Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 5	Month	: October
p-ISSN	: 1693-5462	Volume	: 22	Year	: 2024

Article Processing Dates: Received on 2024-06-11, Reviewed on 2024-07-31, Revised on 2024-08-29, Accepted on 2024-08-30 and Available online on 2024-10-30

Improving quality of air conditioner production through six sigma approach to reducing defects in its heat exchanger manufacturing

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Abstract
Air Conditioners (ACs) are essential electronic products for residential and industrial buildings in tropical countries or during warm weather in general. The penetration ratio of ACs has been increasing annually. This research which was conducted through direct observation, measurement, and calculation, focused on AC heat exchanger production costs, which represent 19% of total costs. A significant portion of these costs (73.7%) arises from pipe leaks. Using the Six Sigma methodology of Define, Measure, Analyze, Improve, Control (DMAIC) approach, the defect rate in heat exchangers was assessed, revealing 1,144.8 defects per million opportunities. This research was conducted Further analysis with Failure Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA) identified two major failure risks: oversized flaring diameter and inconsistent brazing skills. Training and adjusting punch flaring size to 8.5 mm led to a defect rate reduction of 64.7%, achieving a defect reduction of 38.1% in production and saving $31.96 per unit monthly. The improvements made in heat exchanger production processes are transferable to other cooling electronic production processes. (FMEA) methods.

Keywords:
Six Sigma, air conditioner, heat exchanger, FMEA, FTA.

1 Introduction

The development of industrial technology is crucial for the sustainability of industries. The more advanced the technology used, the better the quality and quantity of the products produced. The development of industrial technology in the form of real-time data and analysis has the potential to enhance the effectiveness of lean tools and principles [1]. Continuous technological advancement has sparked a race to meet human needs with increasing precision. Technological innovation is the main driver of industrial development, which has a significant impact on productivity, product quality, and market competitiveness [2].

The influence of industry is becoming increasingly significant, as evidenced by the substantial control of industry over research [3]. Compared to other fields, industry has characteristic impacts from the home country on corporate innovation investment and industrial structure. Currently, the importance of industry to innovation may still be underestimated, as the heterogeneity of companies within the industry is a key factor [4].

The development and innovation in improving industrial processes continue to evolve in line with technological advancements. The primary strategy for enhancing industrial processes is lean manufacturing, although it requires adjustments to needs and maintaining product quality [5]. Furthermore, lean manufacturing practices have a positive impact on process innovation performance, particularly in terms of input and the occurrence of gradual and radical process innovations [6]. In the context of process industries, lean manufacturing practices are associated with improved operational performance, on-time delivery, productivity, first-pass yield, waste elimination or reduction, inventory reduction, cost reduction, defect reduction, and demand management improvement [7].

The electronic industry is a crucial component of the manufacturing sector. Its contribution is significant in providing a large portion of output, exports, and employment opportunities. The electronic industry has a significant impact on employment and economic growth [8]. The electronic industry plays a role in addressing society's needs related to climate change. It was proven by the data on the penetration ratio of electronic products in Indonesia as shown in Fig. 1.

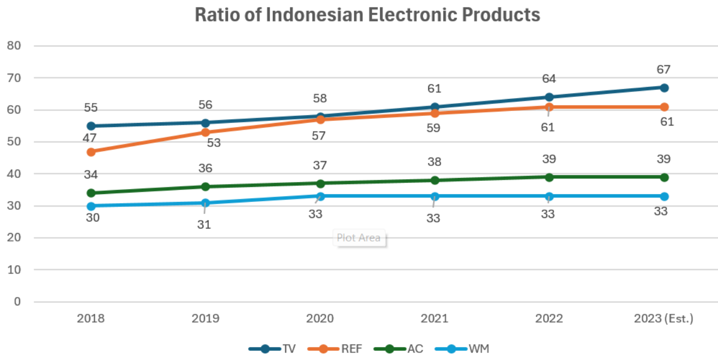

Fig. 1. Penetration ratio of electronic products in Indonesia. (Source: author).

Based on the data in Fig. 1, one tangible aspect that is highly needed is the Air Conditioner (AC). The growing importance of AC usage, both in industrial sector and in society – especially in tropical climates and warm weather – has been highlighted by several researchers. According to researchers, the role of Air Conditioner (AC) is to maintain urban productivity in high-productivity companies [9].

The demand for Air Conditioners (AC) continues to increase to meet consumer needs [10]. Supported by the data on the penetration ratio of electronic products in Indonesia, there is data on the total demand and penetration ratio of Air Conditioners (AC) in Indonesia, as shown in Fig. 2.

Based on the data in Fig. 2, the total demand for Air Conditioners (AC) in Indonesia tends to increase every year. Although in 2020 there was a decrease in demand due to the COVID-19 pandemic in Indonesia, the following years experienced greater total demand compared to 2019 and 2020. This is also consistent with the penetration ratio of Air Conditioners (AC) production in Indonesia. This data indicates that Indonesian society experiences an increasing demand for purchasing electronic products like Air Conditioners (AC) every year.

Inside the Air Conditioner (AC), several main parts support the functionality of the AC system. During production, there are residential air conditioners part costs as shown in Fig. 3.

Based on the data in Fig. 3, the heat exchanger is a part with a relatively high cost, amounting to 19%, second only to the compressor, which is the heart of the Air Conditioner (AC) system. In the functionality of an Air Conditioner (AC), the heat exchanger plays a crucial role, particularly in enhancing dehumidification and cooling. Heat exchanger technology has proven to be effective in reducing the cost of Air Conditioners (AC), especially in tropical countries that are hot and humid [11]. On the other hand, in terms of spare parts costs for Air Conditioners (AC), the heat exchanger constitutes a significant percentage of the overall production cost.

Based on the results of observations that have been made, every month an average of 13 defective air conditioner products are produced. In each production, there are still defective products originating from the production process, resulting in waste in the company. This waste has an impact on the loss of resources and time. To overcome this, the company needs to carry out quality control and improvement that can help reduce product defects so that waste can be reduced.

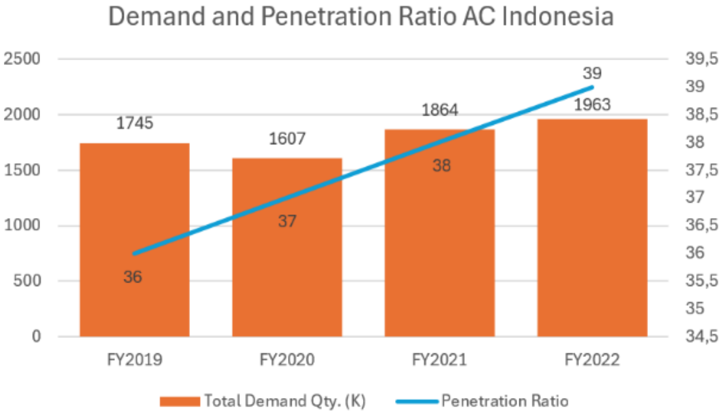

Fig. 2. Total demand and penetration ratio AC Indonesia. (Source: author).

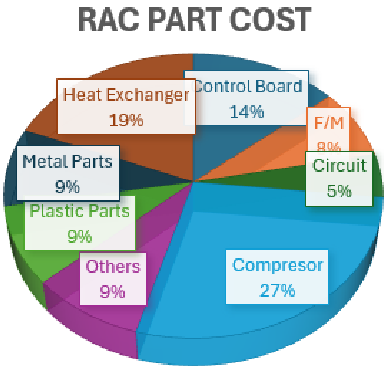

Fig. 3. Residential air conditioner part cost. (Source: author).

The high percentage of production cost attributed to the heat exchanger in Air Conditioner (AC) units is due to various defects, including corrosion-related failures due to fabrication and welding defects, improper material selection, poor water chemistry, erosion, holes, and gaps (Ali, 2020). Failure of the heat exchanger results in the formation of frost or ice on both the condenser and evaporator of the Air Conditioner (AC). Cracks, frost or ice formation, and corrosion holes in the pipes of the Air Conditioner (AC) can lead to a decrease in heat transfer capacity, potentially causing leaks and a decline in Air Conditioner (AC) performance [12]. This is supported by data on the percentage of causes of heat exchanger failure in the production period January to April 2022 is shown in Fig. 4.

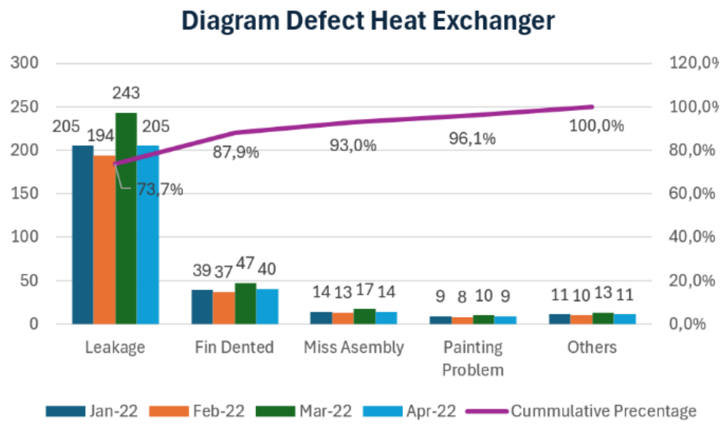

Fig. 4. Defect from heat exchanger. (Source: author).

In Fig. 4, the data shows that the most significant consequence of heat exchanger defects is pipe leakage in the Air Conditioner (AC), with a percentage of 73.7%. To improve quality in Air Conditioner (AC) production by utilizing double rows in the condenser and evaporator, the Six Sigma method can be applied. The Six Sigma method is often used by companies to control products by minimizing the number of defective products [13], [14]. With the Six Sigma method and the five steps of DMAIC, it becomes a tool for improving products and can be applied according to the principles of lean manufacturing, which have the same goals [13]. In the further production problem-solving stage, methods like Failure Mode and Effect Analysis (FMEA) with fuzzy logic and Fault Tree Analysis (FTA) can systematically analyze and sequence problems, thus obtaining an Risk Priority Number (RPN) to determine the priority of improvements to be made [15].

1.1 Literature Review

Sarwar has researched the implementation of Six Sigma principles and DMAIC problem-solving techniques in the case of electrical cable design. The expansion and modification of machines have successfully increased productivity with a 20.5% reduction in production costs [16]. Supported by the research results of Ricky Lu, the DMAIC method was used to reduce the failure/defect rate of measurements in Scanning Electron Microscope (SEM). The failure rate of SEM measurements decreased from 46.3% to 1%, resulting in cost savings equivalent to $39 million [17].

Kania utilized the Failure Mode and Effect Analysis (FMEA) method, resulting in production machines being able to reduce the Risk Priority Number (RPN) to an acceptable level. Through problem analysis, the machines were found to reduce production costs and improve worker effectiveness in performing their tasks [18].

The research conducted by [19] on risk assessment in the visual inspection process of motor vehicle components was carried out using the DMAIC method integrated with fuzzy logic FMEA. The FMEA system enabled detailed classification of failure causes. Furthermore, it was possible to classify fuzzy RPN values according to linguistic RPN variables [19].

Jiadong Ji's study found that the heat exchanger is a commonly used tool for energy exchange in the fields of aviation, chemistry, and cooling production. When conventional tubular heat exchangers operate, the heat transfer elements inside vibrate under the influence of fluid. Excessive heat transfer can weaken the heat exchanger, reducing its lifespan [20].

2 Research Method

In this research article, the Define, Measure, Analyze, Improve, Control (DMAIC) method, derived from the Six Sigma framework, is integrated with the Failure Mode and Effect Analysis (FMEA) method and the Fault Tree Analysis (FTA) method. The aim is to obtain a systematic and sequential analysis method for problem-solving to improve production quality.

The DMAIC method is used to obtain solution analysis to improve quality and reduce defects in Air Conditioner (AC) production. The DMAIC method has been successfully applied in various industries, resulting in increased customer satisfaction [21]–[23]. As an application of the Six Sigma method, the calculation of Defects per Million Opportunities (DPMO) is conducted to determine the magnitude of defects in heat exchanger production. The DPMO calculation is as Eq. 1-Eq. 2.

$$DPO = \frac{\text{the number of defects found (D)}}{\text{number of units inspected (U)x defect criteria (O)}} \quad (1)$$

$$DPMO = DPO \times 1.000.000 \quad (2)$$

In efforts to improve product quality, it's essential to identify issues in the production process. The Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) methods are utilized to analyze problems in production quality, potential production failures, and the likelihood of risks before losses occur. To achieve efficient research results and minimize qualitative defects in visual inspection, the FMEA method with fuzzy logic is employed.

The fuzzy logic FMEA method formulates the Risk Priority Number (RPN) variably with subjective and vague contexts [19].

Data collection techniques using interview and interview techniques. Both of these techniques are used to explore data related to the types of AC produced by PT XYZ, namely the type of central AC, floor-standing AC, and spilt wall AC. The three ACs produced have their respective functions and uses. In addition to using interviews and observations, this study applies the FMEA method using a fishbone diagram to analyze problems in the production of Air Conditioners (AC).

The process stages in implementing the FMEA method use a fishbone diagram to analyze issues in Air Conditioner (AC) production. The application of the FMEA method yields the Risk Priority Number (RPN), with calculations as Eq. 3.

$$RPN = S \times O \times D \tag{3}$$

Information:
S : Severity
O : Occurrence
D : Detection

3 Results and Discussion

The process of checking the production results of the heat exchanger involves immersing the product in water. A water pump or other pressure source is required to increase the pressure inside the heat exchanger. The pressure applied during testing must be higher than the operational pressure of the heat exchanger during normal operation. Changes in pressure during the testing period are used to detect pressure drops indicating leakage. Leakage is detected if air bubbles appear in the water.

The impacts resulting from heat exchanger leakage include the formation of frost on the heat exchanger and suboptimal performance of the air conditioner (AC), resulting in the set temperature not being reached. In field conditions, pipe leakage of the heat exchanger exists based on the types and shapes of pipes as shown in Fig. 5.

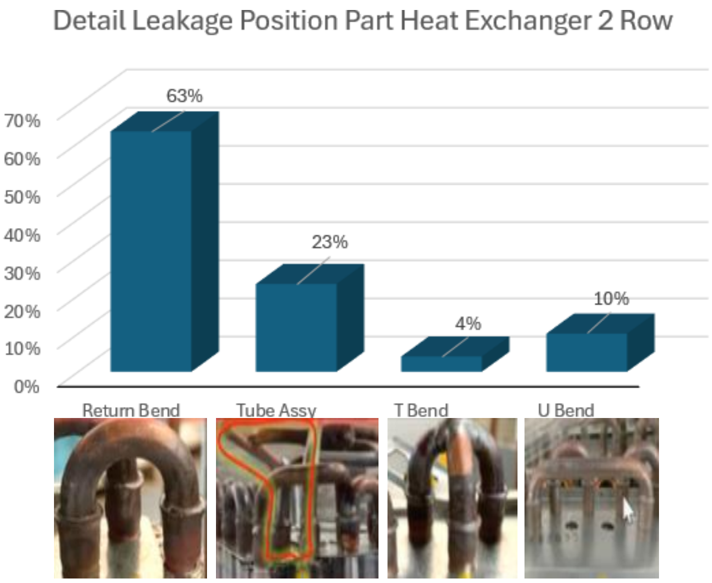

Fig. 5. Percentage of leakage based on pipe shapes. (Source: author).

Based on Fig. 5, pipe leaks occur most frequently in the return bend and tube assembly pipe types, indicating the need for further inspection in the production process to minimize defects in the heat exchanger pipes.

3.1 Measure

Based on the arrangement patterns of heat exchanger pipes, they are divided into 3 types: Evaporator 2 Row (EVA 2-R), Condenser 2 Row (COND-2R), and Condenser 1 Row (COND-1R). Production data on defects occurring in each type of heat exchanger pipe arrangement pattern are listed in Fig. 6.

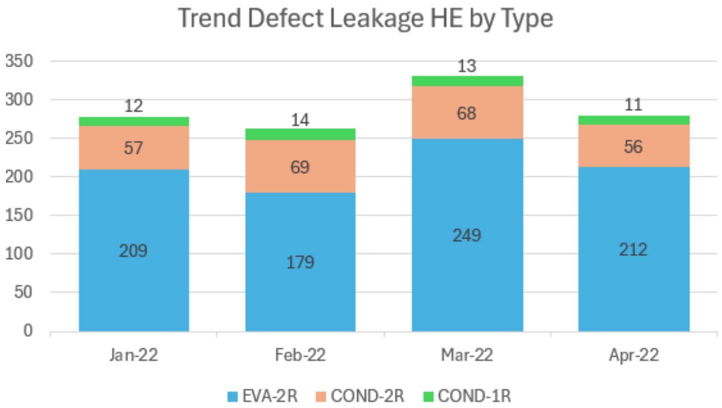

Fig. 6. Leakage of heat exchanger pipes based on arrangement patterns. (Source: author).

Based on Fig. 6, the defects occurring based on the arrangement patterns of heat exchanger pipes are Condenser 2 Row (COND-2R) and Evaporator 2 Row (EVA-2R). In the production process, there are criteria for defects that are the main focus for improvement. The defect criteria in heat exchanger pipe production are listed in Table 1.

Table 1. Defect criteria

Process	Defect criteria
Brazing	Diameter flaring out of spec
	Diameter flaring is too big
	Brazing material is not pure
	Gas flow rate setting is not standard
	Ring solder unbalance
	Brazing skill out of standard
	Brazing skill unstable
	Oil, water, and dust contamination

(Source: author).

The defect criteria in heat exchanger production are found in the brazing stage. In the brazing process of the heat exchanger, 8 criteria have the potential to cause product defects and can serve as indicators of product defects. A summary of the Defects per Million Opportunities (DPMO) calculation results over 4 months as the capability for the brazing process is listed in Table 2.

Table 2. DPMO capability for brazing process

Month	Units inspected (U)	Defects found (D)	Defect criteria (O)	DPMO
Jan-22	30,000	266	8	1,108.4
Feb-22	30,000	248	8	1,033.4
Mar-22	30,000	317	8	1,320.8
Apr-22	30,000	268	8	1,116.7
Average	30,000	275	8	1,144.8

(Source: author).

Based on Table 2, from the four-month sample data of defects, an average of 1,144.8 defective products per one million productions is obtained. Throughout the year 2022, production in each month amounted to 30,000 products. The highest defect found and DPMO occurred during that period in March 2022 with a DPMO of 1,320.8. In this study, the established target is to reduce defective products by 26.2%.

3.2 Analysis

The fuzzy logic Failure Mode and Effect Analysis (FMEA) method involves stages of identification, determination of values, and calculation. The steps for analyzing problems using the FMEA method are as shown in Fig. 7.

The failure mode identification is conducted during the heat exchanger production process. The production process of the heat exchanger starts with the application of high/head pressure to provide high fluid pressure. Fins are added as additional heat exchangers to enhance heat transfer efficiency by increasing the surface area. Expansion tubes are added to the heat exchanger to expand the level and capacity of the pipes as heat exchangers. The heat exchanger is dried as the final step before the manufacturing process. On the other hand, evercut return/bypass insertion is carried out, followed by cleaning processes, and then rings are added as pipe connection media. The manufacturing process begins with pipe cutting using a mechanical high-pressure valve or using airflow capacitor. Three assembly processes are carried out to form them according to requirements, such as r-bend and tube assembly. The key process of the heat exchanger in the condenser and evaporator of the Air Conditioner (AC) is done manually by brazing operators and automatically using brazing robots. Finally, a high-pressure valve check is performed by inspecting and testing whether the heat exchanger can withstand the high pressure from the air-cooling system and leakage inspection.

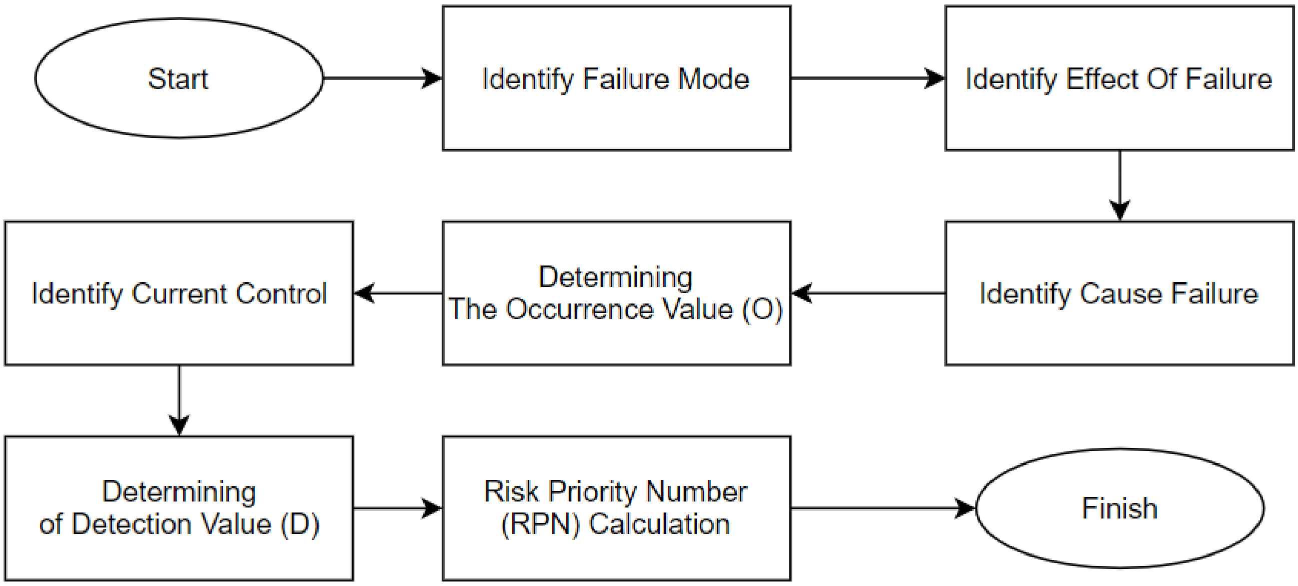

Fig. 7. Steps of Failure Mode and Effect Analysis (FMEA). (Source: author).

Identifying the effects of failure is conducted to analyze the root causes of defects in the production of Air Conditioners (AC) using a double-row heat exchanger with leakage. The root causes are found in both manual and automatic production processes. The analysis of the issues is divided based on supportive elements, namely the 4Ms (Method, Man, Machine, Material). The process of analyzing the root cause factors as the implementation of the fuzzy logic Failure Mode and Effect Analysis (FMEA) method using cause-effect tools is illustrated using a fishbone diagram as shown in Fig. 8.

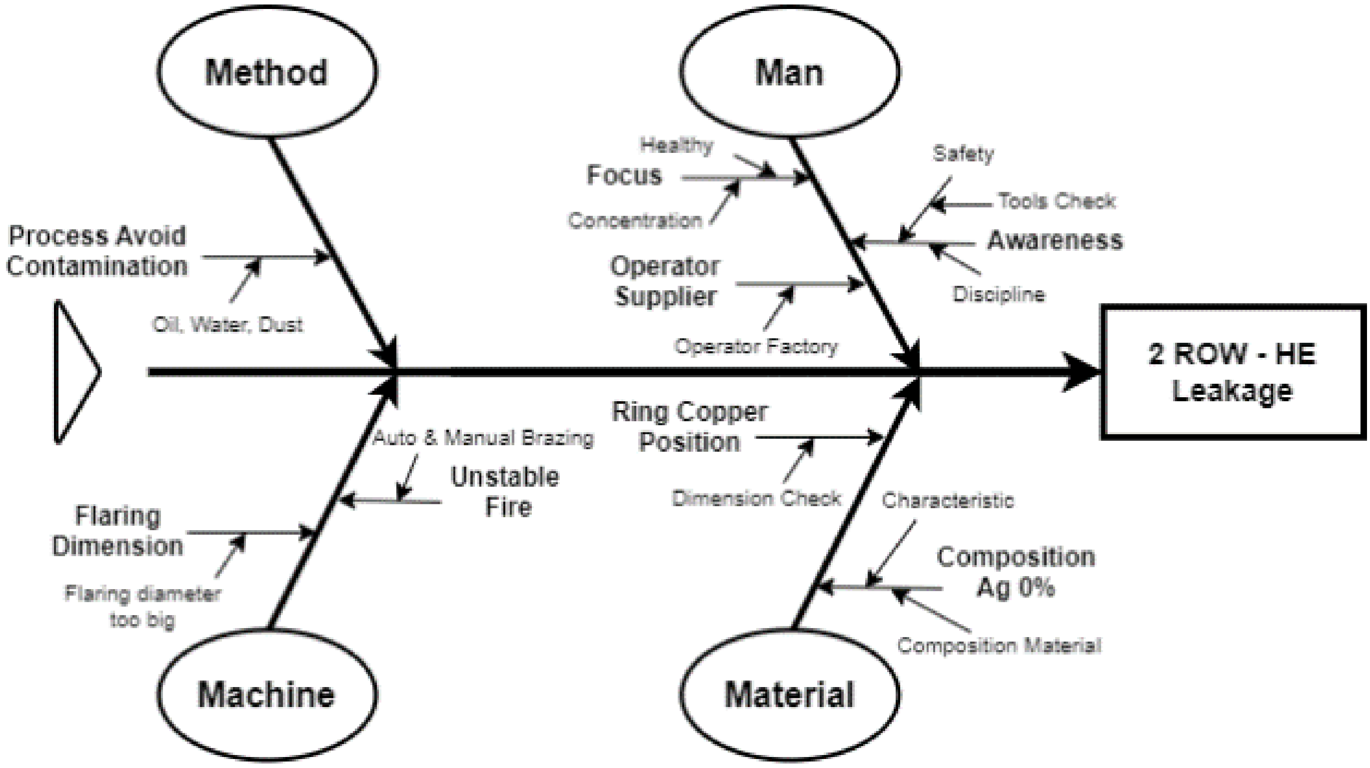

Fig. 8. Fishbone diagram. (Source: author).

Based on Fig. 8, the root causes of defects in Air Conditioner (AC) production can be outlined as: for double row heat exchanger leakage with manual brazing methods: contamination (method), uneven brazing skill (man). For the automatic brazing method, the root causes of defects include poor flaring and gas flow rate (machine), poor r-bend quality, and impure brazing material (material). Further analysis is conducted to identify possible defects using the Fault Tree Analysis (FTA) method, presented as a tree diagram analysis as shown in Fig. 9.

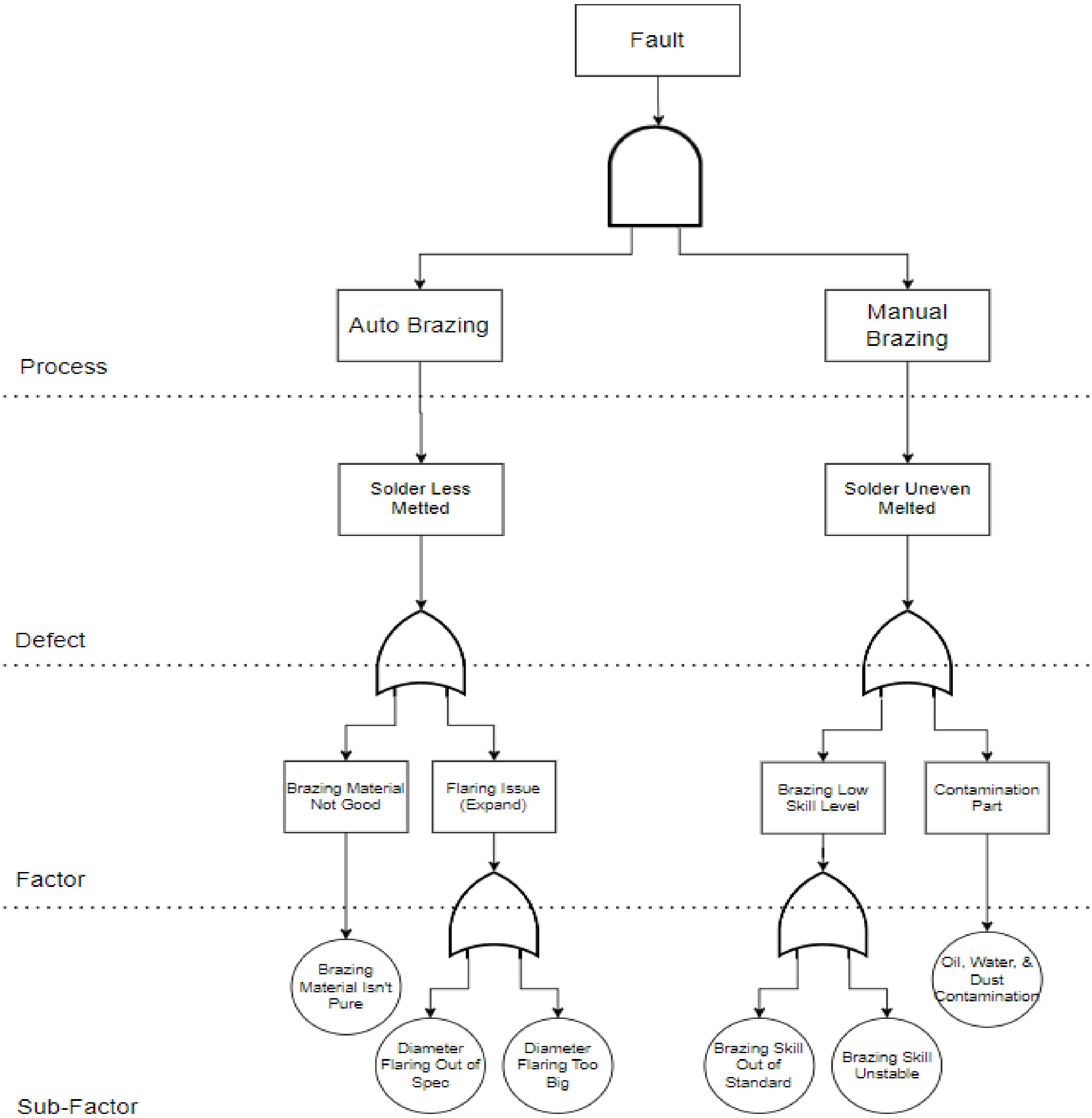

Fig. 9. Tree diagram analysis. (Source: author).

The factor causing solder-less melted defects is a flaring issue with a diameter that is too large. The measured flaring volume (solder melted) is 132.6 mm^3, with a ring solder volume of 54.36 mm^3, resulting in an imperfect pipe connection for the Air Conditioner (AC) heat exchanger. A smaller flaring size than the solder ring is required to ensure proper pipe fitting and prevent leakage [24]. Measurements of the volume and diameter of fluid-exiting pipes and gas-liquid flow continuity can be produced with high precision and reliability [25]. Further analysis involves calculating the volume and diameter of flaring on the heat exchanger pipe using the calculation Eq. 4-Eq. 8.

1. Area

$$A = wl \quad (4)$$

2. Area Δ

$$A = 1/2bh \quad (5)$$

3. Circumference

$$C = \pi D \quad (6)$$

4. Volume

$$V = (A\Delta + A\square) \times C \quad (7)$$

5. Flaring Harpin

$$h = \emptyset Flaring - \emptyset H/P \quad (8)$$

The calculation results for the analysis of flaring diameter and volume, as well as ring solder, yield data with recommended sizes that match the results Table 3.

Table 3. Flaring calculation results

Calculation	Ring solder size	Old flaring size (⌀ 13mm)	Size recom.
Area Δ (mm^2)	2.01	4.55	1.74
Area □ (mm^2)		0.19	0.19
Circumference (mm)	27.03	28.28	28.28
Volume (mm^3)	54.36	132.6	54.58

(Source: author).

Based on Table 3, the flaring volume that approaches the size of the solder ring volume, with a tolerance of ± 0.5 mm, yields a recommended volume size of 54.58 mm^3, with a diameter of 9.5 mm and a tolerance of ± 0.5 mm. The selection of diameter and volume numbers on the flaring should be below the size of the solder ring, but with a small difference to provide tolerance or space in the heat exchanger connection.

The issue with uneven melted solder is caused by the factor of low brazing skill level, specifically unstable brazing skill. Further analysis is conducted on operators with skill level A. A sample monitoring of operators is taken over 10 days, with data on the control defect ratio of brazing results (daily) as shown in Fig. 10.

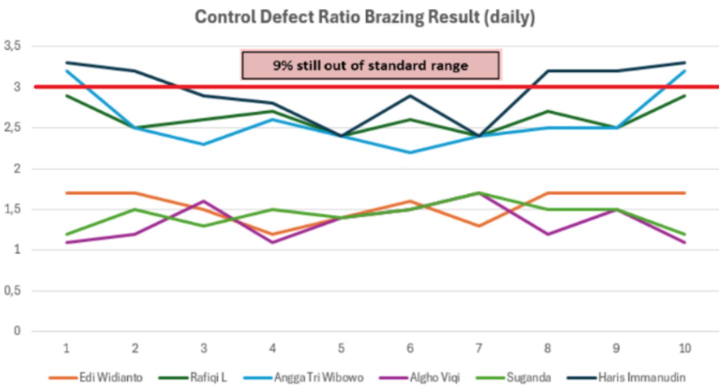

Fig. 10. Control defect ratio brazing result (daily). (Source: author).

Based on the data in Fig. 10, operators with skill level A still have a defect rate in brazing of over 3%. The brazing defect rate by operators with skill level A has several factors, including lack of confidence, lack of motivation, and stress. As an implementation of the Failure Mode and Effect Analysis (FMEA) method, severity, occurrence, and detection ratings are determined, and the Risk Priority Number (RPN) is as shown in Table 4.

Table 4. Risk Priority Number (RPN)

Type of work	What	Why	Risk assessment			RPN
			Severity (S)	Occurrence (O)	Detection (D)	
Automatic brazing	Solderless melted	Diameter flaring is too big	7	10	7	490
Manual brazing	Solder uneven melted	Brazing skill unstable	5	10	7	350

(Source: author).

In the case of solder-less melted defects with the issue of flaring diameter too big in the key process of automatic brazing, a severity rating score of 7 with a high level is determined. The severity of the defect depends on the size of the punch used to form the flaring. If solder-less melting occurs in the heat exchanger, it will have a significant adverse effect. Users will experience a decrease in Air Conditioner (AC) quality beyond tolerance limits, as the AC's performance will not be optimal, leading to ice formation on the heat exchanger.

The defect of uneven melted solder due to unstable brazing skill in the manual brazing key process is determined to have a severity score of 5. The severity of the defect depends on the brazing operator, with a percentage of the 9% control defect ratio of brazing results (daily). Not all 9% of the failures in manual brazing by the brazing operator have a high adverse effect, so they can be categorized as having a moderate adverse effect.

The occurrence score for both manual and automatic brazing key processes is given a score of 10. In manual brazing, based on the control defect ratio of brazing results (daily), it is found that 9% of the work is outside the standard limits. Furthermore, in automatic brazing, if the diameter of the flaring punch is outside the standard, the flaring size remains too large and does not change, so failure is almost certain to occur.

The detection level score for manual and automatic brazing key processes is given a score of 7. There is a possibility that the heat exchanger is currently defective. Defects in the brazing process of heat exchangers are detected by immersing the brazing results in water, making the identification and inspection of defects easy to detect.

3.3 Improvement

In the improvement phase, quality enhancement is undertaken to address the issues. An analysis of solutions is conducted using the 5W+1H method to implement the most appropriate solution to address the defects in the heat exchanger. The results of the 5W+1H analysis as a repair plan for the heat exchanger are listed in Table 5.

Table 5. Analysis of 5W + 1H

What	Why	Where	How	Who	When	Result
Solder less melted	Flaring volume bigger than ring solder	Heat exchanger (expand)	New flaring dimension (diameter) 9.5 ± 0.5 mm	Fiqri & Deny	Oct'22 – Jan'23	0.45% → 0.25% (Up 38.1%)
Brazing skill unstable	Brazing skill unstable	In-house supplier	Upgrade new module and brazing internal convention	Adi Sutisna & Darda	Jun'22	0.41% → 0.36% (Up 22.6%)

(Source: author).

The improvements made in the 5W+1H analysis align with the Risk Priority Number (RPN) to reduce defects in the heat exchanger. The new recommended diameter for the flaring is 9.5 mm. An analysis of the punch size as the mold and the flaring size can be calculated using the Eq. 9.

$$\text{Diameter calculation} = \frac{\text{ØOld Punch}}{\text{ØOld Result}} = \frac{\text{ØNew Punch}}{\text{ØNew Result}} \quad (9)$$

The comparison between the old punch diameter and the new punch diameter is directly proportional to the flaring diameter. Hence, with the new punch diameter set at 8.5 mm, a resulting flaring diameter of 9.5 mm is achieved, with a measured volume of 54.58 mm^3 ± 0.5 mm. The volume of the new flaring has reached a smaller value than the solder ring volume. As a further step, testing is conducted on the new punch diameter and flaring diameter. The test results for the new flaring diameter are shown in Fig. 11.

Based on Fig. 11, in the testing data of the new flaring diameter, out of 50 tests conducted, there are 4 test results below the standard (<9mm/not good). However, the Capability Index Process (CPK) value is significantly above 1, indicating that the punch diameter and flaring diameter sizes can still meet the product specifications effectively.

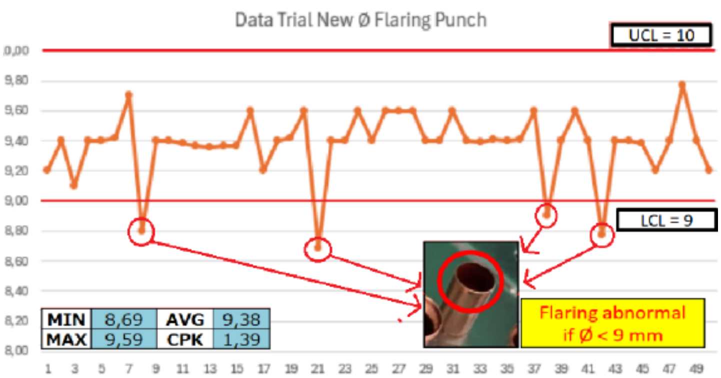

Fig. 11. Data testing results of new flaring diameter. (Source: author).

The brazing operator, certified as Level A, may be considered proficient and possess high standards. However, even with Level A certification, the brazing operators still yield a production defect rate of 3% in manual brazing processes. The instability in skill arises from factors such as lack of confidence, motivation, and stress among the brazing operators. If left unaddressed, this unstable skill level among brazing operators could lead to losses and a decline in product quality.

The improvement strategy regarding unstable skills among brazing operators involves certifying their skills and providing training. The certification and training activities aim to recognize operators with above-average skills and motivate them to consistently deliver high-quality brazing results. The schedule for certifying skills and training brazing operators is outlined in Fig. 12.

Training 1

No	Item Training
1	Reading drawing module
2	Measurement skill

Training 2

No	Item Training
1	Assembling module
2	Bending pipe

Internal Certification

No	Item Training
1	Quality inspection
2	Time management

Internal Convention

No	Item Training
1	Theoretical test
2	Practical test

Fig. 12. Stages of skill certification and training. (Source: author).

The first step involves training operators to read schematic diagrams for planning Air Conditioner (AC) heat exchangers, followed by retraining in reading and using standardized measuring tools. Subsequently, brazing operators receive training in bending pipes and assembling heat exchangers. Once operators have completed these two stages of training, internal and conventional certifications are conducted to assess the quality, speed, theory, and practice of brazing.

Period Aug 2021

Category	Total Brazing Operator	Level			Status
		A	B	C	
Permanent	4	4	0	0	∆
Contract	2	0	2	0	∆
Intern	0	0	0	0	-
Total		4	2	0	
Precentage		66.6%	33.3%	0	

Period Feb 2022

Category	Total Brazing Operator	Level			Status
		A	B	C	
Permanent	4	4	0	0	∆
Contract	2	2	0	0	∆
Intern	0	0	0	0	-
Total		6	0	0	
Precentage		100%	0%	0	

Level Up Operator

Category	Total Brazing Operator	Level			Status
		A	B	C	
Permanent	4	4	0	0	∆
Contract	3	0	3	0	-
Intern	0	0	0	0	-
Total		57.1%	42.8%	0	

Category	Total Brazing Operator	Level			Status
		A	B	C	
Permanent	4	4	0	0	∆
Contract	3	3	0	0	∆
Intern	0	0	0	0	-
Total		100%	0%	0	

Level Up Operator

Fig. 13. Results of operator competence implementation. (Source: author).

Based on the results of the brazing operator certification and training, the operator's skill level has increased to 100%, and the defects produced have been minimized. The certification and training activities can be considered successful in maintaining skills and raising awareness of operator quality.

Based on the improvements made, standardization in the heat exchanger production process can be formulated. The goal of standardizing the heat exchanger production process is to ensure that every innovation that has been established will be documented and serve as a reference for future heat exchanger manufacturing. Consequently, the defects produced in the heat exchanger decrease. The form of standardization conducted is:

1. Diameter flaring to big
   a. Releasing standardization of 4M design regarding the change in flaring diameter to 9.5 mm ± 0.5 mm tolerance.
   b. Revising the working drawing related to flaring on the fin and tube condenser.
2. Brazing skill unstable
   a. Updating the standard brazing convention module.
   b. Updating the operator evaluation check sheet.

3.4 Control

The control phase is carried out to monitor the production process of the heat exchanger for the defects that have been improved. The goal is to improve the quality of the heat exchanger products and reduce defects in the heat exchanger. Controls implemented in the heat exchanger production process include:

3.4.1 Monitoring after Flaring Diameter Changes

After standardizing the diameter changes in flaring, operators began creating flares with the new diameter. Defect monitoring was conducted for five months in the heat exchanger production process, with the results as shown in Fig. 14.

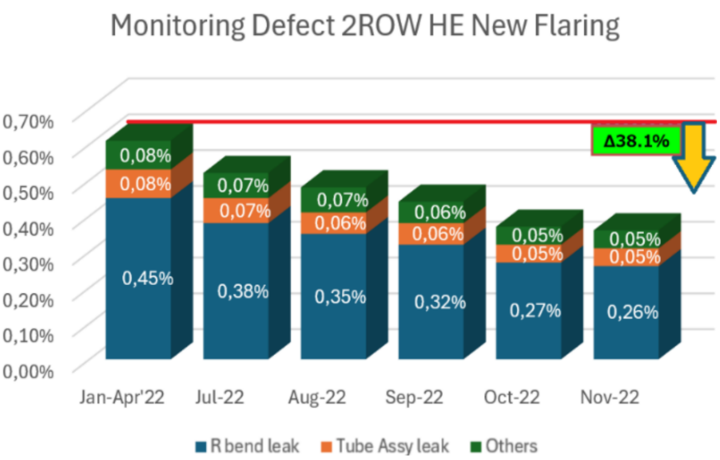

Fig. 14. Monitoring after flaring diameter changes. (Source: author).

Based on Fig. 14, after standardizing the new flaring diameter, there was a decrease in the production defect rate in the heat exchanger every month. When compared to the average production defect data of the heat exchanger during January-April 2022, with November 2022, there was a decrease in the production defect rate of 38.1%.

3.4.2 Monitoring after Skill Certification and Training Operator Brazing

After conducting skill certification and training for brazing operators, monitoring and comparison of the percentage of brazing defects were performed for each type of pipe bend in the heat exchanger. The comparison was made with the average data from January to April 2022 with the data from May to June 2022. The defect monitoring results are shown in Fig. 15.

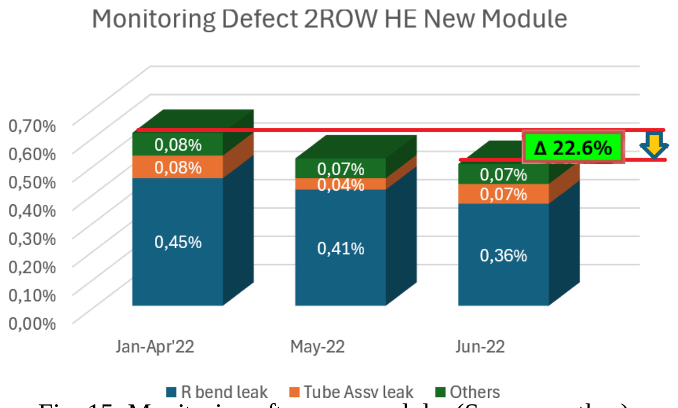

Fig. 15. Monitoring after new module. (Source: author).

Based on the data in Fig. 15, there was a significant decrease after conducting skill certification and training for brazing operators. In just two months, brazing operators demonstrated more stable skills in brazing heat exchangers. Certainly, in the next stage, it is necessary to conduct skill certification and training for brazing operators periodically to maintain the stability of their brazing skills.

3.4.3 Check Sheet Creation

The creation of a brazing evaluation check sheet is conducted to determine indicators and parameters for successful brazing by operators. It allows evaluation and monitoring of operators' brazing by quality control. The results of the check sheet creation are shown in Fig. 16.

In Fig. 16, there are points assigned to each indicator for evaluating the operator's brazing. A minimum total score is set for the brazing results to be deemed acceptable or to meet the minimum standard.

3.4.4 Calculation of DPMO after Improvement

After the improvement of the heat exchanger defects, DPMO calculation monitoring was conducted from October 2022 to December 2023. The results of the DPMO calculation are shown in Table 6.

Table 6. DPMO capability after improvement

Month	Units inspected (U)	Defects found (D)	Defect criteria (O)	DPMO
Oct-22	30,000	75	8	312.5
Nov-22	30,000	90	8	375
Dec-22	30,000	115	8	479.2
Jan-23	33,300	119	8	446.7
Average	30,825	100	8	403.35

(Source: author).

Brazing Evaluation Sheet 1

Participant No.	1st total point

Dimension Item and Evaluation Standard				Minus Point	Max. Limit	Evaluation		Total deducted points
Practical time	Standard time	60	mins	1 point/min	No Limit		mins.	
	Maximum time	80	mins					
Remain Brazing rod (Ag=1pcs, Ag =1pcs)	Silver (Ag: 5%)	250	mm	1 points / 5 mm	25 points		mm	
	Copper (Cu=Ag; 0 %)	200	mm				mm	
Wrong brazing rod used (Ag)	Sambungan beda bahan			5 points/ joint	15 points		location	
Wrong brazing rod used (Cu)	Sambungan bahan yang sama						location	
Brazed joint	Salah mengelas nyambung			3 location	6 points		location	
	Lupa mengelas sambungan			3 location	6 points		location	
Flare nut	Salah Mengelas			5 points/joint	5 points		location	
Dimension A	Lebar Modul	180,0	mm ±2	2 pnts /2mm or /2 °	10 points		mm	
B	Panjang dalam Modul	300,0	mm ±2				mm	
C	Tinggi dari base pan	150,0	mm ±2				mm	
D	Jarak pipa manipol dengan Nut	100,0	mm ±2				mm	
E	Panjang Capilary	86,0	mm ±3				mm	
F	Tinggi pipa U bending Nut	20,0	mm ±3				mm	
G	Jarak pipa L dengan U shaped tube	30,0	mm ±3				mm	
H	Jarak U Bending ke R/bend	68,0	mm ±3				mm	
Kondisi Pipa [Melengkung , Melintir]				3 pnts /1loc.	No Limit		location	
				Total				

Fig. 16. Operator evaluation check sheet. (Source: author).

Based on Table 6, the DPMO value after the improvement shows a significant decrease. With the previous average DPMO of 1,144.8, and the average DPMO from October 2022 to January 2023 reaching 415.6. When comparing the highest DPMO before and after the improvement, there is a decrease of 841.6. So, it can be interpreted that the improvements made have successfully reduced defects in the product by referring to the decrease that occurred.

Improvements were implemented over a period of one year and one month based on the established Risk Priority Number (RPN), with the results shown in Fig. 17.

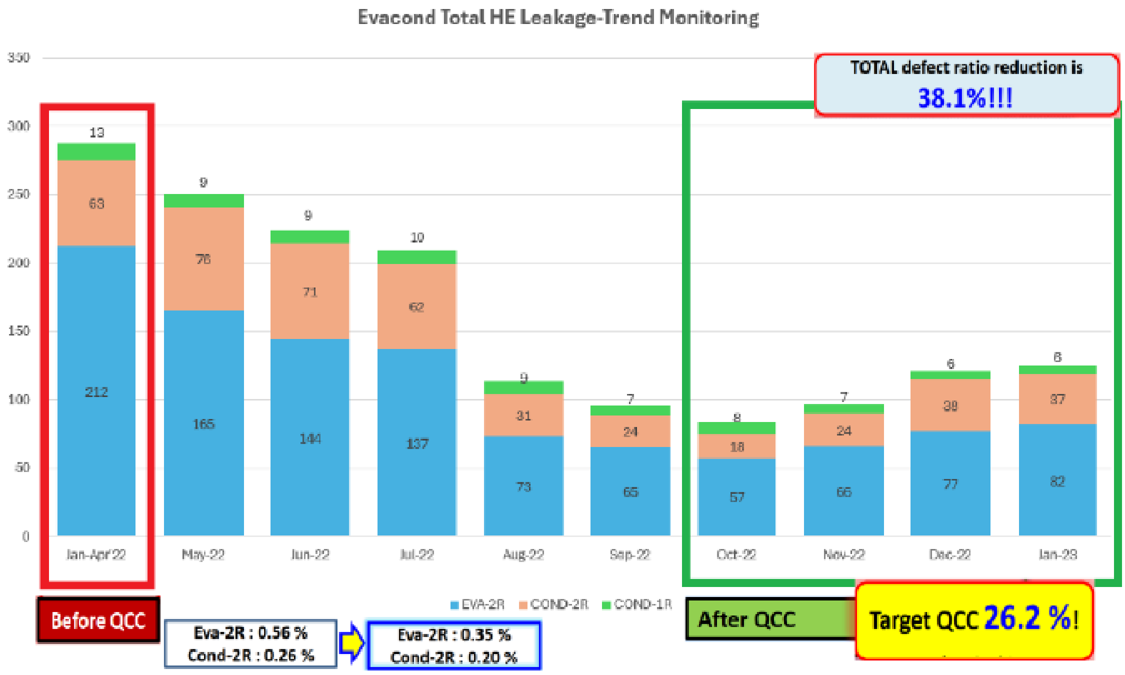

Fig. 17. Results of heat exchanger monitoring. (Source: author).

Based on the data in Fig. 17, the results of the improvements yielded a defect ratio reduction of 38.1%, equivalent to $31.96 per month or $383.5 per year. This reduction in defect ratio far exceeded the target of 26.2%.

The reduction in defect rates in heat exchanger production can be compared to the study by Sawant, which discusses the application of Six Sigma principles in the construction industry to improve quality. Construction quality significantly and directly impacts potential influencing factors. The use of the Six Sigma method demonstrates a systematic approach to identifying and improving processes to reduce defect rates [26].

In a similar industry, Harisupriyanto discusses improving the quality of manufacturing products using the Six Sigma method. Using the same method and analysis as this study, there was a cost reduction of 25%. Three critical wastes were identified as the basis for continuous process improvement, totalling 66% [27]. However, this study shows that the impact of improvements resulted in a 38.1% improvement with a residential part cost of 19%. This indicates that the impact of production defects results in greater improvement than the percentage of defects that occur.

4 Conclusion

In air conditioner production, the heat exchanger ranks as the second-highest cost component after the compressor. Leakage in the heat exchanger, often due to issues in the brazing process, forces the compressor to overwork, reducing AC performance, and can visually appear as frost on the exchanger. The research was concluded as:

1. Defect analysis with Six Sigma's DMAIC approach on heat exchangers, especially in double-row condensers and evaporators, showed a defect rate of 1,144.8 Defects per Million Opportunities (DPMO) through. Fault Tree Analysis (FTA) pinpointed two main issues. The first one was solder less melted due to oversized flaring (8.5 mm) and the second one was uneven solder melt from inconsistent brazing skills of the welders. The highest risk, with an RPN of 490, was associated with automatic brazing.
2. To address these issues, the punch diameter was refined to 8.5 mm, and operator skill certification and training were implemented. These steps led to a 64.7% decrease in DPMO and a 38.1% reduction in defect rate, surpassing the 26.2% target. Standardizing these improvements enhances consistent production quality and offers a model for expansion to other cooling electronics production.

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