculating the length of the repair process, namely the time difference when the damage is completed and the time of damage.
3. Calculating the Index of fit, parameter estimation, goodness of fit, MTTF, and MTTR values.

$$M = \alpha \left(1 \frac{1}{p}\right) \quad \text{…………………………(1)}$$

Where:
α = Scale parameter (alpha)
β = Shape parameter (beta)
Γ = Gamma function

$$M = \frac{A \quad \alpha \quad R \quad Ti}{A \quad \alpha \quad R} \quad \text{……………….…….(2)}$$

4. Calculating the intervals for preventive maintenance and component inspection.
5. Calculate the replacement interval of components that must be replaced if damaged.

Inspection intervals and availability levels.

The calculation formula for the Age Replacement method is as follows (Muzakki, 2021)

$$D(t) = \frac{T \quad (t)+T(1-R(t))}{(t+T)R(t)+(M(t))+T(1-R(t))} \quad \text{……..………..(3)}$$

Where:
D(tp) = total downtime per unit time for preventive replacement
tp = length of cycle (time interval) preventive
Tp = downtime due to preventive action
Tf = downtime due to component failure
M(tp) = expected value of the failure cycle length

III. Results and Discussion

After collecting data, the next step is to determine the critical components using the ABC method, which is carried out on the molding machine as in Table 1:

Table 1 Critical Component Data

Component	Amount	Price/Unit (IDR)	Breakdown Frequency	Total Cost (IDR)
Inventers	1	1.520.000	2	3.000.000
GearBox	6	525.000	5	15.750.000
Bering	16	350.000	6	33.600.000
AS	6	935.000	3	16.830.000
Roller Trans	5	750.000	6	22.500.000
Sensors	22	390.000	8	68.640.000

After that, calculate the percentage cost of each component and sort it from the largest to the smallest amount, then the components are classified using the ABC method as in Table 2:

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Table 2: ABC Method

No	Component	Percentage Frequency	Category
1	Sensors	42.80%	A
2	Bering	63.75%	
3	Roller Trans	77.78%	
4	AS	88.28%	B
5	GearBox	98.1%	
6	Inventers	100%	C

The goodness of fit test is conducted to determine the type of distribution of TTR and TTF data and to determine the MTTR and MTTF values of each component. Table 3 shows the results of the TTR repair time distribution test, while Table 4 shows the results of the TTF damage time distribution test.

Table 3 Goodness Of Fit TTR

Component	Distribution	Scale	Shape
Sensors	Weibull	6.05864	1236.86
Bering	Weibull	3.95032	3.95032
Roller Trans	Weibull	3.46938	155.094

Table 4 MTTR Result

Component	Distribution	α	β	MTTR
Sensors	Weibull	6.05864	1236.86	110.69
Bering	Weibull	3.95032	3.95032	41.521
Roller Trans	Weibull	3.46398	155.094	139.46

The Mean Time to Failure calculation requires parameters from the selected distribution calculation. Therefore, to calculate MTTF, each component is different. Table 5 is a table of parameters and MTTF results for each component.

Table 5: MTTF Result

Component	Distribution	Scale	Shape	MTTF
Sensors	Weibull	6.05864	1236.86	1148
Bering	Weibull	3.95032	3.95032	1603
Roller Trans	Weibull	1161.51	4.14963	1055

From the calculation results, the MTTF value is then calculated to determine the reliability value of each component. The calculation results can be seen in Table 6 as follows.

Table 6 Reliability

Component	Distribution	MTTF	R9t)
Sensors	Weibull	1148	0.529151315
Bering	Weibull	1603	0.509078758
Roller Trans	Weibull	1053	0.51092252

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The next step is to calculate the maintenance costs and component damage. The results of this calculation are to find the optimal time for the maintenance interval that should be carried out. Maintenance costs are costs that arise due to maintenance. Maintenance costs include labor costs, downtime costs, and spare part costs. Maintenance costs for each component can be seen in Table 7 as follows.

Table 7: Maintenance Costs

Component	Price (IDR)	MTTR (Hours)	Labour Cost (IDR)	CM (IDR)
Sensors	390.000	107.698	37.500	4.425.000
Bering	350.000	126.87	37.500	5.105.000
Roller Trans	750.000	139.46	37.500	5.979.750

The results of the calculation of repair costs due to component damage for each maintenance cycle are shown in Table 8 as follows.

Table 8: Repair Costs

Component	Price (IDR)	MTTR (Hours)	Labour Cost (IDR)	Loss Costs(IDR)	CF (IDR)
Sensors	390.000	107.698	37.500	20.000.000	215.237.500
Bering	350.000	126.87	37.500	20.000.000	253.637.500
Roller Trans	750.000	139.46	37.500	20.000.000	278.957.500

Next is to calculate using the Age replacement method to find out the results of reducing repair costs. The calculation results of the Age replacement method can be seen in Table 9 below.

Table 9: Age Replacement Method

Component	tp	R(tp)	M(tp)	D(tp) (IDR)
Sensors	128	0.529151315	2.438312	1.848.097
Bering	261	0.509078758	3266.812	1.301.553
Roller Trans	251	0.51092252	2157.139	1.646.870

Unexpected machine failures often occur, causing the production process to stop. One way to increase productivity is to schedule replacement of components that are prone to damage, especially sensors, bearings, and roller trans. The recommended replacement time is 128 days for sensors with a cost reduction of IDR 1.848.097 for replacement of sensor components, 261 days for bearing components with a cost reduction of IDR.1.301.553, and 251 days for roller trans components with a cost reduction of IDR 1.646.870.

IV. CONCLUSION

By using the ABC method, 3 critical components can be found, namely sensors and bearings with a percentage value of 42.80% for sensors, 20.95% for bearings, and 14.03% for Roller trans. The ABC method has proven effective in identifying key components that require more attention to optimizing maintenance strategies. The implementation of this method provides an efficient solution that can significantly reduce downtime costs while ensuring system performance remains stable and reliable.

The application of the Age Replacement method has successfully determined the optimal

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maintenance interval for three critical components, namely sensors, bearings, and roller trans, as follows:

a. Sensor: A replacement interval of every 128 days provides downtime cost savings of Rp1,848,097, with a contribution of 42.80% of the total damage cost.

b. Bearing: A replacement interval of every 261 days provides downtime cost savings of Rp1,301,553, with a contribution of 20.95% of the total damage cost.

c. Roller trans: A replacement interval of every 251 days provides downtime cost savings of Rp1,646,870, with a contribution of 14.03% of the total damage cost.

This Age Replacement approach has proven its effectiveness in significantly reducing downtime costs by determining the optimal component replacement schedule. Implementing this strategy not only increases cost efficiency but also extends the overall system life.

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