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Study of Material Flow Analysis Mapping in Supply Management Chain for the Management of Non Functional Device Transformers

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Abstract

This research investigates the optimization of supply chain management for Non-Functional Device (NFD) transformers at PT XYZ through the integration of Material Flow Analysis (MFA) and Analytic Hierarchy Process (AHP). The study addresses the issue of material accumulation and environmental impact arising from inefficient management of decommissioned transformers. MFA to model and evaluate three management scenarios based on mass flow and carbon emissions, while AHP facilitated decision-making by prioritizing five key criteria and eleven sub-criteria. Data were collected through interviews, questionnaires, and internal company records. The results show that Scenario 3 eaturing transformer oil regeneration and component reuse yielded the lowest carbon emissions (101.981 kg CO_2/month) and the highest priority score (0.628) in AHP analysis, with regulatory compliance emerging as the most critical factor. This indicates that Scenario 3 offers the most sustainable and efficient strategy, enabling the company to reduce emissions, recover material value, and improve overall supply chain performance

Introduction

In the context of the industry modern, Material Flow Analysis (MFA) has become an important tool in supporting sustainable resource management, especially in the context of supply chains (Thushari et al., 2020). Material Flow Analysis (MFA) is a material flow analysis which is a systematic assessment of the flow process and material inventory in the system which is defined in space and time(Brunner and Rechberger, 2004). MFA allows the identification of material flows in a system, so that it can map potential inefficiencies and material losses (Houssini et al., 2025). According to research Budihardjo et al., (2023), the application of MFA has shown its effectiveness including in the energy and manufacturing sectors, to optimize the use of resources and reduce waste. Research by Giboulot et al., (2024) indicates that MFA assists companies in identifying material flow critical points that can lead to decreased operational efficiency. On a global scale, efforts to improve supply chain efficiency through material flow analysis are also driven by the need for sustainability and increasingly stringent environmental regulations (Azizi et al., 2023; Sun et al., 2025; Houssini et al., 2025; Cullen & Cooper, 2022). The importance of efficient waste management to support circularity and environmental sustainability (Azizi et al., 2023). The purpose of the MFA method is to measure the flow of material flowing in the process so that it can be used as a step to provide input or suggestions for the improvement of industrial system models (Faisal, 2020). In a system, the process changes the flow of incoming material (Input) outflow material (Output). Output of any of the processes may represent Input from the next process

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(Yusuf, 2022; Bochkay et al., 2023; Rossi, 1991). Thus, the application of MFA in the supply management chain becomes relevant.

PT XYZ in the management of Non-Functional Device (NFD) transformers is one of the challenges in the supply chain. In January 2025 at the PT XYZ warehouse, there are various transformer materials with different statuses and treatments. Of the total 45 existing transformer units, 1 unit (2.22%) is in *standby* condition, and 2 units (4.44%) are transformers in the warranty claim process, 32 units (71.11%) are categorized as removal or waste transformers that no longer have a warranty, 3 units (6.67%) are in the repair period without warranty, and 7 units (15.56%) are transformers in PDP (Work In Implementation), namely materials that are being prepared for the project that is being implemented.

According to Wijaya et al. (2021) the high number of transformers that are no longer in use or NFDs, especially in the category of removal/waste and repair without warranty, indicates potential problems in asset management and *supply chain* efficiency (Mastos et al., 2021).. This condition poses potential such as material accumulation and space limitations, maintenance costs and environmental losses due to inappropriate waste handling (Hosseini and Crawford, 2024). This problem is exacerbated by the lack of integration in the material flow management system, which leads to delays in the decision-making process regarding the effectiveness of NFD management. Thus, a structured approach is needed to map the flow of materials comprehensively so that this problem can be overcome efficiently and effectively (Valle & Oliver, 2021; Papetti et al., 20219; Kalteh et al., 2008).

Taking into account the urgency of the problem, the main purpose of this study is to map the flow of non-functional transformer materials (Non-Functional Devices / NFDs) at PT XYZ, where until now there is no clear flow diagram regarding the journey of transformer materials from upstream to downstream. In the use of the Material Flow Analysis (MFA) method, is lined up and determines the optimal management strategy with the Analytic Hierarchy Process (AHP) approach (Vásquez-Ibarra et al., 2024). So that the application of MFA in this study aims to identify and analyze the flow of transformer materials from upstream to downstream (Shahbudin & Kamal, 2020), with the use of 3 scenarios including the stages of procurement, use, maintenance, to the final handling process such as recycling, reuse, or disposal. Meanwhile, Detiar et al., (2023) the AHP method will be used to assist decision-makers in choosing the best strategy based on the scenarios presented with a focus on operational and environmental efficiency (Mikkelsen et al., 2020).

The use of a combination of MFA and AHP in this study aims to determine treatment priorities based on certain criteria, environmental risks and urgency of replacement. Material Flow Analysis (MFA) enables systematic analysis of material flows within the life cycle of the NFD transformer, helping to identify inefficiencies, optimize resource utilization, and reduce environmental impact with STAN software. Meanwhile, the Analytical Hierarchy Process (AHP) is used to assess these scenarios based on aspects such as energy efficiency, cost, and sustainability, resulting in the best choice in the management of NFD transformers. Therefore, this study will fill the gap by focusing on the integration of Material Flow Analysis (MFA) and Analytical Hierarchy Process (AHP) in the context of NFD transformer management.The urgency of this difference lies in company need to manage NFD transformer assets efficiently to minimize environmental impacts, as well as ensure reliable continuity of electricity services for the community.

Methods

The methods used to collect data in this study are interviews and observations. It contains an explanation of how data is collected before it is processed and analyzed. There are two types of data collection methods carried out, namely:

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Primary Data Collection

Primary data is the data collected by the research (Kristianto & Rudianto, 2020), namely the criteria and subcriteria data for the necessary environmental impact decisions, the level of importance of the criteria and the evaluation data for the assessment of the final decision of processing by conducting direct observations in the field of the research object taken. To obtain primary data in the study, two methods of collection were carried out, namely:

Interview Method

Interviews are used to obtain data and information or information from things that have not been disclosed in data related to research (Harjono & Tute, 2022) or observation documents through direct communication with 2 people occupying the positions of logistics team leader and logistics junior office respectively, where both workers are said to be experts. The interview was conducted using a semi-structured technique, namely semi-structured with flexible prompts.

Questionnaire Method

The questionnaire in this study consists of two stages used to determine the best scenario in the final management of non-functional transformers (NFD) based on the results of Material Flow Analysis (MFA) analysis. The first questionnaire aimed to assess the level of importance of criteria in the selection of the final management scenario of the NFD transformer using a paired comparison scale. Respondents were asked to compare each criterion on a scale of 1 (equally important) – 9 (very much more important) to determine the relative level of priority in the decision-making process (Palasara et al., 2022). The respondents for this questionnaire are logistics warehouse officers and logistics staff of PT XYZ who have experience in material management in warehouses with a total of two respondents (Amalia et al., 2022).

Secondary Data Collection

Secondary data is a type of additional data that is not obtained from the primary source, but has been through other sources before (Jabnabillah et al., 2023). The secondary data collection technique in this study was carried out by collecting data on the movement of non-functional transformer (NFD) materials from internal sources of PT XYZ. Material movement data records the number of units moved, the origin and destination of the move, the date of the move, and the status after the move, so that the distribution patterns and flow of materials in the supply chain can be analyzed.

In the study, it is necessary to identify variables that will affect the analysis of the material flow and the determination of the putation at the end. Referring to the research problem, the following related variables can be identified:

Bound Variables

Bound variables are variables that are affected or that are the result of the existence of independent variables. In this study, the bound variables are the mapping of *Material Flow Analysis* (MFA) and the determination of the best NFD management strategy based on scenario priority.

Independent Variables

An independent variable is a variable that affects or causes the emergence or change of a bound variable (Fajri et al., 2022). The independent variables in this study are the number of NFD transformers, the type of handling of the transformer (*Standby*, repairs, removals, warranty claims, PDP), process times at each stage of the supply chain, as well as storage efficiency in warehouses, recycling methods applied, and energy efficiency in the transformer management process.

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Results and Discussion

The transformer material supply chain model at PT XYZ starts from the process of procuring new transformers by official vendors that have been registered in company procurement system. After being received, the transformer is stored in a warehouse to be distributed to the field according to the operational needs of the distribution network. In the operational process, the transformer can be damaged or expire of its service life, so it is returned to the warehouse as *a Non-Functional Device* (NFD) Transformer. In the research that has been conducted by Gawusu and Amadu (2021) this NFD transformer then goes through an identification process and technical examination to determine its condition and potential use. If it is still considered feasible, the transformer will be repaired or reused as a spare unit, while if it is not feasible, the transformer will be temporarily stored or submitted for removal through auction.

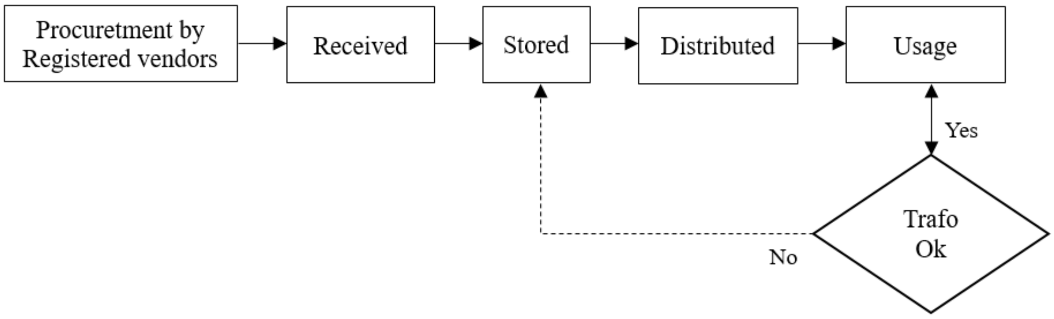

Figure 1. Transformer Flow at PT XYZ

Source: PT XYZ (2025)

This study aims to find out the mapping results of 3 scenarios for the implementation of *Material Flow Analysis* in NFD transformers using the AHP method. AHP is chosen because it enables transparent, hierarchical pairwise comparisons of criteria and sub-criteria with a built-in consistency check to derive reliable weights tailored to the multifaceted environmental, economic, and operational factors in MFA scenario selection. In contrast, TOPSIS and other distance- or outranking-based methods cannot readily model multi-level decision structures or verify judgment consistency, risking oversimplification of complex trade-offs. The AHP method helps to determine the value weight of each of the factors and sub-factors of MFA implementation. The initial stage of this AHP method is to compile an MFA hierarchy consisting of goals, criteria, sub-criteria, and alternatives. The next step is to compare comparison pairs between criteria, sub-criteria, and alternatives (Afifah & Cahyana, 2024). the criteria are taken based on suggestions from research results by Setyawan (2017) which discusses used transformers or transformers NFD and based on interview results regarding nfd transformer management.

The comparison value is filled in with a Saaty scale which has a value of 1 (equally important) – 9 (very much more important) (Herraprastanti et al., 2023). The stages in the AHP analysis include making a matrix from the results of the respondents' questionnaire, calculating the value of the normality matrix, calculating *the weight criteria*, calculating the consistency value, calculating the *weighted sum value, calculating the* ratio, calculating the consistency of the index, and the consistency of the ratio (Setyawan, 2017). The selection of MFA scenarios requires benchmarks in the form of criteria and subcriteria that companies use in the selection of scenarios (Putra & Diana, 2022). These criteria and subcriteria are obtained from the questionnaire identifying criteria and subcriteria in table 1.

Table 1. Criteria and Subcriteria on Scenario Weighting

Criterion	Subcriteria
Carbon Emissions (K1)	Transportation Emissions (SK1)

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Criterion	Subcriteria
	Repair, recycle, or reconditioning process emissions (SK2)
	Disposal or final discharge (SK3)
Regulation (K2)	Compliance with environmental regulations (SK4)
	Compliance with the Company's internal SOP (SK5)
Material Efficiency (K3)	Ratio of materials reused (SK6)
	Total final waste (SK7)
Potential *of Reuse* and *Circular Economy* (K4)	Number of transformer components that can be reconditioned / restored (SK8)
	Economic value of the components successfully utilized (SK9)
Processing time (K5)	Processing time (SK10)
	Energy consumption per time (SK11)

Source : PT XYZ

Based on table 1.1, there are 5 criteria and 11 sub-criteria used by companies in choosing mapping scenarios. The K symbol is the symbol for the criteria and the SK symbol is the symbol used for the subcriterion (Utami, 2023). The following is the hierarchical structure in selecting the optimal scenario for the management of NFD transformers:

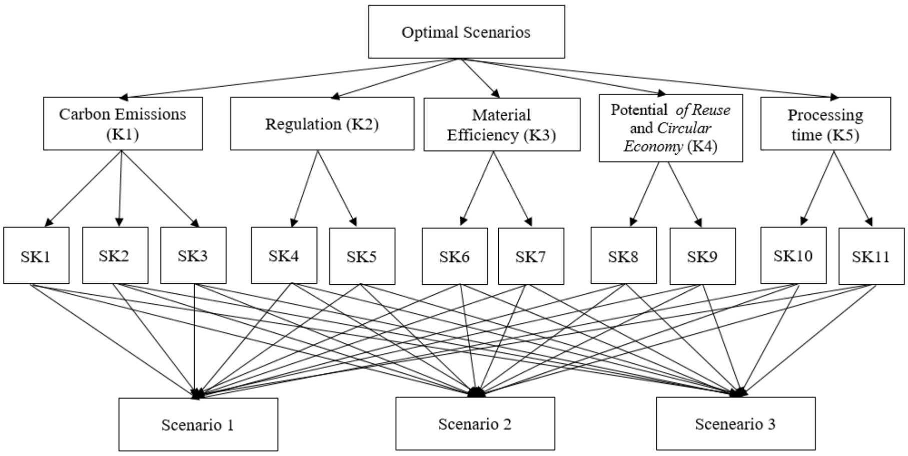

Figure 2. Hierarchical Structure of Mapping Scenario Selection

Source: Processed Data (2025)

***Material Flow Analysis* (MFA)**

This processing is carried out by comparing three scenarios to quantify material mass, carbon emissions, and process efficiency in each option implemented with *material flow analysis* (Haqq, 2018).

Alternative Transformer Management System Design Scenario 1

The scenario 1 (existing) transformer management system is based on technical aspects using the MFA method. From the mapping results, it can be seen in Figure 3. This scenario illustrates the current operational practice in handling transformers, where material flow generally follows a linear pattern starting from procurement, utilization, and maintenance, then proceeding to disposal once transformers reach the end of their functional lifespan. The mapping reflects the absence of a recovery or regeneration mechanism, indicating that valuable materials tend to be treated as waste rather than being optimized for reuse. Therefore,

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scenario 1 serves as a baseline condition for comparison with subsequent improvements proposed in later scenarios., namely:

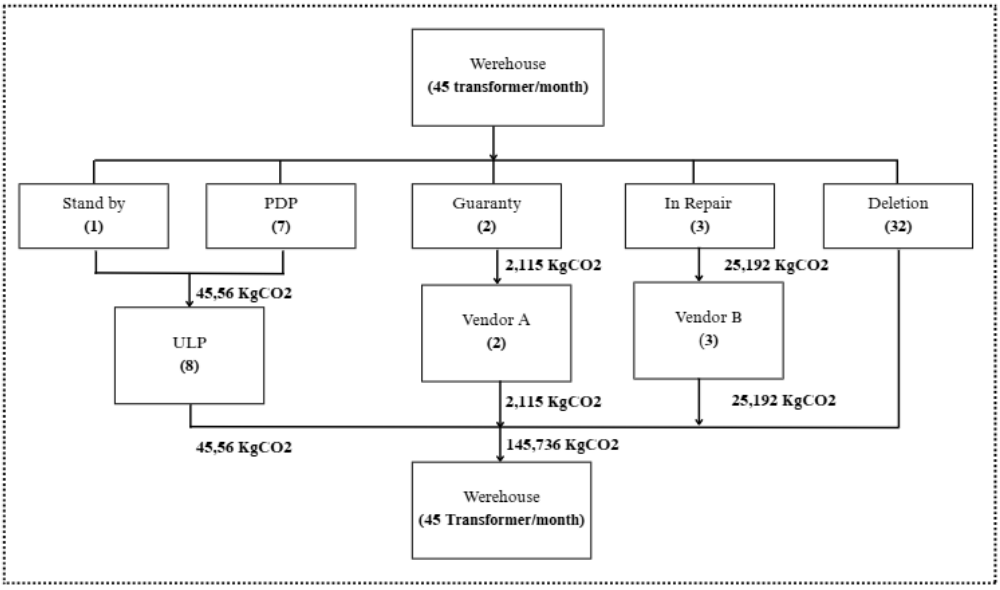

Figure 3. Scenario 1 (Existing) Transformer Management System

Source: MFA Data Processing (2025)

Total carbon dioxide emissions are calculated from the emission burden of the transportation mode used by taking into account the number of monthly mode rentals. Therefore, a lift of 145,736 KgCo2 was obtained, by calculating (Serlina et al., 2024):

Functional Device Transformer Transportation Activities:

Transportation activity: warehouse to ULP

Mode of transportation: Pick Up Truck

Weight of transported transformer (kg) = 8 transformers x 1000 kg/transformer = 8000

Maximum capacity of transportation mode (kg) = 1000 kg

Distance: 17 km

Fuel consumption (km/l) = 8 km/l

Gasoline Emission Factor (kgCO2/l) = 2.68 CO2/liter (because the pickup truck uses diesel)

So that:

Number of Fleet Units Required (units) = $\frac{\text{Weight of transported transformer (kg)}}{\text{Maximum capacity of transportation mode (kg)}}$

Number of Fleet Units Required (units) = $\frac{8000}{1000}$ = 8 units

Total Fuel Consumption (l) = $\frac{\text{Distance (km)}}{\text{Fuel consumption (km/l)}}$

Total Fuel Consumption (l) = = $\frac{17\text{ km}}{8\text{ (km/l)}}$= 2,125 liters

Vehicle Emissions = Number of Fleet Units Required (units) x Total Fuel Consumption (l) x Gasoline Emission Factor (kgCO2/l) = 8 x 2.125 x 2.68 = 45.56 kgCO2

The carbon dioxide emission load for the "Warehouse → ULP" stream was calculated using the rition method of a pick-up truck transport mode transporting 8 transformers (a total of 8,000 kg) at a distance of 17 km. With a maximum capacity of 1,000 kg per unit, 8 fleet units

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are needed; diesel fuel consumption of 8 km per liter yields 2,125 liters per liter; and an emission factor of 2.68 $kgCO_2$ per liter, then the emissions arising for this flow are $8 \times 2.125 \times 2.68 = 45.56$ kg CO_2 per month. All transportation routes (to Vendor A, Vendor B, and ULP) were then summed up to produce a total carbon dioxide emission of 145,736 $kgCO_2$.

Alternative Transformer Management System Design Scenario 2

The scenario 2 transformer management system is based on technical aspects using the MFA method. In scenario 2, in the NFD transformer category, the removal is not only stationary in the werehouse, but there are stages to vendor B to recondition the material (Zaky & Rakhmah, 2023). From the mapping results, it can be seen in figure 4.3, namely:

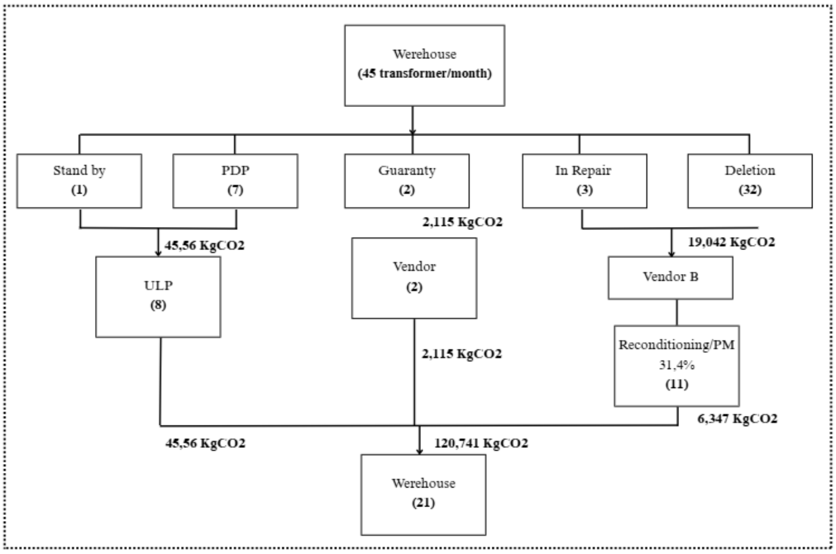

Figure 4. Scenario 2 (Existing) Transformer Management System

Source: MFA Data Processing (2025)

The carbon dioxide emission load in scenario 2 was calculated by the pick-up truck and ankle truck rationation method for the three transformer distribution flows: from the warehouse to the ULP (45.56 kg CO_2/month), from the warehouse to vendor A (2,115 kg CO_2/month), from the warehouse to vendor B 19,042 kgCO2, and for the removal and reconditioning process from vendor B (6,347 kg CO_2/month). By adding up all these contributions, a total emission of 120,741 kg CO_2 per month is obtained.

Alternative Transformer Management System Design Scenario 3

The scenario 3 transformer management system is based on technical aspects using the MFA method. In scenario three, the implementation process adopts scenario two, but there is an addition of processes in the category of NFD transformers in the deletion status. This process is an alternative to inventory of nfd transformers in the B3 waste produced by the transformer, where one of them is oil regeneration (*filtering* and *decontamination*) into reusable oil (Constantia & Pellegrini, 2021). Thus, it will later increase income in terms of the economy if managed correctly. From the mapping results, it can be seen in figure 5.

The carbon dioxide emission burden in scenario 3 is calculated based on the mode rides of pick-up trucks and ankle trucks for four main grooves, namely distribution to ULP (45.56 kg CO_2/month), return of warranty claims to vendor A (2,115 kg CO_2/month), delivery of units under repair to vendor B for reconditioning/PM (3,314 kg CO_2/month), and transfer of 32 NFD transformers to elimination (including 22 units to B3 waste and 10 units to auction) by unloading flow, recycling, and oil regeneration that adds to the burden of transportation. By

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accumulating all these emission values, a total emission of 101,981 kg CO_2 per month is obtained.

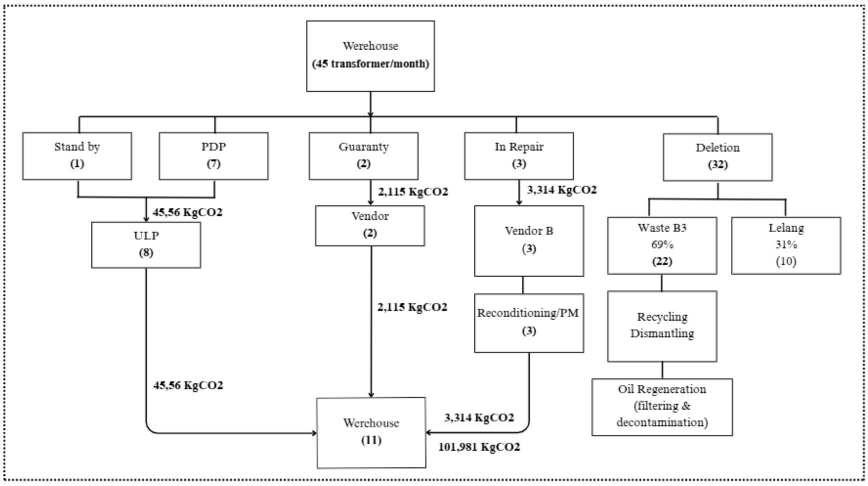

Figure 5. Scenario 3 (Existing) Transformer Management System

Source: MFA Data Processing (2025)

AHP Calculation Using Expert Choice Software

The following is the display of the output results from the combination of R1 to R2 data shown in Figure 6, Figure 7, and Figure 8 Figure 6 shows the value of the criterion weights of each element. Figure 1.6 shows the value of the comparison matrix for the criteria. Figure 6 shows the result of the weighting of the criteria for the alternative.

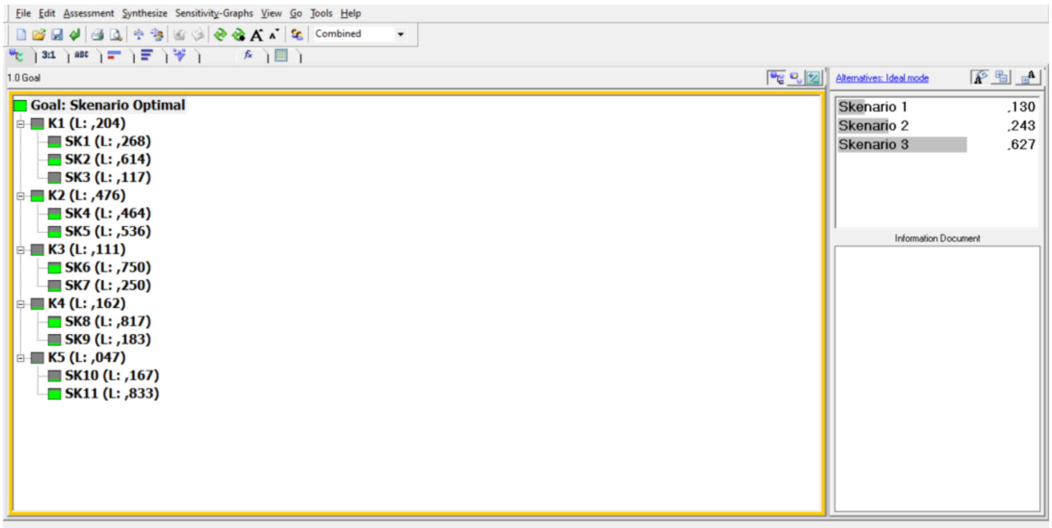

Figure 6. Data Output Display

Source: Data Processing Results (2025)

Based on figure 6, it shows that the criterion that has the highest weight in determining the optimal scenario is Regulation (K2) with a weight of 0.476. In K2, the most dominant sub-criteria are Compliance with the company's internal SOPs (SK5) with a weight of 0.536, followed by Compliance with environmental regulations (SK4) with a weight of 0.464. The next criterion that has a big influence is Carbon Emissions (K1) with a weight of 0.204, which consists of the sub-criteria of Emissions of repair, recycling, or reconditioning process (SK2) 0.614 as the most dominant, followed by Transportation Emissions (SK1) 0.268 and Emissions of disposal or final discharge (SK3) with a weight of 0.117.

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Furthermore, the Reuse and Circular Economy (K4) Potential criteria have a weight of 0.162, which includes the number of transformer components that can be reconditioned / restored (SK8) with a weight of 0.817 as the main sub-criterion and the economic value of the components that are successfully utilized (SK9) with a weight of 0.183. The Material Efficiency Criterion (K3) contributed a weight of 0.111, with the ratio of materials reused (SK6) with a weight of 0.750 as the dominant sub-criterion and the amount of final waste (SK7) with a weight of 0.250 as a complement. Finally, the processing time (K5) has the smallest weight of 0.047, but in it there is energy consumption per time (SK11) with a weight of 0.833 which is much more dominant than the processing time length (SK10) with a weight of 0.167

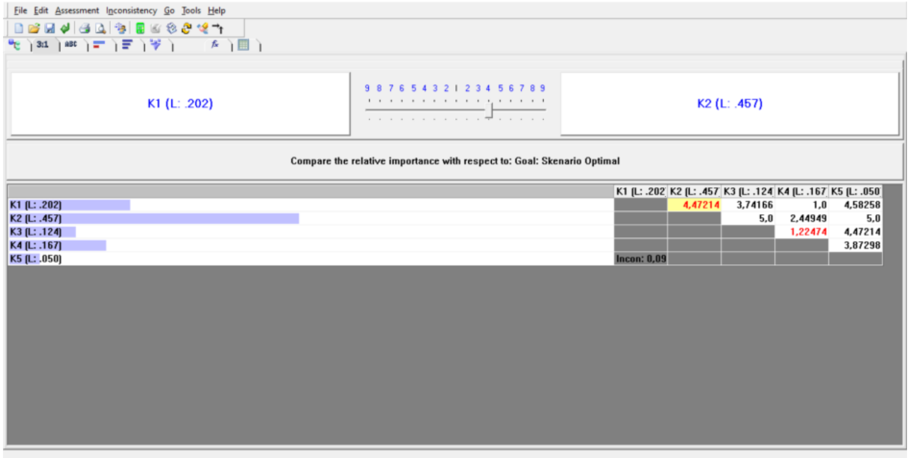

Figure 7. Criteria Comparison Matrix

Source: Data Processing Results (2025)

Based on Figure 7 it shows that the five-criterion comparison matrix (K1–K5) in the AHP framework to determine the relative weights to the "Optimal Scenario" goal, in the upper left there is a normalized weight value (L) for each criterion K1 (0.202), K2 (0.457), K3 (0.124), K4 (0.167), and K5 (0.050) which shows K2 as the most dominant criterion and K5 the weakest. while on the right of the table is presented the numerical comparison value between the criteria (for example, in line K1, the comparison to K2 is 4.472; to K3 is 3.741; to K4 is equally important (1.0); and to K5 is 4.582), thus the following lines show the comparative value between K2–K5 with other criteria; In the lower right corner, the inconsistency ratio value of 0.09 is listed, which is still below the threshold (0.10), indicating that the consistency of the assessment is quite good, so that the resulting L weight can be used to rank and choose the best scenario.

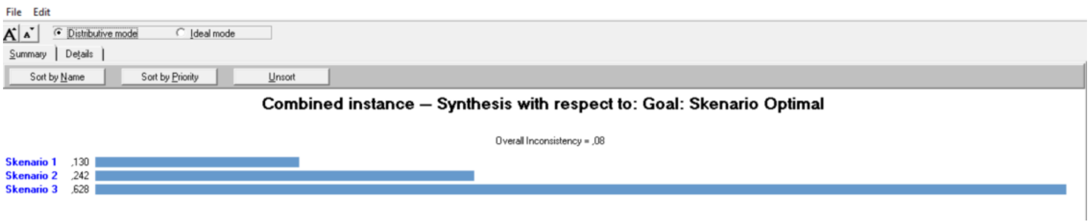

Figure 8. Weighted Results of Alternative Criteria

Source: Data Processing Results (2025)

Based on Figure 8, it shows that the results of the synthesis of alternative weights in the framework of the AHP to determine the "Optimal Scenario". Where it can be seen that three alternative scenarios with their respective weights, namely Scenario 1 gets a value of 0.130, Scenario 2 gets a value of 0.242, and Scenario 3 (which includes the Vendor → Warehouse process → *Preventive maintenance & reconditioning* repair) gets the highest weight of 0.628,

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so it is significantly prioritized over the other two scenarios, while the *overall* inconsistency value is 0.08, which indicates that the consistency of the assessment is still below the threshold of 0.10 so that this alternative weight is valid to be used as a basis for selecting the best scenario.

All stages and implementation of the MFA and AHP methods have been carried out, the sub-chapter of analysis and discussion will outline the results of the analysis of the two methods that have been made for the case in this company (Detiar et al., 2023).

***Material Flow Analysis* (MFA)**

Based on the results of *the Material Flow Analysis* (MFA) for the three transformer management scenarios at PLN UP3 West Surabaya: Scenario 1 (existing), Scenario 2 (NFD reconditioning), and Scenario 3 (oil reconditioning + regeneration).

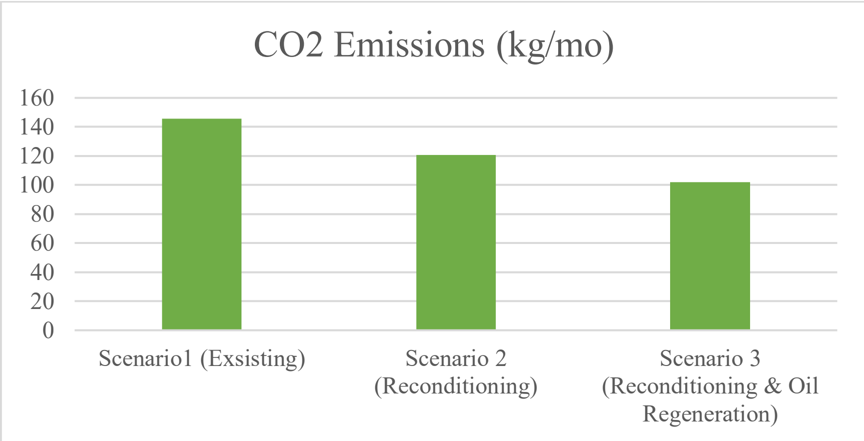

Figure 9. Comparison Chart of Monthly CO2 Emissions

Source: Data Processing Results (2025)

Based on the figure 1.8 results from data processing, in Scenario 1 a "*business as usual*" practice where all NFD transformers directly return to the warehouse after repair without material recovery by producing 145,736 kgCO_2/month. This high figure is mainly due to the volume of massive transport rites for final disposal, as well as the loss of potential reuse of existing oils and components of NFD transformers (Faisal, 2020).

Scenario 2 of the partial transformer flow is directed to Vendor B for internal reconditioning, so that the total emissions drop to 120,741 kgCO_2/month (a decrease of 17.2%). These changes lower the burden of transportation directly to landfills and optimize ritase routes, while allowing for the recovery of usable components that return to the operating cycle.

In Scenario 3 (reconditioning + oil regeneration), the transformer oil regeneration process from B3 waste is added with a recovery rate of up to 80% of the volume of suitable oil, as well as the auction of residual components. This combination of material reconditioning and oil recycling reduces emissions the most, at 101,981 kg CO_2/month (a 30% reduction from Scenario 1). Furthermore, the auction step creates alternative sources of income and reduces the need to purchase new components (Rahayuningsih et al., 2021).

The reduction in emissions in Scenario 2 and scenario 3 not only shows carbon efficiency, but also operational cost efficiency. Internal reconditioning (Scenario 2) reduces the frequency of new transformer purchases by 15–20%, while oil regeneration (Scenario 3) reduces the cost of procuring new oil by almost 60%. This combination extends the economic life of the transformer and lowers *the overall lifecycle cost* of the NFD unit In the research that has been conducted by Gawusu and Amadu (2021). The implications and final recommendations are as follows:

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Carbon Efficiency: The shift from Scenario 1 to Scenario 3 shows the potential for emission reductions of up to more than 40 kg of CO_2 per month (Serlina et al., 2024).

Economic Value: The process of oil reconditioning and regeneration can add value to the remaining assets, reduce capital expenditures, and open up additional revenue opportunities from auctions (Hosseini & Crawford, 2024).

Policies and SOPs: It is recommended that PT XYZ develop an NFD management SOP that integrates the reconditioning feasibility selection stages, B3 oil regeneration standards, and emission reporting mechanisms to support corporate sustainability targets (Ghirardini et al., 2021).

***Analytic Hierarchy Process* (AHP)**

Based on the data processing carried out, it can be concluded that the sub-criteria that have the most influence on determining the optimal scenario are SK5, SK4, SK2, SK8, and SK6. The alternative scenario chosen in obtaining the optimal scenario is scenario 3 with a weight of 0.628, followed by scenario 2 with a weight of 0.242, and scenario 1 has the smallest weight of 0.130.

Thus, based on the results of the AHP analysis, Regulation (K2) emerged as the most decisive criterion in the selection of the optimal scenario. This emphasizes that the compliance aspect of external procedures and regulations is the main foundation in ensuring the feasibility and sustainability of the management of NFD transformers both in terms of legal and organizational governance.

The implications for the selection of scenarios are clear where Scenario 3 obtained the highest weight of 0.628, followed by Scenario 2 (0.242) and Scenario 1 (0.130). The combination of regulatory compliance, minimization of process emissions, and maximization of reconditioned components in Scenario 3 makes it the most superior choice. Thus, the implementation of Scenario 3 will not only meet strict internal and external standards, but also maximize environmental and economic benefits through *a circular economy* approach. (Mikkelsen et al., 2020).

The implications for the selection of scenarios are clear where Scenario 3 obtained the highest weight of 0.628, followed by Scenario 2 (0.242) and Scenario 1 (0.130). The combination of regulatory compliance, minimization of process emissions, and maximization of reconditioned components in Scenario 3 makes it the most superior choice. Thus, the implementation of Scenario 3 will not only meet strict internal and external standards, but also maximize environmental and economic benefits through *a circular economy* approach.

Conclusion

Based on the results of the research conducted, the mapping of material flow and the efficiency of the Non-Functional Device (NFD) transformer management process at PT XYZ has been successfully carried out using *the Material Flow Analysis* (MFA) approach. Three management scenarios were analyzed to see the difference in environmental impact and the efficiency of the materials produced. Scenario 1, which is the existing condition, shows that the entire flow of NFD transformers only ends up in the post-repair warehouse without any process of material value recovery. This results in the highest carbon emissions of 145,736 kg CO_2 per month and signifies low efficiency of the material life cycle. Scenario 2 introduces the reconditioning process through Vendor B, which successfully reduces carbon emissions to 120,741 kg CO_2 per month, while increasing the reuse of transformer components that are still suitable for use.

Meanwhile, Scenario 3 is the best-performing scenario, as it integrates oil reconditioning and regeneration processes, resulting in the lowest emissions of 101,981 kg CO_2 per month,

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recovering up to 80% of usable oil, and adding economic value through the auction of metal components. Thus, scenario three provides the most optimal solution in improving material efficiency and significantly reducing environmental impact. The results of the analysis show that based on the overall weighting, Scenario 3 obtained the highest score of 0.628, indicating that this scenario is not only technically and environmentally superior, but also meets the organization's compliance and governance requirements.

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