



## Sustainable Waste Management Strategies for Metal Button Production Using Integrated LCA and ANP-BOCR

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### ABSTRACT

This study integrates life cycle assessment (LCA) and the Analytic Network Process with Benefit, Opportunity, Cost, and Risk (ANP-BOCR) to evaluate sustainable waste management in metal button production at PT. XYZ. Using the ReCiPe 2016 method with openLCA, the LCA identified electroplating as the main environmental hotspot, with human toxicity (53%) and terrestrial ecotoxicity (21%) as the dominant impacts due to heavy metal emissions. Three alternatives were assessed: chemical precipitation, bioremediation, and sludge valorization. The ANP-BOCR results showed that bioremediation ranked highest in both additive and multiplicative models, indicating its superiority in balancing environmental benefits and risk reduction despite higher technical demands. The novelty of this research lies in combining LCA with ANP-BOCR, providing a robust and transferable framework for decision-making in small and medium-sized manufacturing. For PT. XYZ and similar industries, adopting bioremediation offers a practical pathway toward sustainable wastewater management.

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### 1. INTRODUCTION

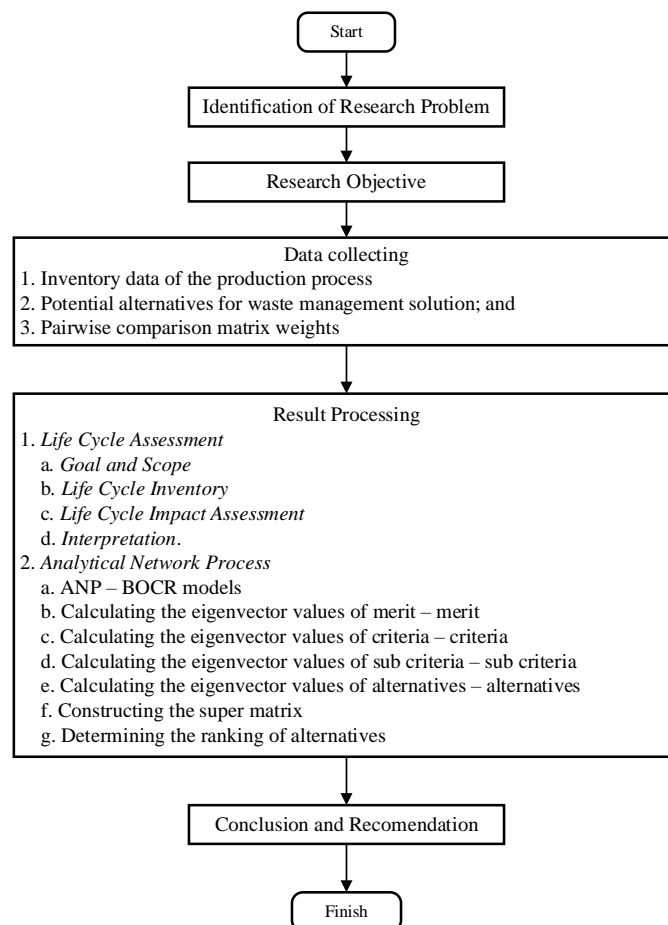
The metal industry has shown remarkable growth in Indonesia and continues to play a vital role in the global market. Metals are widely used across various sectors, including the fashion industry, where they are processed into accessories such as buttons, zippers, and garment ornaments. PT. XYZ is one of the local manufacturers producing metal buttons, with an output of nearly one million pieces per production cycle.

Despite its economic contribution, the production process generates liquid waste containing hazardous heavy metals, including lead (Pb), nickel (Ni), and zinc (Zn). These substances pose serious risks to both environmental quality and human health when not properly treated. Although the company operates a wastewater treatment plant (WWTP), the facility has not achieved optimal performance, leaving residual heavy metals in the discharged effluent. This condition raises environmental concerns as well as challenges in meeting regulatory standards. Moreover, the company lacks a comprehensive assessment of the long-term environmental impacts of its operations and has yet to develop effective and sustainable waste management strategies.

To address these challenges, this study employs Life Cycle Assessment (LCA) to evaluate potential environmental impacts across the production process, providing a holistic perspective on the associated burdens. Furthermore, the Analytical Network Process (ANP) combined with the BOCR (Benefits, Opportunities, Costs, and Risks) framework is applied to identify and prioritize alternative strategies for hazardous waste management. By integrating LCA and ANP–BOCR, this research aims to propose feasible and sustainable solutions that improve environmental performance in the metal button industry.

## 2. METHODS

This research integrates Life Cycle Assessment (LCA) with the Analytical Network Process (ANP) under the Benefits, Opportunities, Costs, and Risks (BOCR) framework to evaluate environmental impacts and prioritize sustainable waste management strategies. The overall procedure is illustrated in the research flowchart.



**Figure 1.** Flowchart of Research Methodology

The research was conducted in four stages. The first stage involved conducting an LCA to identify key environmental impacts. Based on these results, several alternative waste management strategies were formulated. The third stage applied the ANP–BOCR framework to evaluate the alternatives. Each stage is explained in detail in the following subsections.

## 2.1 Life Cycle Assessment

The LCA was conducted according to ISO 14040 and ISO 14044 standards. Life Cycle Assessment (LCA) comprises four key stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Jolliet, 2016.). LCA is increasingly applied in meta-analyses, particularly in evaluating waste management and biomass utilization, to provide a comprehensive range of environmental indicators across product life cycles.

### (i) Goal and Scope

This initial stage establishes the purpose, boundaries, and functional unit of the study, along with baseline and alternative scenarios. It defines the system's primary function, sets quantitative reference measures, and determines whether the analysis extends from cradle-to-gate or cradle-to-grave.

### (ii) Life Cycle Inventory (LCI)

At this stage, inputs and outputs are quantified, including resource use (energy, water, raw materials) and pollutant emissions to air, water, and soil. Both renewable and non-renewable resource consumption are assessed.

### (iii) Life Cycle Impact Assessment (LCIA)

LCIA translates inventory data into environmental impact categories. The process involves classification (grouping emissions into categories such as global warming or eutrophication), characterization (quantifying contributions in standard units, e.g., kg CO<sub>2</sub>-eq), normalization (relating results to regional/global averages), and weighting (assigning importance to categories based on social, economic, or environmental priorities).

### (iv) Interpretation

This stage evaluates results, identifies key parameters, and examines uncertainties through sensitivity analysis. Critical review ensures methodological assumptions and system boundaries do not bias findings. Results can then be integrated with economic or social considerations to support decision-making.

This method has specific characteristics and limitations that must be understood for effective application. According to Jolliet (2016), the key features of Life Cycle Assessment (LCA) are:

- (i) LCA adopts a holistic approach covering the entire life cycle of a product or process, from raw material extraction to final disposal, enabling comprehensive identification of environmental impacts.
- (ii) It links environmental impacts to system functions, facilitating comparison among alternatives.
- (iii) Measurements are conducted throughout the product or service life cycle, from cradle to grave, including raw material acquisition and waste management.
- (iv) LCA addresses all major known environmental issues, such as global warming, resource depletion, toxic impacts on humans and ecosystems, and land use.

## 2.2 Development of Waste Management Alternatives

The LCA results served as the basis for designing potential strategies to mitigate heavy metal contamination in wastewater. Three alternatives were formulated by considering both technical feasibility and environmental relevance.

- (i) Calcium hydroxide is used in wastewater treatment to increase pH, facilitating the precipitation of heavy metals as hydroxides under alkaline conditions. Alkali compounds such as  $\text{Ca(OH)}_2$ ,  $\text{Mg(OH)}_2$ ,  $\text{NaOH}$ , and  $\text{NaHCO}_3$  are commonly used. In particular,  $\text{Cr(OH)}_3$  precipitation is achieved optimally at pH 8.5–9.0, where its solubility is minimal.  $\text{Cr(OH)}_3$ , formed from  $\text{Cr}_2\text{O}_3$  precipitation, is considered stable and less hazardous to the environment than hexavalent chromium compounds. However, under certain oxidative conditions, trivalent chromium can oxidize to hexavalent chromium, so proper handling of  $\text{Cr(OH)}_3$  residues is necessary to prevent future environmental risks (Oktiawan et al., 2009).
- (ii) The second alternative focused on bioremediation through the introduction of indigenous bacteria capable of reducing the concentrations of heavy metals. Indigenous bacteria are naturally occurring microorganisms that thrive in specific environments, such as certain wastes or substrates, where they have been present from the beginning. These bacteria are adapted to their environment and are expected to degrade organic compounds and pollutants in wastewater under suitable conditions (Martiningsih et al., n.d.). Effective microbes include bacteria (e.g., *Bacillus* sp., *Pseudomonas* sp., *Escherichia coli*), fungi (e.g., *Penicillium stolonifera*, *Aspergillus oryzae*, *Rhizopus*), and yeast (*Saccharomyces cerevisiae*) (Sumberdaya et al., n.d.). Indigenous bacteria can reduce lead, chromium, copper, and mercury, offering an environmentally friendly alternative for soil or water remediation depending on site conditions. One approach is the activated sludge method, using paddy soil as a microbial source. Applying indigenous bacteria in activated sludge for PCB etching wastewater treatment aims to reduce hazardous substrates (Shendy Anggriany et al., 2018).
- (iii) The third alternative proposed the conversion of sludge into fertilizer by combining it with organic additives such as compost and lime. Murtika (1999) found that using sludge for sweet corn (*Zea mays* L. cv. Sachanata Sturt) yields positive results when sludge composition is below 50%, but higher proportions inhibit plant growth, likely due to toxic levels of Fe, Zn, and Cu. Therefore, sludge must undergo treatment, such as composting with microbial technology, lime, or organic fertilizers—before safe agricultural application (Yazid et al., n.d.).

## 2.3 Analytical Network Process with BOCR Framework

The Analytical Network Process (ANP) is a decision-making method developed by Thomas L. Saaty to address complexities in interrelated systems. According to (Saaty, 2013), the ANP procedure involves several steps.

- (i) Develop the ANP Model  
Structure the problem into a network that reflects interdependencies and feedback among elements, both within (inner) and between (outer) clusters.
- (ii) Construct Pairwise Comparison Matrices  
Compare elements in pairs based on the importance of specific criteria, as used in AHP and ANP.
- (iii) Calculate the super matrix  
Represent all relationships within the network model in a single matrix.

## (iv) Determine cluster and node weights

Convert the unweighted super matrix into a weighted super matrix by adjusting each cluster's relative contribution.

To prioritize the alternatives, the Analytical Network Process (ANP) was applied in conjunction with the BOCR (Benefits, Opportunities, Costs, and Risks) framework. The following is an example of a BOCR network structure (Şahin et al., 2016).

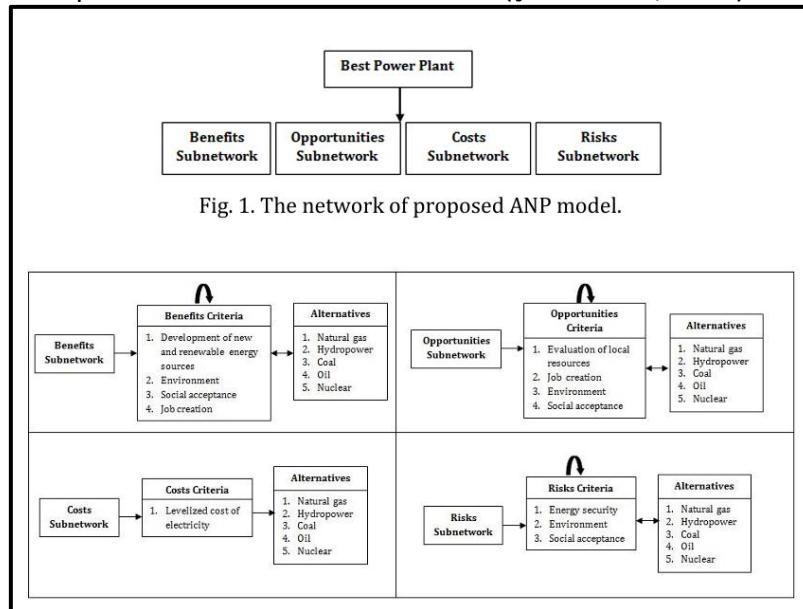


Figure 2. Example of ANP – BOCR Models

Expert judgments were then collected from production managers, environmental officers, and academics specializing in waste management. These experts performed pairwise comparisons using Saaty's nine-point scale, evaluating the relative importance of criteria and alternatives.

Table 1. The Fundamental Scale

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate Importance	Experience and judgment slightly favor one activity over another
4	Moderate Plus	
5	Strong Importance	Experience and judgment strongly favor one activity over another
6	Strong Plus	
7	Very Strong or Demonstrated Importance	An activity is favored very strongly over another; its dominance is demonstrated in practice
8	Very-very Strong	
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocal of above	If activity $i$ has one of the above nonzero numbers assigned to it when compared with activity $j$ , then $j$ has the reciprocal value when compared with $i$	
Rational	Ratios arising from the scale	If consistency were to be forced by obtaining numerical values to span the matrix

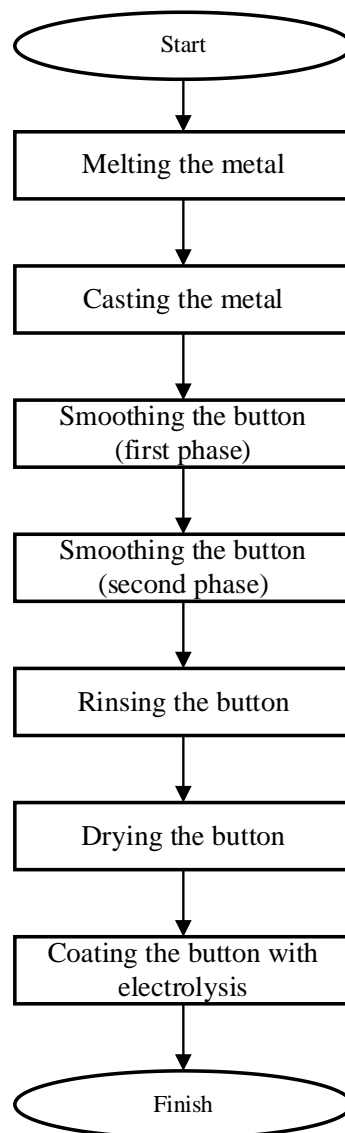
Source: (Saaty, 2022)

The comparison results were synthesized into a super matrix, which was subsequently normalized and converted into a weighted super matrix. Final priority rankings were obtained through both additive and multiplicative synthesis, ensuring that short-term and long-term perspectives were simultaneously considered.

### 3. RESULTS AND DISCUSSION

#### 3.1 Production Process

In general, the production process at Company XYZ is illustrated in **Figure 3**. Flowchart of Production Process.



**Figure 3.** Flowchart of Production Process

The flowchart illustrates the systematic stages of the metal button production process. It begins with melting the metal, followed by casting the metal into the basic button shape. Once cast, the button undergoes two phases of surface refinement, namely smoothing the button (first phase) and smoothing the button (second phase), to ensure a cleaner and more polished finish. Subsequently, the button is subjected to rinsing to remove any remaining particles or impurities, before proceeding to the drying stage. The final step involves coating

the button through an electrolysis process, which enhances both its durability and aesthetic quality. Upon completion of these stages, the button production process is finalized.

3.2 Existing Condition at Wastewater Treatment Plant (WWTP)

The current wastewater treatment system (WWTP) at PT. XYZ consists of several units, including a pre-treatment tank, equalization basin, neutralization basin, coagulation and flocculation tanks, clarifier, intermediate basin, sand/carbon filter, clear water tank, and sludge drying bed. However, effluent analysis shows that several parameters still exceed the regulatory standards. While certain heavy metals such as silver (Ag), cadmium (Cd), and cyanide (CN<sup>-</sup>) meet permissible limits, others—such as total suspended solids (TSS), pH, BOD, COD, nickel (Ni), zinc (Zn), copper (Cu), chromium (Cr and Cr<sup>6+</sup>), and lead (Pb)—remain above the threshold. This indicates that the coagulation-flocculation process and filtration units are not yet fully effective, thus requiring optimization strategies to reduce heavy metal concentrations and minimize environmental pollution.

Table 2. Wastewater Quality at PT. XYZ

Parameter	Quality Standard	Wastewater Quality	Unit	Parameter	Quality Standard	Wastewater Quality	Unit
Temperature	0	27,17±0,29	°C	Cr	0,5	0,6±0,01	mg/L
TSS	20	21,33±0,58	mg/L	Cr <sup>+6</sup>	0,1	0,4±0,01	mg/L
Ph	6 - 9	7,17±0,42	-	Ni	1,0	2,98±0,19	mg/L
Ag	0,5	0,02±0,01	mg/L	Zn	1,0	3,10±0,64	mg/L
Cd	0,1	0,02±0,02	mg/L	CN	0,2	0,1±0,01	mg/L
BOD	50,0	110,90±9,75	mg/L	Cu	0,5	0,82±0,16	mg/L
COD	100,0	167±25,87	mg/L	Pb	0,1	0,58±0,12	mg/L

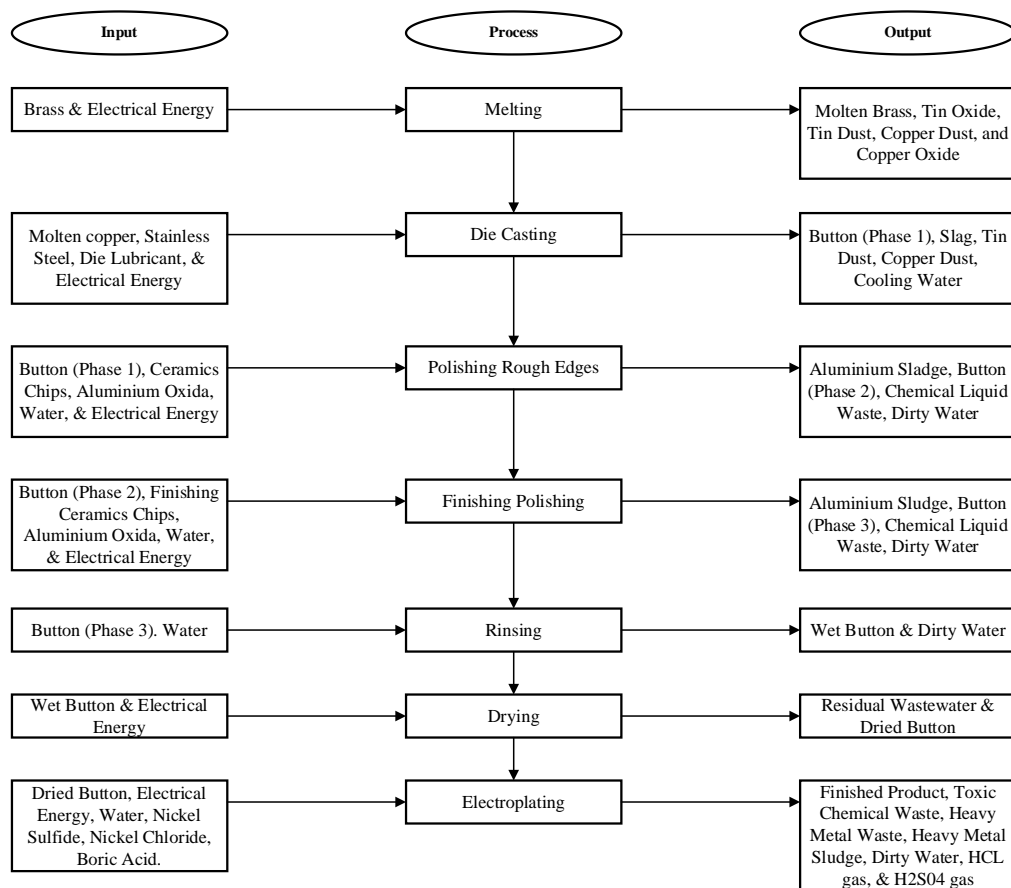
(Source: PT. XYZ, 2025)

3.3 Life Cycle Assessment (LCA)

Life Cycle Assessment has several steps for systematically assessing the environmental aspects and potential impacts associated with a product, process, or service. These steps typically include goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation, which together provide a comprehensive understanding of sustainability performance.

(i) Goal and Scope

The goal of the life cycle assessment for a metal button is to evaluate its environmental impacts throughout its entire life cycle. The life cycle assessment (LCA) of the metal button production at PT. XYZ was conducted with a gate-to-gate system boundary, covering the processes from brass melting to electroplating. In this section, the formulation and definition of the input-output diagram are carried out to identify and illustrate the various types of inputs and outputs at each stage of the production process.



**Figure 4.** Input and Output

The production process illustrated in the diagram begins with the melting of brass using electrical energy, which generates by-products such as oxides and metal dust. The molten material is then subjected to die casting, producing the first phase of buttons along with slag, dust, and cooling water as waste. Subsequent polishing stages, including rough edge polishing and finishing polishing, utilize ceramics chips, aluminium oxide, water, and electrical energy, resulting in aluminium sludge, chemical liquid waste, and dirty water. Afterward, the buttons undergo rinsing, which produces wet buttons and wastewater, followed by a drying stage that leaves residual wastewater and dried buttons. The final stage is electroplating, which requires additional chemicals such as nickel sulfide, nickel chloride, and boric acid, producing the finished product but also generating toxic chemical waste, heavy metal residues, wastewater, and hazardous gases such as HCl and H<sub>2</sub>SO<sub>4</sub>.

#### (ii) Life Cycle Inventory (LCI) and System Boundary

The life cycle inventory (LCI) was compiled from on-site measurements and company records. The original inventories were arranged per process stage—melting, die casting, rough edges polishing, finish polishing, rinsing, drying, and electroplating. For clarity and conciseness in this article, these inventories are consolidated into a single summary, which is presented in **Table 3**.



**Table 3.** Wastewater Quality at PT. XYZ

Melting						
Input			Output			
Material	Quantity	Unit	Material	Quantity	Unit	Description
Brass	1900	Kg	Molten brass	1871,8	kg	Product
Electrical Energy	935,9	kWh	Tin oxide	10,55	kg	Waste
			Tin dust	2,5	kg	
			Copper oxide	9,35	kg	
			Copper dust	5,8	kg	
Die Casting						
Molten Brass	1871,8	kg	Stage-1 button	950000	pcs	Product
Alloying metal	467,95	kg	Slag	25	kg	Waste
Die lubricant	93,59	kg	Tin dust	12,67	kg	
Electrical energy	1872	kWh	Copper dust	11	kg	
			Cooling water	31,9	L	
Polishing Rough Edges						
Stage-1 button	950000	pcs	Stage-2 button	947000	pcs	Product
Ceramic chips	950500	pcs	Aluminium precipitate	14	kg	Waste
Aluminium oxide	30	kg	Stable chemical waste	14,37	L	
Water	2000	L	Contaminated water	1970	L	
Electrical Energy	85,5	kWh				
Finishing Polishing						
Stage-2 button	947000	pcs	Stage-3 button	947000	pcs	Product
Finishing ceramics chips	947500	pcs	Aluminium precipitate	14	kg	Waste
Aluminium oxide	15	kg	Stable chemical waste	14,37	L	
Water	1990	L	Contaminated water	1950	L	
Electrical energy	85,5	kWh				
Rinsing						
Stage-3 button	947000	pcs	Wet button	947000	pcs	Product
Water	500	L	Contaminated water	500	L	Waste
Drying						
Wet button	947000	pcs	Dry button	947000	pcs	Product
Electrical energy	171	kWh	Contaminated water	3,9	L	Waste
Electroplating						
Dry button	947000	pcs	Barang Jadi	947000	pcs	Product
Electrical energy	2500	kWh	Toxic chemical waste	40	L	Waste
Water	2000	L	Heavy metal precipitate	145	kg	
Nickel Sulfide	300	g/L	Heavy metal dust	15,57	kg	
Nickel chloride	50	g/L	Contaminated water	1900	L	
Boric acid	40	g/L	Tin oxide	30	g/L	
			Tin dust	24	g/L	

(Source: PT.XYZ, 2025)

The consolidated data show that the production of approximately 947,000 metal buttons required 1,900 kg of brass, 468 kg of alloy, and nearly 4,000 kWh of electricity. Water use exceeded 8,000 L, primarily during polishing and washing stages. Major environmental releases included sludge containing heavy metals such as Ni, Cr, Cu, Pb, and Zn, as well as acidic wastewater and gaseous emissions from electroplating. These LCI results from the essential foundation for the subsequent life cycle impact assessment (LCIA), enabling the identification of key environmental burdens and process hotspots within the production system.

## (iii) Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) has several steps including classification, characterization, normalization, and weighting. Classification is the process of assigning inventory results to specific environmental impact categories. Characterization quantifies the contribution of each classified input or emission to its respective impact category using scientific models. Normalization expresses characterized results in relation to a reference value, allowing for comparability across categories. Weighting involves assigning relative importance to different impact categories to support decision-making. This research was conducted using the ReCiPe 2016 (H/H) method in openLCA 2.4.1 with the ILCD database system. The outcomes of the weighting analysis are illustrated in **Table 4**.

**Table 4.** Weighting Result

Impact Category	Melting	Die Casting	Polishing Rough Edges	Finishing Polishing	Rinsing	Drying	Electroplating
Fine Particular Matter Formation	1,10E-02	6,67E-02	6,67E-02	6,67E-02	6,67E-02	6,67E-02	7,20E-10
Fossil Resource Scarcity	5,22E+08	3,17E+09	3,17E+09	3,17E+09	3,17E+09	3,17E+09	5,07E+04
Freshwater Ecotoxicity	1,12E-09	6,77E-09	6,77E-09	6,77E-09	6,77E-09	6,77E-09	6,81E-09
Freshwater Eutrophication	6,91E-10	4,20E-09	4,20E-09	4,20E-09	4,20E-09	4,20E-09	6,41E-09
Global Warming, Freshwater Ecosystems	3,02E-11	1,83E-10	1,83E-10	1,83E-10	1,83E-10	1,83E-10	2,75E-10
Global Warming, Human Health	1,21E-02	7,36E-02	7,36E-02	7,36E-02	7,36E-02	7,36E-02	1,11E-01
Global Warming, Terrestrial Ecosystems	1,10E-06	6,70E-06	6,70E-06	6,70E-06	6,70E-06	6,70E-06	1,01E-05
Human Carcinogenic Toxicity	1,18E-04	7,14E-04	7,14E-04	7,14E-04	7,15E-04	7,14E-04	7,77E-04
Human Non-Carcinogenic Toxicity	3,24E-03	1,97E-02	1,97E-02	1,97E-02	1,97E-02	1,97E-02	2,03E-02
Ionizing Radiation	5,14E-06	3,12E-05	3,12E-05	3,12E-05	3,12E-05	3,12E-05	4,17E-05
Land Use	-1,46E-27	-8,87E-27	-8,87E-27	-8,87E-27	-8,87E-27	-8,87E-27	3,13E-09
Marine Ecotoxicity	6,75E-10	4,10E-09	4,10E-09	4,10E-09	4,10E-09	4,10E-09	4,14E-09
Marine Eutrophication	1,51E-11	9,18E-11	9,18E-11	9,18E-11	9,18E-11	9,18E-11	1,20E-10
Mineral Resource Scarcity	2,26E+05	1,37E+06	1,37E+06	1,37E+06	1,37E+06	1,37E+06	2,04E+06
Ozone Formation, Human Health	3,33E-05	2,02E-04	2,02E-04	2,02E-04	2,02E-04	2,02E-04	2,50E-04
Ozone Formation, Terrestrial Ecosystems	1,43E-07	8,67E-07	8,67E-07	8,67E-07	8,67E-07	8,67E-07	1,07E-06
Stratospheric Ozone Depletion	1,78E-06	1,08E-05	1,08E-05	1,08E-05	1,08E-05	1,08E-05	1,37E-05
Terrestrial Acidification	3,66E-07	2,22E-06	2,22E-06	2,22E-06	2,22E-06	2,22E-06	3,04E-06
Terrestrial Ecotoxicity	1,01E-07	6,14E-07	6,14E-07	6,14E-07	6,14E-07	6,14E-07	6,20E+07
Water Consumption, Aquatic Ecosystems	6,69E-13	4,06E-12	4,06E-12	4,06E-12	4,06E-12	4,06E-12	5,25E-12
Water Consumption, Human Health	8,16E-05	4,95E-04	4,95E-04	4,95E-04	4,95E-04	4,95E-04	6,39E-04
Water Consumption, Terrestrial Ecosystem	1,50E-08	9,08E-08	9,08E-08	9,08E-08	9,08E-08	9,91E-07	1,17E-07

## (iv) Interpretation

Based on the results of the LCIA, it is evident that the greatest environmental impact of the coating process is associated with the dominant impact category, namely terrestrial ecotoxicity, with a significantly high contribution of 6.2E+07 pt. Terrestrial ecotoxicity represents an environmental impact category that measures the potential of hazardous substances (commonly heavy metals) to contaminate and harm terrestrial ecosystems, including soil, soil organisms, and other living beings. This environmental burden arises when toxic materials, such as lead used in the coating process, are released into terrestrial ecosystems.

**3.4 Identification of Waste Management Alternatives**

Based on the results of the life cycle assessment, wastewater and sludge generated in the electroplating process were identified as the major contributors to environmental impacts, particularly in human toxicity and terrestrial ecotoxicity categories. To address these issues, three alternative waste management strategies were formulated.

- (i) The first alternative is chemical precipitation using  $\text{Ca}(\text{OH})_2$ , which can neutralize acidic effluents and precipitate heavy metals as hydroxides. This method is relatively simple and widely applied in industrial wastewater treatment; however, it generates large amounts of secondary sludge that require further handling.
- (ii) The second alternative is bioremediation, which utilizes specific microorganisms to remove or stabilize heavy metals. This approach offers environmentally friendly characteristics and the potential for long-term sustainability. Nevertheless, its effectiveness depends on the selection of suitable microbial strains and controlled operating conditions, which may require additional investment in technical capacity.
- (iii) The third alternative is sludge valorization, where electroplating sludge is processed into secondary raw materials, such as pigments or additives for construction materials. This option contributes to resource recovery and waste minimization, but the economic feasibility and market acceptance of such by-products remain as challenges.

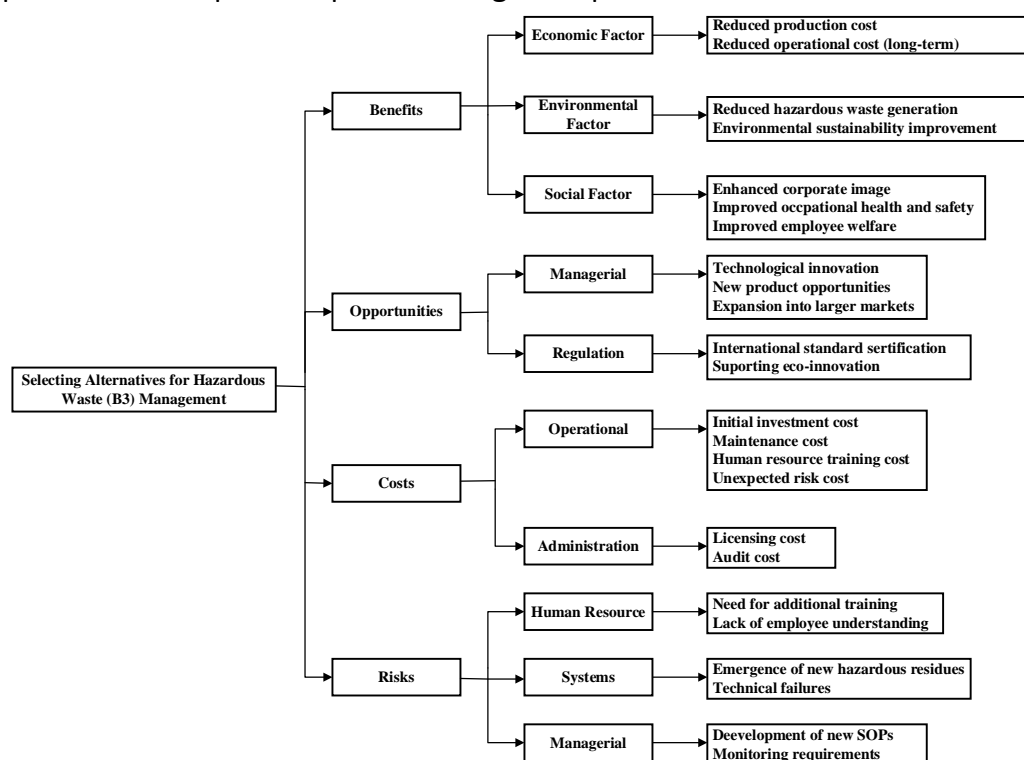
These three alternatives were selected based on the environmental hotspots identified in the LCA and supported by findings from relevant literature in electroplating and metal-finishing industries. They provide a basis for further evaluation using the ANP–BOCR method in order to determine the most suitable strategy for PT XYZ.

### 3.5 Analytical Network Process – BOCR

The ANP-BOCR method involves several steps, beginning with the development of the ANP-BOCR model, followed by determining the eigenvector of merit - merit, the eigenvector of criteria - criteria, the eigenvector of sub-criteria - sub-criteria, and the eigenvector of alternatives - alternatives. These steps are then continued with the construction of the super matrix and finalized by determining the overall BOCR priority.

#### (i) ANP -BOCR models

This model is employed to evaluate and select the most suitable alternative in addressing complex and interdependent problems. **Figure 5.** presents the ANP–BOCR model.



**Figure 5.** ANP – BOCR Models

## (ii) Determined the eigen vector of merit – merit

The Analytic Network Process (ANP) was employed to evaluate the relative importance of criteria under the BOCR (Benefit, Opportunity, Cost, Risk) framework. Pairwise comparisons were conducted with expert respondents using Saaty's 1–9 scale. **Table 5.** presents one example of the pairwise comparison matrix used in this study.

**Table 5.** Eigenvector of Merit – Merit of the First Respondent

	Benefits	Opportunities	Costs	Risks	Normalization Value
Benefits	1	3	4	4	0,5082
Opportunities	1/3	1	3	2	0,2572
Costs	¼	1/3	1	3	0,1441
Risks	¼	½	1/3	1	0,0905

The normalized results show that Benefit received the highest weight (0.5082), followed by Opportunity (0.2572), Cost (0.1441), and Risk (0.0905). Subsequently, the calculation of the eigenvector of merit – merit for the second respondent was conducted, and the results of the normalization are presented in **Table 6.**

**Table 6.** Eigenvector of Merit – Merit of the Second Respondent

	Benefits	Opportunities	Costs	Risks	Normalization Value
Benefits	1	2	3	2	0,3885
Opportunities	½	1	¼	½	0,1119
Costs	1/3	4	1	¼	0,1833
Risks	½	2	4	1	0,3161

The overall weights of the BOCR merits, based on the evaluations provided by respondents 1 and 2 are summarized in **Table 7.**

**Table 7.** Conclusion of Merits Priorities

No	Aspect	Normalization Value		Average
		Respondent 1	Respondent 2	
1	Benefits	0,5082	0,3885	0.4484
2	Opportunities	0,2572	0,1119	0.1846
3	Costs	0,1441	0,1833	0.1637
4	Risks	0,0905	0,3161	0.2033

As shown in **Table 6**, the Benefit criterion received the highest weight, followed by Risk, whereas Opportunity and Cost obtained relatively lower weights. This distribution suggests that the decision-making process prioritized long-term environmental and social benefits, while also giving considerable attention to risk management, with financial cost being placed as the least important factor. These results are consistent with previous studies applying ANP in environmental management, where benefits and risks are often emphasized as key considerations, while economic costs tend to receive lower priority. In the context of PT. XYZ, this implies that waste management strategies providing strong environmental performance and minimizing potential risks are more likely to be preferred, even if they require additional costs.

## (iii) Determining the eigen vector of criteria – criteria

In this section, the comparison is made between criteria with respect to each merit—benefits, opportunities, costs, and risks. However, not all calculations of the criteria are presented. The following shows the eigenvector calculation for the criteria under the merit of benefits.

**Table 8.** Eigenvector of Criteria Under Benefits of the First Respondent

	Economical Factor	Environmental Factor	Social Factor	Normalization Value
Economical Factor	1	1/5	4	0.2123
Environmental Factor	5	1	6	0.7083
Social Factor	¼	1/6	1	0.0793

The normalized results show that environmental factor received the highest weight (0.7083), followed by economical factor (0.2123), and social factor (0.0793). Subsequently, the calculation of the eigenvector of criteria under benefits for the second respondent was conducted, and the results of the normalization are presented in **Table 9**.

**Table 9.** Eigenvector of Criteria Under Benefits of the Second Respondent

	Economical Factor	Environmental Factor	Social Factor	Normalization Value
Economical Factor	1	¼	4	0.2452
Environmental Factor	4	1	5	0.6642
Social Factor	¼	1/5	1	0.0904

The overall weights of the BOCR criteria, based on the evaluations provided by respondents 1 and 2 are summarized in **Table 10**.

**Table 10.** Conclusion of Criteria Under Benefits Priorities

No	Aspect	Normalization Value		Average
		Respondent 1	Respondent 2	
1	Economical Factor	0.2123	0.2452	0.2286
2	Environmental Factor	0.7083	0.6642	0.6863
3	Social Factor	0.0793	0.0904	0.0849

**Table 10** illustrates the comparison of criteria under benefits priorities based on the responses of two respondents. The results show that the Environmental Factor holds the highest priority with an average value of 0.6863, indicating its dominant role in the benefits merit. The Economical Factor (0.2286) and Social Factor (0.0849) follow with relatively balanced contributions.

(iv) Determined the eigen vector of sub criteria – sub criteria

In this section, each sub-criterion is compared with one another based on their level of importance. The following discussion presents the determination of eigenvector values for the sub-criteria under each merit, as evaluated by each respondent.

**Table 11.** Eigenvector of Benefit – Economical Factor of the First Respondent

	Reduced Production Cost	Reduced Operational Cost	Normalization Value
Reduced Production Cost	1	1/8	0.1111
Reduced Operational Cost	8	1	0.8889

**Table 11** presents the eigenvector results for the benefit–economical factor of the first respondent. The analysis indicates that Reduced Operational Cost has the highest priority with a normalized weight of 0.8889, while Reduced Production Cost is considered less significant with a normalized weight of 0.1111. Subsequently, the calculation of the eigenvector of benefit – economical factor of the second respondent was conducted, and the results of the normalization are presented in **Table 12**.

**Table 12.** Eigenvector of Benefit – Economical Factor of the Second Respondent

	Reduced Production Cost	Reduced Operational Cost	Normalization Value
Reduced Production Cost	1	1/5	0.1667
Reduced Operational Cost	5	1	0.8333

The overall weights of the BOCR sub criteria, based on the evaluations provided by respondents 1 and 2 are summarized in **Table 13**.

**Table 13.** Conclusion of Criteria Under Benefits Priorities

No	Aspect	Normalization Value		Average
		Respondent 1	Respondent 2	
1	Reduced Production Cost	0,1111	0,1667	0.1389
2	Reduced Operational Cost	0,8889	0,8333	0.8611

**Table 13** summarizes the conclusion of criteria under benefits priorities. Both respondents consistently assigned higher importance to Reduced Operational Cost, with average normalization value of 0.8611, compared to Reduced Production Cost, which received a significantly lower average value of 0.1389. This indicates that reducing operational costs is considered the most critical aspect in achieving benefits.

(v) Determined the eigen vector of alternative – alternative

This section aims to obtain the relative priority values of each alternative with respect to the previously defined alternatives. The following presents the calculations for determining the eigenvector values of each alternative as assessed by the first and second respondents.

**Table 14.** Alternative Based on Sub Criteria Reduced Production Cost

	Respondent 1				Respondent 2			
	A1	A2	A3	Normalization Value	A1	A2	A3	Normalization Value
<b>A1</b>	1	1	2	0.4000	1	½	1/5	0,1282
<b>A2</b>	1	1	2	0.4000	2	1	½	0,2764
<b>A3</b>	½	½	1	0.2000	5	2	1	0,5954

**Table 14** shows that among the three alternatives, A3 has the highest priority (0.3977), followed by A2 (0.3382), while A1 has the lowest priority (0.2641) under the Benefits criteria. The overall weights of the BOCR criteria, based on the evaluations provided by respondents 1 and 2 are summarized in **Table 15**.

**Table 15.** Conclusion of Alternative Priority

No	Alternative	Normalization Value		Average
		Respondent 1	Respondent 2	
1	<b>A1</b>	0,4000	0,1282	0,2641
2	<b>A2</b>	0,4000	0,2764	0,3382
3	<b>A3</b>	0,2000	0,5954	0,3977

The results in **Table 15** indicate the relative priorities of the three alternatives under the *Benefits* criteria. Based on the average normalization values, Alternative A3 holds the highest priority (0.3977), followed by Alternative A2 (0.3382), while Alternative A1 has the lowest priority (0.2641). This suggests that, from the perspective of benefits, A3 is considered the most favorable alternative.

## (vi) Construction of super matrix

The super matrix functions as a mathematical representation tool that illustrates the interdependence and interconnections among elements and clusters within a complex decision-making system. After the weights of each merit, criterion, and sub-criterion have been determined, they are incorporated into the super matrix.

**Table 16.** Super Matrix

Merit	Criteria	Sub Criteria	A1	A2	A3
Benefits (0,4484)	Economical Factor (0,2286)	Reduced production cost (0,1389)	0,2641	0,3382	0,3977
		Reduced operational cost (0,8611)	0,2547	0,2812	0,4640
		Reduced hazardous waste generation (0,1834)	0,1220	0,5815	0,2965
	Environmental Factor (0,6863)	Environmental sustainability improvement (0,8166)	0,2887	0,5041	0,2072
		Enhanced corporate image (0,2955)	0,3250	0,3250	0,3500
		Improved environmental awareness (0,1945)	0,1891	0,3881	0,4228
	Social Factor (0,0849)	Improved employee Welfare (0,5100)	0,3216	0,4620	0,2164
	Synthesis benefits		0,2609	0,4563	0,2825
	Normalization benefits		0,2610	0,4564	0,2826
Opportunities (0,1846)	Managerial (0,4334)	Technological innovation (0,4000)	0,1891	0,2632	0,5477
		New product opportunities (0,4000)	0,1891	0,2632	0,5477
		Expanse into larger markets (0,2000)	0,1872	0,3836	0,4292
		International standard certification (0,8166)	0,3216	0,4621	0,2163
	Regulation (0,5666)	Supporting eco-innovation (0,1834)	0,1997	0,3621	0,4382
	Synthesis opportunities		0,2513	0,3759	0,3727
	Normalization opportunities		0,2513	0,3759	0,3727
Costs (0,1637)	Operational (0,8334)	Initial investment cost (0,0703)	0,3638	0,2300	0,4062
		Maintenance cost (0,1276)	0,3967	0,4120	0,1913
		Human resource training cost (0,4915)	0,1873	0,3836	0,4291
		Unexpected risk cost (0,3106)	0,3638	0,2300	0,4062
	Administration (0,1666)	Licensing cost (0,7333)	0,1891	0,2632	0,5477
		Audit cost (0,2667)	0,1997	0,4871	0,3132

Synthesis <i>costs</i>			0,2664	0,3278	0,4059	
Normalization <i>costs</i>			0,2663	0,3278	0,4059	
<i>Risks</i> (0,2033)	Human resource (0,7304)	Need for additional training (0,7500)	0,2278	0,2682	0,5040	
		Lack of employee understanding (0,2500)	0,1891	0,2632	0,5477	
	Systems (0,1854)	Emergence of new hazardous residues (0,8166)	0,4615	0,2682	0,2704	
		Technical failures (0,1834)	0,3604	0,3420	0,2976	
	Managerial (0,0842)	Development new SOPs (0,7333)	0,1668	0,3611	0,4721	
		Monitoring requirement (0,2667)	0,2747	0,4371	0,2882	
	Synthesis <i>risks</i>			0,2579	0,2793	0,4628
	Normalization <i>risks</i>			0,2579	0,2793	0,4628

(vii) determining the overall BOCR priority

The final prioritization of waste management alternatives was conducted using the ANP–BOCR framework with both additive and multiplicative synthesis. The consolidated results are presented in **Table 17**.

**Table 17.** Conclusion of Criteria Under Benefits Priorities

Alternative	Benefits	Opportunities	Costs	Risks	Additive	Multiplicative	Ranking
	0,4484	0,1846	0,1637	0,2033	wB + wO – wC – wR	(B × O)/ (C × R)	
A1	0,2610	0,2513	0,2663	0,2579	0,0674	0,9550	2
A2	0,4565	0,3759	0,3278	0,2793	0,1636	1,8739	1
A3	0,2826	0,3727	0,4059	0,4628	0,0350	0,5607	3

The analysis shows that bioremediation (A2) obtained the highest score in both additive (1.1636) and multiplicative (1.8739) models, indicating its superiority compared to the other options. Chemical precipitation (A1) ranked second, while sludge valorization (A3) consistently received the lowest scores under both approaches.

The preference for bioremediation reflects its strong performance under the Benefit and Risk dimensions. While it may require greater technical capacity and investment, it offers long-term environmental sustainability by reducing heavy metal concentrations in wastewater and minimizing sludge toxicity. Chemical precipitation, though simple and cost-effective, produces significant volumes of secondary sludge, which reduces its overall ranking. Sludge valorization contributes to circular economy practices, yet uncertainties regarding economic feasibility and market demand resulted in its lowest priority.

These findings are consistent with previous studies in metal-finishing industries, which also identified bioremediation as a promising strategy for sustainable wastewater treatment. Therefore, in the context of PT XYZ, bioremediation represents the most suitable option for managing electroplating waste and addressing the environmental hotspots identified through LCA.



#### 4. CONCLUSION

This study integrated life cycle assessment (LCA) and the Analytic Network Process with Benefit, Opportunity, Cost, and Risk (ANP–BOCR) analysis to evaluate waste management alternatives in metal button production at PT XYZ. The conclusion of this study is presented as follows

- (i) The Life Cycle Assessment (LCA) identified *terrestrial ecotoxicity* ( $6.2\text{E}+07$  pt) as the most significant environmental impact, primarily caused by hazardous waste from smelting processes that were insufficiently treated by the wastewater treatment plant (WWTP).
- (ii) three alternative solutions were proposed: (a) adding calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) to increase pH and precipitate chromium as  $\text{Cr}(\text{OH})_3$ , (b) introducing indigenous bacteria to reduce Pb, Hg, Cu, and Cr, and (c) valorizing sludge into fertilizer by mixing it with animal manure, lime, and compost.
- (iii) The ANP–BOCR analysis determined that the second alternative was the most prioritized, with the highest additive and multiplicative values (0.1636 and 1.8739). The first alternative ranked second (0.0674 and 0.9550), while the third ranked lowest (0.0350 and 0.5607). These results indicate that the second alternative offers the greatest benefits and opportunities, while posing the least risks and costs, making it the most viable option for both short- and long-term implementation.

#### 5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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## Appendices

(i) example of pairwise comparison matrix calculation

	Technological Innovation	New Product Opportunities	Expansion into larger markets	Normalization Value
Technological Innovation	1	1	2	0.4000
New Product Opportunities	1	1	2	0.4000
Expansion into larger markets	$\frac{1}{2}$	$\frac{1}{2}$	1	0.2000

Solution:

a. Converting weights into a matrix

$$\begin{bmatrix} 1.0000 & 1.0000 & 2.0000 \\ 1.0000 & 1.0000 & 2.0000 \\ 0.5000 & 0.5000 & 1.0000 \end{bmatrix}$$

b. Multiplying the matrix by itself

$$\begin{bmatrix} 1.0000 & 1.0000 & 2.0000 \\ 1.0000 & 1.0000 & 2.0000 \\ 0.5000 & 0.5000 & 1.0000 \end{bmatrix} \bullet \begin{bmatrix} 1.0000 & 1.0000 & 2.0000 \\ 1.0000 & 1.0000 & 2.0000 \\ 0.5000 & 0.5000 & 1.0000 \end{bmatrix} = \begin{bmatrix} 3.0000 & 3.0000 & 6.0000 \\ 3.0000 & 3.0000 & 6.0000 \\ 1.5000 & 1.5000 & 3.0000 \end{bmatrix}$$

$$\begin{bmatrix} 3.0000+3.0000+6.0000 \\ 3.0000+3.0000+6.0000 \\ 1.5000+1.5000+3.0000 \end{bmatrix} = \begin{bmatrix} 12.0000 \\ 12.0000 \\ 6.0000 \end{bmatrix}$$

c. Calculating the eigenvector

$$12.0000 + 12.0000 + 6.0000 = 30.0000$$

$$\begin{bmatrix} 12.0000 / 30.0000 \\ 12.0000 / 30.0000 \\ 6.0000 / 30.0000 \end{bmatrix} = \begin{bmatrix} 0.4000 \\ 0.4000 \\ 0.2000 \end{bmatrix}$$

d. Calculating the ratio scale

$$\begin{bmatrix} 3.0000 & 3.0000 & 6.0000 \\ 3.0000 & 3.0000 & 6.0000 \\ 1.5000 & 1.5000 & 3.0000 \end{bmatrix} \bullet \begin{bmatrix} 3.0000 & 3.0000 & 6.0000 \\ 3.0000 & 3.0000 & 6.0000 \\ 1.5000 & 1.5000 & 3.0000 \end{bmatrix} = \begin{bmatrix} 27.0000 & 27.0000 & 54.0000 \\ 27.0000 & 27.0000 & 54.0000 \\ 13.5000 & 13.5000 & 27.0000 \end{bmatrix}$$

$$\begin{bmatrix} 27.0000+27.0000+54.0000 \\ 27.0000+27.0000+54.0000 \\ 13.5000+13.5000+27.0000 \end{bmatrix} = \begin{bmatrix} 108.0000 \\ 108.0000 \\ 54.0000 \end{bmatrix}$$

$$108.0000 + 108.0000 + 54.0000 = 270.0000$$

$$\begin{bmatrix} 108.0000 / 270.0000 \\ 108.0000 / 270.0000 \\ 54.0000 / 270.0000 \end{bmatrix} = \begin{bmatrix} 0.4000 \\ 0.4000 \\ 0.2000 \end{bmatrix} \quad \begin{matrix} 0.4000 - 0.4000 & 0 \\ 0.4000 - 0.4000 & 0 \\ 0.2000 - 0.2000 & 0 \end{matrix}$$