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Application of Material Flow Analysis and Life Cycle Assessment for The Sustainability of The Hard Chrome Plating Process on Dies Products

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Abstract. *The increasing need for material durability in the manufacturing industry encourages the use of hard chrome plating processes for iron, metal, and steel components. However, this process produces significant environmental impacts due to high energy consumption, carbon emissions, and the use of hazardous compounds such as hexavalent chromium (Cr6+). This study aims to apply MFA and LCA to the hard chrome plating process at PT X. The MFA method is used to map the material flow, including raw material input and output in the form of liquid, solid waste and emissions. Meanwhile, LCA is carried out with a gate-to-gate approach to measure the environmental impact of energy consumption, carbon emissions, and toxic waste, using SimaPro 9 software and the ReCiPe 2016 method. The results showed that the total waste from the process reached 464.59 tons/year with carbon emissions of 5.6 kg CO2-eq/m2 of the layer. The largest impact comes from the use of Cr6+ solution and energy consumption in the process through chemical substitution. Energy and waste efficiency to improve dryness. Strategy recommendations are also provided to reduce environmental impacts and process desirability values at PT X by using the 6R method, such as replacing Cr6+ with Cr3+, using biodiesel, and recirculating air and metals. The results of the 6R method showed that the Human Health impact score decreased from 0.3015 to 0.0681, Resources from 0.0016 to 0.00048 and carbon emissions from 5.6 to 3.0 kg CO2-eq/m2. However, the impact on the Ecosystem increased from 0.0061 to 0.0143 due to the use of biodiesel. This strategy supports energy efficiency and sustainable waste management.*

Keywords: *hard chrome plating, material flow analysis, life cycle assessment, SimaPro 9, hexavalent chromium*

I. INTRODUCTION

Currently, all companies are in an era of rapid and advanced industrial globalization. With the rapid and advanced industrial globalization, there are increasingly strict and stringent global environmental regulations. The increasing demand for iron, metal, and steel products has driven the use of hard chrome plating to enhance material durability in the global manufacturing industry. Hard chrome plating is used to improve resistance to corrosion and wear for machine components, automotive parts, and industrial equipment (Moura et al., 2023a).

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The hard chrome plating process has a significant impact on the environment, particularly in terms of high energy consumption, greenhouse gas (GHG) emissions, and hazardous waste such as hexavalent chromium (Cr6+), which is carcinogenic (Merlo & Léonard, 2021). A study found that total carbon emissions in the lifecycle of a steel product undergoing hard chrome plating, if not properly managed, can contribute up to 45% of total carbon emissions. Additionally, energy consumption during the electroplating stage ranges between 1.8–3.2 MWh/kg of steel, depending on process parameters and the type of electrodes used (Yousefzadeh, 2021). During the hard chrome plating process, carbon emissions are quite high, with carbon emissions reaching 5.6 kg CO2-eq/m^2 of plating (Merlo et al., 2023b). In addition to carbon emissions, waste generated from the electroplating industry, such as nickel and chromium, can cause environmental pollution when the recycling system is not managed properly and effectively.

Hard chrome plating has advantages in terms of wear and corrosion resistance for iron, metal, and steel products. However, this process poses significant challenges in terms of environmental impact, energy efficiency, and occupational safety. The primary issue in this industry is the use of hexavalent chromium (Cr6+) solutions. The use of these solutions has the potential to contaminate water and air if not properly managed and is a carcinogenic substance. (Merlo et al., 2023).

In the hard chrome plating process, the solution used contains hexavalent chromium (Cr6+). During the electroplating process, Cr6+ ions undergo electrochemical reduction reactions on the cathode surface, forming chromium metal (Cr0) that is deposited on the substrate surface. This chromium metal deposit functions as a protective layer with high hardness and resistance to wear and corrosion, thereby extending the service life of the coated metal components.

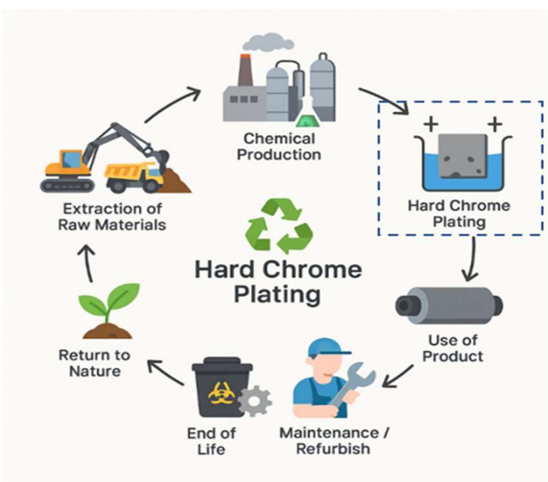

Figure 1. Research Focus Area

Figure 1 illustrates the stages of the hard chrome plating life cycle and the areas of focus of the research, from raw materials to waste disposal, each stage, starting from chemical extraction, the plating process, product use, maintenance, to end of life and return to nature. The research focus is on the stages marked with dotted boxes, namely the hard chrome plating process, which is the core of PT X's production system. This focus was chosen because it is a point that generates significant environmental impacts, such as high energy consumption, carbon emissions, and the use of hazardous compounds such as Cr6+, which is carcinogenic. The analysis was conducted using an LCA approach with a gate-to-gate system, covering internal processes at PT X.

The main issue during the hard chrome plating process is high carbon emissions. Plating 1 m^2 of hard chrome produces approximately 5.6 kg of CO2-eq. If this value is applied on an industrial scale, the total would reach 1.2 million tons of CO2 per year globally (Merlo et al., 2023). High energy consumption: The hard chrome plating process requires 2.1–3.2 MJ of energy per kilogram of steel processed, with 40–60% of this energy lost as heat (Yousefzadeh, 2021). Toxic waste production: In the hard chrome plating process, every 1,000 liters of electroplating solution used can produce approximately 20–30 kg of toxic solid waste, such as chromium and nickel residues that are difficult to recycle (Rúa Ramirez et al., 2024). Health impacts on workers directly exposed to hexavalent chromium (Cr6+) during the hard chrome plating process increase the risk of lung cancer by up to 35% compared to the general population (Laiden & Kamp). Additionally, current regulations are becoming increasingly stringent regarding the use of hexavalent chromium. Under the REACH regulation (Registration, Evaluation, Authorization, and Restriction of Chemicals) in the European Union, the use of Cr6+ will be restricted by 2025. This has prompted the manufacturing industry to seek alternative coating methods that are more environmentally friendly (Bandinelli et al., 2021).

Previous research (E. Rúa Ramirez, 2024) conducted an observation to address the environmental impact of hard chrome plating. One of the solutions proposed was the use of more environmentally friendly alternative materials. The study demonstrated that tungsten-carbide cobalt (WC-Co) technology serves as an alternative to hard chrome plating and can reduce carbon emissions by up to 98% (Rúa Ramirez et al., 2024). In another study (A. Nyström, 2022), an LCA was conducted on steel-based electrical components, which found that the use of recycled raw materials and energy optimization in the electroplating process can reduce environmental impacts by up to 45% compared to conventional methods.

The objective of this study is to apply MFA to determine the flow of materials used and identify waste generated in the hard chrome plating production process on dies. MFA is used to input raw materials in the hard chrome plating process, as well as product output, liquid and solid waste, and emissions. This analysis helps identify critical points with the greatest environmental impact in terms of waste (Martinez-Hernando et al. 2022).

LCA will be used to measure energy consumption, carbon emissions, and toxic waste. Thus, this study will identify the impact of the hard chrome plating process at PT X and also provide appropriate solutions for improving production sustainability and analyze to determine critical points that have an environmental impact and waste (Güleroğlu & Yumurtacı, 2025).

PT X is a company engaged in industrial services, specializing in maintenance and repair of industrial service parts. The company provides a range of repair and coating services for industrial needs, specializing in hard chrome plating, thermal coating, ceramic coating, metal spray, machining, and fabrication. These processes are essential in the industrial world, particularly for maintaining the durability of machine components, extending service life, and improving operational efficiency.

This study will use LCA with a "Gate-to-gate" boundary system to calculate carbon emissions, energy consumption, and waste in the hard chrome plating process at PT X. This approach will critique the environment with existing analyses and assess sustainability efficiency.

LCA is often used as a tool to determine environmental impact effectively and comprehensively, thereby optimizing parameters to reduce energy consumption, carbon emissions, and toxic waste. Thus, this study is expected to provide data-based solutions for PT X to improve electroplating efficiency, reduce environmental impact, and support industrial operations.

II. RESEARCH METHOD

Figure 2 shows data processing flow in this research. The data used in this study consists of two types of data sources, namely primary data collected directly by researchers from PT X through methods such as interviews, surveys, or field observations regarding the hard chrome plating process. This data is novel and specific to the current study, and secondary data collected from observations of the production process at PT X and data from companies and literature on raw materials, consumption, energy, emissions,

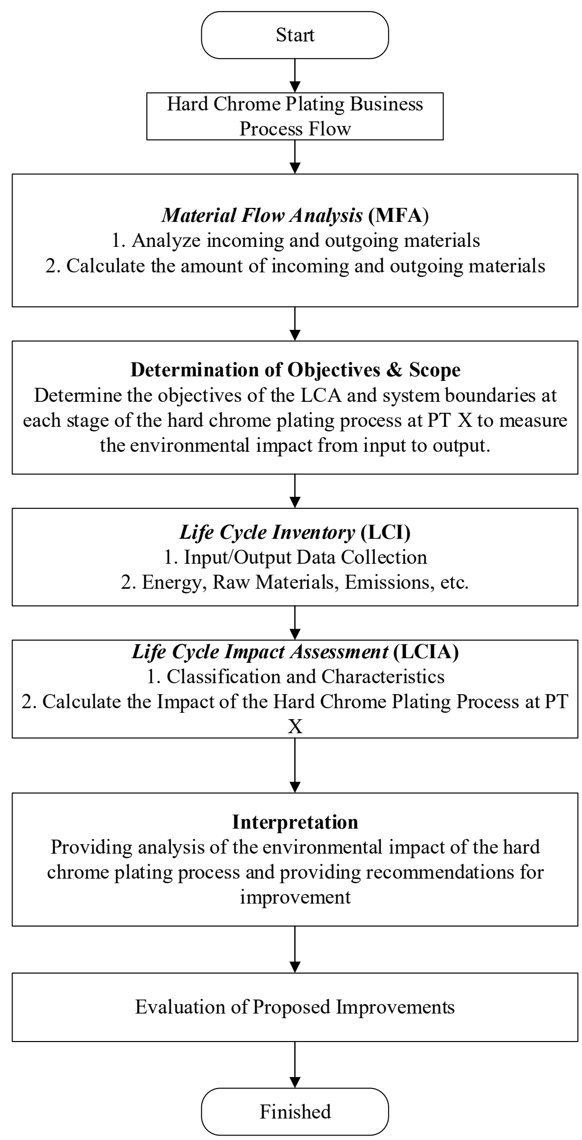

Figure 2. Data Processing Flow

and waste in the hard chrome plating process as input for the MFA and LCA methods. Data collection techniques in this study were conducted through observation, interviews, and documentation.

III. RESULT AND DISCUSSION

Material Flow Analysis (MFA)

To determine the sustainability of the hard chrome plating process, the first step is to analyze the materials used in the process, from input materials to output materials, as well as the waste produced. By analyzing the material flow, the quantity of materials used and the amount of waste generated can be determined through MFA analysis. Figure 4.6 shows the MFA occurring in the hard chrome plating process using the calculation formula in Figure 3.

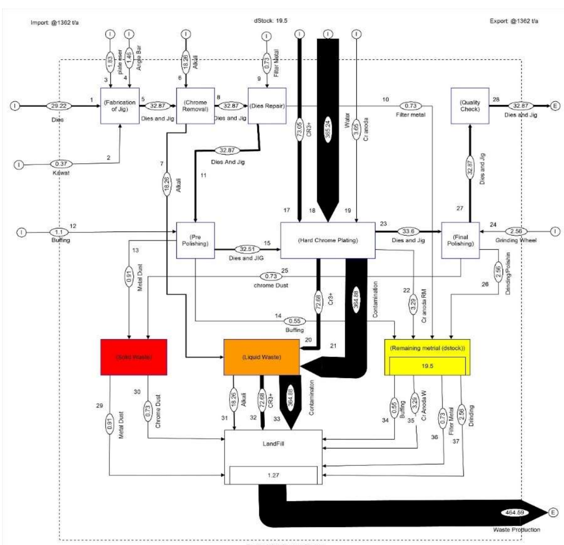

Figure 3. Material Flow Analisis (MFA) Hard Chrome Plating Dies

MFA specifications for hard chrome plating dies:

1. System and Limitations
   - System: Hard chrome plating production process on dies.
   - Limitations: The flow begins with the entry of raw materials and ends with the finished product and waste.
   - Objective: to identify and understand the flow of materials, material residues, and unused raw materials (waste).
2. Material Sources and Imports
   - Total material : 1.362 ton/a
3. Main Material : Waste generated from the hard chrome plating process, such as used liquid waste and chemical liquid waste used for hard chrome plating, accounts for the largest amount of waste.
4. Process Flow, are consists of:
   a. Fabrication of jig : Adjusting the jig to be used for the hard chrome plating process on dies.
   b. Chrome removal : The process of removing old chrome plating.
   c. Dies Repair : melakukan perbaikan bila ada dies yang terdapat sedikit kerusakan.
   d. Pre-polishing : Perform initial polishing of dies before coating.
   e. Hard chrome plating : Hard chrome plating process for dies.
   f. Final polishing : Surface smoothing process for dies that have been coated with chrome.
   g. Quality check : Final process for checking the final results of the dies that have been chromed.
5. Waste and Material Stock
   a. Solid Waste: Solid waste from the hard chrome plating process, such as metal dust and chrome dust generated from buffing and plating.
   b. Liquid waste: There are several types of liquid waste, such as alkali residue, Cr6+ liquid residue, and water contaminated with chromium liquid.
   c. Landfill: This is the final stage of liquid and solid waste management. The total waste generated from the hard chrome plating process is 464.59 tons per year.
   d. Remaining material (dstock): Material that can still be used or cannot be used after the hard chrome plating process.
6. Export of Products and Waste
   - Export products in the hard chrome process on these dies amount to 1362 t/a (after processing).
   - Waste: total waste (solid, liquid, and landfill) generated from the production process amounted to 464.59 t/a.

Table 1. LCI Pickup Process

Dies Pickup								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Dies	80	Kg	Dies Arrived	80	Kg	CO2	50.6	kg CO2
Diesel	22	Liter						

Table 2. LCI Fabrication of Jig

Fabrication of jig process								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Dies	80	Kg	Dies and Jig	90	Kg	No Waste		
Engle Bar	5	Kg						
Plate Eser	4	Kg						
Wire	1	Kg						

Table 3. LCI Chrome Removal Process

Chrome removal process								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Dies and Jig	90	Kg	Dies chrome removal	90	Kg	Alkali	50	Kg
Alkali	50	Kg						
Electricity	5	Kwh						

Life Cycle Analysis (LCA)

The first step in implementing Life Cycle Assessment (LCA) is to determine the scope of the study. The objectives of the LCA calculation include the following:

1. To reduce the negative impact on the environment caused by the hard chrome plating process.
2. To determine which hard chrome plating process contributes the most to carbon emissions.

Provide continuous improvement suggestions to enhance an environmentally friendly work environment.

Life Cycle Inventori (LCI)

The first Life Cycle Inventory conducted on the hard chrome plating process involved picking up dies from customers and transporting them to the company. The dies were picked up using a diesel truck, traveling a distance of 22 km. Information about the materials entering and leaving the LCI during the pickup process can be seen in Table 1.

LCI Fabrication Process of jig. In the second Life Cycle Inventory conducted on the hard chrome plating process, the jig fabrication process was carried out when the dies arrived at the company. Information about the materials entering and leaving the LCI in the jig fabrication process can be seen in Table 2

LCI Old Chrome Removal Process. In the third Life Cycle Inventory conducted on the hard chrome plating process, the old chrome was removed after the jig had been installed. Information regarding the materials entering and leaving the LCI during the jig fabrication process can be seen in Table 3.

LCI Process Dies Repair. In the fourth Life Cycle Inventory conducted on the hard chrome plating process, dies repair was carried out after chrome removal. Information on materials entering and leaving the LCI in the Dies Repair process can be seen in Table 4.

LCI Pre-Polishing Process. In the fifth Life Cycle Inventory conducted on the hard chrome plating process, a pre-polishing process was carried out after the dies had undergone repair.

Table 4. LCI Dies Repair Process

Dies Repair Process								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Dies Chorme Removal	90	Kg	Dies repair	90	Kg	Filter Metal	2	Kg
Filter Metal	2	Kg						
Electricity	5	Kwh						

Table 5. LCI Dies Pre-polishing Process

Pre-polishing Process								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Dies Repair	90	Kg	Dies Pre-Polishing	89	Kg	Metal Dust	2.5	Kg
Buffing	3	Kg				Buffing	1.5	Kg
Electricity	5	Kwh						

Table 6. LCI chrome plating process

Hard chrome plating process								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Dies Pre-Polishing	89	Kg	Dies Hard chrome plating	92	Kg	Chromium (Cr^{6+})	199	Liter
Chromium (Cr^{6+})	200	Liter				Cr Anoda	9	Kg
Cr Anoda Katoda	10	Kg				Air	999	Liter
Air	1000	Liter						
Electricity	30	Kwh						

Table 7. LCI Final Polishing process

Final Polishing Process								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Dies Hard chrome plating	92	Kg	Dies And Jig Final	90	Kg	Chrome Dust	2	Kg
Buffing	7	Kg				Buffing	7	Kg
Electricity	5	Kwh						

Information regarding the materials entering and leaving the LCI during the pre-polishing process can be seen in Table 5.

LCI Hard Chrome Plating Process. The sixth Life Cycle Inventory is the main process that performs the chrome plating process when the dies have undergone pre-polishing. Information about the materials entering and leaving the LCI during the chrome plating process can be seen in Table 6.

LCI Final polishing process. In the seventh Life Cycle Inventory conducted on the hard chrome plating process, final polishing is carried out after the dies have undergone the chrome plating process. Information regarding the materials entering and leaving the LCI in the final polishing process can be seen in Table 7.

LCI Quality Check Process. In the eighth Life Cycle Inventory conducted on the hard chrome plating process, a quality check was performed after the dies had undergone final polishing. Information regarding materials entering and leaving the LCI during the final polishing process can be seen in Table 8.

LCI Die Delivery Process. The ninth Life Cycle Inventory is the final process that delivers the dies back to the Cosmuter once the dies have been delivered. Information about the materials entering and leaving the LCI during the die delivery process can be seen in Table 9.

Table 8. LCI Quality Check Process

Quality Check Process								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
DiesAnd Jig Final	90	Kg	Dies Final	80	Kg	Jig	10	Kg

Table 9. LCI Delivery Process

Delivery Process								
Input			Output			Waste		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Dies	80	Kg	Dies Sampai	80	Kg	CO2	50.6	kg CO2
Diesel	22	Liter						

Life Cycle Impact Assessment (LCIA)

During the Life Cycle Impact Assessment (LCIA) stage, the environmental impacts generated during the hard chrome plating process are classified and evaluated.

Based on the results in Figure 4, the relative results of each component in the hard chrome plating stage on the total environmental impact based on the LCA (Life Cycle Assessment) approach are shown. From these results, it can also be concluded that the main raw materials, namely Chromium Oxide and flakes, contribute the greatest impact, followed by sodium dichromate and stainless steel base materials. The use of electricity, supporting processes, and other metal alloys is relatively small.

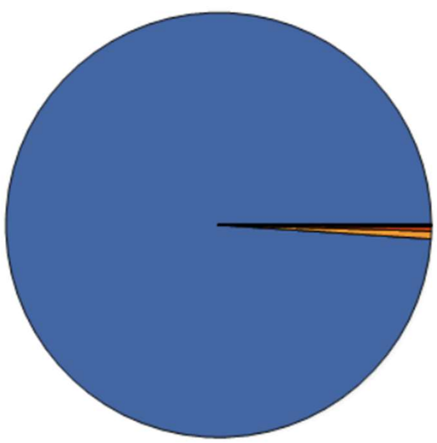

Figure 4. Contribution Processes in the Hard Chrome Plating Process

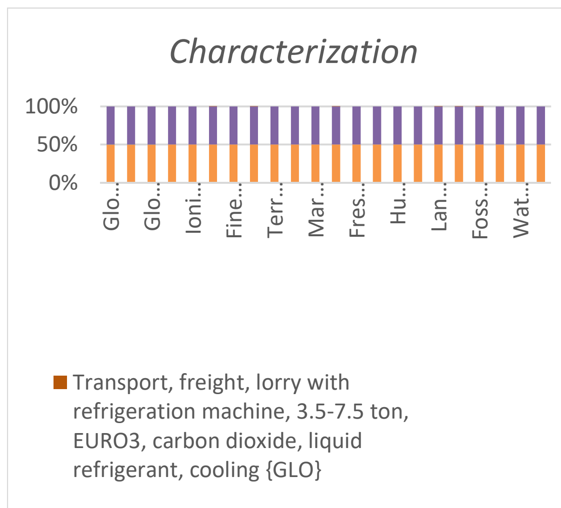

Figure 6. Data Characteristic Proses Hard chrome plating

Figure 5 shows the characteristic data of each stage of the hard chrome plating process in graphic form, making it easier to identify the comparative environmental impact of each process. For more detailed and quantitative results, the data can be viewed in table form from SimaPro 9

Table 10 shows the results of environmental impact normalization from the dies hard chrome plating process in three main categories, namely human health, ecosystems, and resources. The category with the greatest impact is human health with a value of 0.301491. This indicates

Table 10. LCA Normalization

Normalisation					
Damage category	Unit	Total	Dies Delivery	Quality check	Transport, freight, lorry with refrigeration machine
Human health		0.301491	2.47E-05	0.30146631	1.84E-07
Ecosystems		0.00607	2.47E-06	0.006067649	1.41E-08
Resources		0.001614	0	0.001614293	1.07E-08

that this process has the potential to pose a high risk to human health due to exposure to hazardous chemicals. The impact on resources is also significant, with a value of 0.00607, primarily driven by energy consumption and metal consumption. The contribution to ecosystem damage is relatively smaller, with a value of 0.001614, though it remains a concern, particularly due to transportation emissions.

Chrome plating with dies weighing 80 kg, the largest environmental impact contribution comes from the use of hard chrome coating, 122.056 Pt, followed by sodium dichromate, 0.7276 Pt, and stainless steel, 0.35858 Pt. The contribution from the use of electricity and other supporting processes is less than 0.005 Pt each.

Overall, the total environmental impact for the hard chrome plating process based on the ReCipe 2016 Endpoint H method in Simapro 9 reached 0.301491 for the Human Health category, 0.00607 for Ecosystem, and 0.001614 for Resources. These values indicate that the primary

Table 11. Proposed Improvements Using 6R

No	Process	Input	Output		6R						6R Strategy
			Product	Waste	Re-duce	Re-use	Re-cycle	Re-pair	Remanu-facturing	Re-place	
1	Dies picking	Dies Diesel	Dies Sampai	CO2	□						Using more environmentally friendly vehicles or materials (from diesel fuel to bio-diesel)
2	Fabrication of jig	Dies Engle Bar Plate Eser Kawat	Dies and Jig	No waste							-
3	Chrome removal	Dies and Jig	Dies chrome removal	Alkali			□				Performing purification and recycling of alkali so that it can be reused in the next process
4	Dies Repair	Dies Chorme Removal Filter Metal	Dies repair	Filter Metal			□				Processing unused metal filter waste by cleaning and recycling it.
5	Pre-polishing Pre-polishing	Electricity Dies Repair Buffing Electricity	Dies Pre-polishing Dies Pre-polishing	Metal Dust Buffing	□	□	□				Using a metal dust filtration system (industrial vacuum) Buffing on items that are still usable and can be cleaned and recycled
6	Hard chrome plating	Dies Pre-Polishg	Dies Hard chrome plating	Chromi um (Cr6+)						□	Replacing the more environmentally friendly material Cr^6+ with the more environmentally friendly Cr^3+
7	Final polishing	Dies Hard chrome plating	Dies And Jig Final	Chrome Dust	□						Using a metal dust filtration system (industrial vacuum)
		Buffing		Buffing		□	□				Buffing on items that are still usable and can be cleaned and recycled
8	Quality check	Dies And Jig Final	Dies Final	Jig		□					Re-inspect the jig, reuse the jig if there is no damage.
9	Delivery	Dies	Dies Sampai	CO2	□						Using more environmentally friendly vehicles or materials (from diesel fuel to biodiesel)

chemicals and raw materials are the main sources of impact, so improvement efforts should focus on reducing or replacing these materials, as well as improving process efficiency and waste management.

Proposed Improvements

Based on the results of MFA and LCA analyses of the hard chrome plating process at PT X, it was found that the largest contributions to the environmental impact were the use of hazardous chemicals, particularly hexavalent chromium (Cr6+), high energy consumption, and heavy waste. Therefore, improvements were suggested in the form of strategies to reduce hazardous materials, improve energy efficiency, and recycle waste. The improvement strategy is formulated based on the 6R approach (Reduce, Reuse, Repair, Remanufacture, Replace).

The 6R approach was chosen because it provides improvement guidelines that not only emphasize process efficiency, extend service life, and replace high-risk chemicals. Its other capabilities provide a systematic framework for reducing resource waste, reducing emissions, and improving process efficiency. This approach aligns with modern industry trends toward green manufacturing and compliance with international regulations, while supporting the transition toward a responsible production system. The following are process improvement proposals for hard chrome plating at PT X using the 6R approach, summarized in Table 11.

The proposed improvements in the hard chrome plating process for die products at PT X focus on increasing material and energy efficiency through a sustainability approach based on Life Cycle Inventory (LCI) results, as shown in Table 12.

Contribution to Sustainable Development Goals (SDGs)

The SDGs are a global agenda consisting of 17 main goals for achieving sustainable development. This research supports these efforts by identifying and reducing the environmental impact of the hard chrome plating process.

Table 12. Comparison of LCI Before and After Repair

No	Before						After						
	Input			Waste			No	Input			Waste		
	Material	Amount	Unit	Material	Amount	Unit		Material	Amount	Unit	Material	Amount	Unit
Dies Picking													
1	Diesel	22	Liter	CO2	50.6	kg CO2	1	Bio-Diesel	22	Liter	CO2	8.36	kg CO2
Chrome Removal Process													
2	Alkali	50	Kg	Alkali	50	Kg				-			
Dies Repair Process													
3	Filter Metal	2	Kg	Filter Metal	2	Kg				-			
Pre-Polishing Process													
4	Buffing	3	Kg	Buffing	1.5	Kg	2		3	Kg	Metal Dust	1	Kg
				Metal Dust	2.5	Kg							
Hard Chrome Plating Process													
5	Chromium (Cr6+)	200	Liter	Chromium (Cr6+)	199	Liter	3	Chromium (Cr3+)	200	Liter	Chromium (Cr3+)	199	Liter
6	Cr Anoda	10	Kg	Cr Anoda	9	Kg	4	Cr Anoda	10	Kg			
7	Water	1000	Liter	Air	999	Liter	5	Water	1000	Liter			
Final Polishing Process													
8	Buffing	3	Kg	Buffing	1.5	Kg	6	Buffing	3	Kg	Chrome Dust	1	Kg
				Chrome Dust	2.5	Kg							
Quality Check Process													
9	Dies And Jig Final	90	Kg	Jig	10	Kg							
Delivery Process													
10	Diesel	22	Liter	CO2	50.6	kg CO2	7	Bio-Diesel	22	Liter	CO2	8.36	kg CO2

Table 13. SDG's Relevant

Image & Related SDGs	Research Relevance
SDG 6 - Clean Water and Sanitation	The hard chrome plating process produces hazardous wastewater (alkali and Cr6+) that has the potential to pollute water. This study identifies and measures wastewater and provides recommendations for its management.
SDG 7 - Affordable and Clean Energy	The electroplating process consumes high energy; this study uses LCA to evaluate the energy consumption used, such as pickup and delivery dies.
SDG 12 - Responsible Consumption and production	This study uses MFA and LCA to identify chemical consumption (Cr6+), emissions, and hazardous waste so that they can be better managed.
SDG 15 - Life on Land	Solid waste and heavy metals from the plating process can contaminate soil and terrestrial ecosystems. This study maps the waste and provides suggestions for reducing its impact on the environment.

IV. Conclusion

The conclusions of this study are as follows:

1. This study successfully mapped the business process flow of hard chrome plating on dies at PT X. The process begins with the collection of dies, fabrication of jigs, chrome removal, dies repair, pre-polishing, hard chrome plating, final polishing, and quality check. All of these stages produce various types of solid and liquid waste as well as significant energy and material consumption. The primary process with the greatest environmental impact is the hard chrome plating process due to the use of Cr^{6+} solutions.
2. Based on the MFA results, the total material entering the system is 1,362 tons/year. The total waste generated from the entire process reaches 464.59 tons/year, with the largest proportion coming from liquid waste (455.82 tons/year), mainly from solutions and contaminated water. The processes with the highest waste levels were identified in the hard chrome plating and chrome removal stages. This indicates that the critical points in the material flow are at the stages of hazardous chemical use and water consumption, which significantly contribute to the potential for environmental pollution.
   - LCA analysis was conducted using a gate-to-gate approach with SimaPro 9 software. Based on input and output data from MFA, LCA modeling was conducted in four main stages: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.
   - The greatest impact on the environment comes from the use of chromium (Cr^{6+}), which contributes to the highest potential carcinogenic toxicity to humans.
   - The three most significant impact categories as seen from the Unit are:
   - Global warming, human health by 0.00091 DALY.
   - Global warming, terrestrial ecosystems at a rate of 2.75×10^{-6} species per year.
   - Fossil resource scarcity of 44,8075 USD2013
3. The results of the MFA and LCA show that the hard chrome plating process has the most significant environmental impact. Therefore, PT X can make the following improvements:
   - Replacing Cr6+ solutions with more environmentally friendly coating alternatives such as Cr3+ technology.
   - Optimizing energy use by improving efficiency or energy recovery systems.
   - Improving liquid and solid waste treatment systems, and recycling water and heavy metals.
   - Conduct regular environmental monitoring using the MFA and LCA approaches for continuous monitoring.
4. The proposed improvements using the 6R method successfully reduced the impact score in the Human Health category from 0.3015 to 0.0618, and in the Resources category from

0.0016 to 0.00048. In addition, carbon emissions were reduced from 5.6 to 3.0 kg CO2-eq/m2. However, there was an increase in the impact on Ecosystems from 0.0061 to 0.0143 due to the use of biodiesel. Overall, this strategy demonstrates improved energy efficiency and more sustainable waste management.

5. Recommendations that can be given regarding the application of Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) methods to evaluate the sustainability of the hard chrome plating process are to expand the scope of LCA to a cradle-to-gate or cradle-to-grave approach for a more comprehensive analysis and to add cost analysis using the Life Cycle Costing (LCC) approach.

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