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Life Cycle Assessment Analysis of Corrugated Carton Box Production Process to Measure Eco-Efficiency Level

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Abstract

The production of carton boxes is an energy-intensive process that generates various contaminants, polluting water and air, and affecting both ecology and human health. This study focuses on the environmental impact during the carton box production process at PT XYZ, aiming to calculate and analyze the environmental impact while measuring the eco-efficiency level of the production process. The research method employed in this study is quantitative descriptive, with primary data sources consisting of interviews, while secondary data includes company reports. Data were processed using SimaPro software and the Eco Indicator 99 method. Eco-efficiency measurement was conducted using the Life Cycle Assessment approach. The results indicate that the production of 1 ton of carton boxes generates an environmental impact of 315 Pt, with the largest contributions coming from the corrugating, folding, and customer delivery stages. The eco-cost value was IDR8,922,503, yielding an eco-efficiency index of 1.34, indicating that the production process is environmentally friendly and economical. However, the eco-efficiency ratio of 25.6% is still considered low, necessitating improvements in energy efficiency and emission reduction. Recommended improvements include substituting fossil fuels with renewable energy, selecting environmentally friendly suppliers, and replacing or modifying machinery to enhance efficiency and reduce emissions.

Introduction

The industrial sector in Indonesia is currently experiencing rapid growth. Given the high industrial growth requiring packaging, shifting consumer behavior, and government regulations supporting eco-friendly products, there is significant potential for increased demand for paper packaging particularly corrugated carton boxes (Hutahaean & Basuki, 2022). According to the Indonesian Corrugated Carton Box Industries Association (PICCI), Indonesia's corrugated carton box packaging industry grew by an estimated 15% in 2018. However, cardboard paper production is an energy-intensive process that generates various contaminants, polluting water, air, and ecosystems while also affecting human health (Vistanty et al., 2015; Vishnuvarthanan, 2025; Baweja & Gautam, 2024; Waste, 2025).

Increased production by industries to meet market demand also leads to higher waste generation, significantly impacting the environment (Ulvi & Harmawan, 2022; Ncube et al., 2021; Yang et al., 2023). Industrial operations rely on fossil fuels such as coal, diesel, oil, and natural gas, as well as electricity all of which are non-environmentally friendly energy sources. These contribute to high volumes of CO_2 emissions, accounting for approximately

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78% of the total increase in global greenhouse gas emissions during the same period (Alfarisy et al., 2023). Additionally, industrial wastewater contributes about 8% of surface water pollution (Busyairi et al., 2020). Furthermore, inorganic solid waste, such as carton box scraps, contains metal compounds that are difficult for microorganisms to decompose. Solid waste can also contribute to disease spread, ecosystem damage, and accelerated climate change (Suhartawan et al., 2023; Bilal, 2025; Fei et al., 2021).

PT XYZ is one of the corrugated box manufacturers located in an industrial area in East Java. Its production process uses raw materials in the form of paper rolls, which undergo three stages: forming, printing, and finishing. In its operational processes, the company faces a major challenge: not only must it maintain product quantity and quality, but it must also implement sustainable production practices. In analyzing sustainable production systems, it is essential to consider the product life cycle (Raja, 2024; Enyoghasi & Badurdeen, 2021; Wang et al., 2021). The company is expected to achieve more sustainable corrugated box production with minimal environmental impact while maintaining economic value. However, to date, PT XYZ has not conducted any measurements regarding emissions and environmental impacts resulting from material and energy use in its production processes. Additionally, PT XYZ faces challenges related to high waste management costs during production the more waste generated, the higher the environmental costs incurred. Waste from corrugated box production includes solid waste (carton box scraps), liquid waste, sludge, and air emissions from fuel and electricity consumption. These waste management costs encompass not only disposal but also processing, minimization efforts, and environmental mitigation, which are becoming increasingly expensive due to stricter environmental regulations and sustainability demands (Agianto, 2023; Karim et al., 2025).

To address these issues, an analysis of energy use, waste, and emissions from the production process is necessary. One method that can be used for such evaluation is Life Cycle Assessment (LCA), a methodology for analyzing a product's environmental impact throughout its life cycle (Prabowo & Suhariyanto, 2021). The purpose of LCA is to identify, quantify, and implement sustainable environmental improvements, either partially or entirely, based on environmental considerations, sustainable natural resource use, and waste disposal (Brilliantina et al., 2023).

In addition to LCA, eco-efficiency must also be considered, as it measures both economic and environmental performance. Eco-efficiency takes into account the environmental impacts derived from LCA results. Eco-efficiency analysis is crucial for industries to improve management quality by optimizing resource use and minimizing waste. Environmental considerations can influence economic value the lower the environmental impact, the higher the economic value, in line with the eco-efficiency formula (economic value divided by environmental impact). Strong environmental performance can enhance a company's value, as improved environmental efficiency can lead to greater economic efficiency and a competitive market advantage (Pratama & Ainiyah, 2023).

Applying LCA in corrugated box production is expected to help PT XYZ optimize resource use, reduce waste, and identify critical points in the production process that have the most negative environmental impact. It will also measure eco-efficiency levels and uncover opportunities for efficiency improvements through proposed corrective actions. Integrating LCA and eco-efficiency enables the company to contribute not only to environmental sustainability but also to economic efficiency. Therefore, understanding eco-efficiency levels is a crucial step for PT XYZ in achieving sustainable and competitive business objectives.

Methods

The research was conducted at PT XYZ, a company that produces carton boxes. Data collection was carried out through literature review, field research, interviews, and secondary data analysis. Primary data collection methods included direct observation and interviews with the Production Manager to gather information related to the production process, inputs, outputs, and associated costs. The research scope covers the production process, starting from raw material retrieval from the warehouse to delivery to the customer for 1 ton of carton box products. Each production process requires inputs and produces 1 ton of carton boxes as well as non-product outputs in the form of waste and emissions. The research scope covers the production process for 1 ton of carton boxes, representing the average order batch size at PT XYZ. This unit was selected based on production data from January–December 2023, where 1 ton constituted 85% of total orders. Using this benchmark ensures the results reflect real-world operational conditions and facilitate comparison with industry standards. This study uses the Life Cycle Assessment (LCA) method with SimaPro software. This study employs the Eco-Indicator 99 method, which falls under the category of endpoint approaches. This method assesses environmental impacts in a comprehensive manner by evaluating the potential damage caused at the end of the impact pathway. The Eco-Indicator 99 method offers a more comprehensive evaluation of environmental impacts compared to other assessment approaches (Sirait, 2016). It was selected as the primary calculation method because it belongs to the group of methodologies that model environmental impacts based on endpoint mechanisms.

Data processing in LCA begins with the goals and scope definition stage, which determines the objectives and boundaries. The second stage is the Life Cycle Inventory (LCI), which identifies inputs and outputs. The third stage is the Life Cycle Impact Assessment (LCIA) using the Eco-Indicator 99 (H) method, an environmental impact analysis to determine potential environmental damage categories. This stage consists of classification, characterization, normalization, weighting, and single-score calculation. Finally, the interpretation stage involves identifying and evaluating the results of the LCI and LCIA to ensure integration across all stages.

The LCA calculation results will be used to determine the eco-cost value. Environmental costs represent the expenses incurred to mitigate the environmental impact generated (Fahmi et al., 2024). The eco-efficiency level calculation begins with a cost-benefit analysis. This stage aims to determine the net value of a product. The net value can be calculated using the following equation (Kresnanggara & Purwaningsih, 2024):

$$Net\ Value = Selling\ Price - Production\ Cost$$

The results of the Eco-Cost and Cost-Benefit Analysis calculations serve as the basis for determining the Eco-Efficiency Index (EEI), which measures the economic and environmental performance of an industry or company by considering resource efficiency and environmental impact. The EEI is calculated using the following equation (Kresnanggara & Purwaningsih, 2024):

$$EEI = \frac{Price - Cost}{Eco\ Cost} = \frac{Net\ Value}{Eco\ Cost}$$

The final step is calculating the Eco-Cost Value Ratio (EVR) to determine the Eco-Efficiency Ratio (EER). The results of this equation can be used to assess the level of production eco-efficiency, determined by the EVR value (Kresnanggara & Purwaningsih, 2024):

$$EVR = \frac{Eco - cost}{Net\ Value}$$

$$EER = (1 - EVR) \times 100\%$$

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Results and Discussion

Determining the goal and scope is a crucial initial step in Life Cycle Assessment (LCA), as it forms the foundation for ensuring the clarity of the research objectives and the system boundaries being analyzed (Kresnanggara & Purwaningsih, 2024). This study aims to analyze the environmental impacts arising from the production process of carton boxes and to measure the eco-efficiency level of their production. The scope boundary of this research follows a gate-to-gate approach, encompassing the stages from raw material retrieval from the supply warehouse to the production area, the production process, and the distribution of finished products to customers. Processes carried out by suppliers and product use by customers are excluded from this study's scope. Emissions and energy consumption from shared resources (machinery, transportation, utilities) are allocated to each production stage based on the proportion of usage time. Electricity consumption is distributed according to the measured machine load (kWh) at each production stage, while fuel consumption is based on the travel distance of the transportation modes. This approach is consistent with the recommendations of ISO 14044 (2006).

Before conducting an environmental impact analysis of a product, it is essential to first collect and identify all relevant data concerning material flows, energy consumption, and emissions at each stage of the product's life cycle. Life Cycle Inventory (LCI) is a critical phase in LCA, aimed at identifying and quantifying all inputs and outputs (such as emissions, waste, and by-products) involved in each stage of the production process (Luthfia et al., 2020). The LCI is conducted for each production stage by calculating the quantities of inputs, outputs, and emissions generated. The inputs required in SimaPro include data on the amount of raw materials used, water consumption, electricity as an energy source, and diesel for motorized vehicles. The product output is the carton box, while the non-product outputs consist of carton box trimming waste, liquid waste, and air emissions. Below is the life cycle inventory for each stage of the carton box production process to produce 1 ton of finished carton box product.

Table 1. Life Cycle Inventory of the Raw Material Retrieval from Warehouse to Production Area Stage

Stage of Raw Material Retrieval from Warehouse to Production Area					
Input			**Output**		
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**
Paper Roll Transport Capacity	0,46	tkm	Paper Roll Transport Capacity	0,46	tkm
Diesel	0,32	liter	Nitrogen Oxide (NO_x)	0,0050592	kg
			Methane (CH_4)	0,0000128	kg
			Non-Metal Volatil Organic Compound (NMVOC)	0,001264	kg
			Carbon Monoxide (CO)	0,0050592	kg
			Dinitrogen Oxide (N_2O)	0,0000512	kg
			Carbon Dioxide (CO_2)	0,935968	kg

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The table 1 above presents the input and output data for the stage of raw material retrieval, specifically the transportation of paper rolls from the warehouse to the production area. This process involves a transport capacity of 0.46 tkm and a diesel consumption of 0.32 liters. As a result of diesel combustion, several environmental emissions are generated, including 0.0050592 kg of nitrogen oxides (NOx), 0.0000128 kg of methane (CH_4), 0.001264 kg of non-metal volatile organic compounds (NMVOC), 0.0050592 kg of carbon monoxide (CO), 0.0000512 kg of nitrous oxide (N_2O), and 0.935968 kg of carbon dioxide (CO_2).

Table 2. Life Cycle Inventory of the Corrugating Stage

Corrugating Stage					
Input			**Output**		
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**
Kraft Liner Paper	575	kg	Single-Wall Corrugated Carton Box Sheets	1150	kg
Fluting Medium Paper	575	kg			
Stratch	2,5	kg			
Borax ($Na_2B_4O_7$)	0,075	kg			
Caustic Soda (NaOH)	0,03	kg			
Polyvinyl Alcohol	0,15	kg			
Electricity	58,19	kWh	Carbon Dioxide (CO_2)	0,0506253	ton
Water	200	liter	Waste Water	160	liter
			Biochemical Oxygen Demand (BOD_5)	0,10416	kg
			Chemical Oxygen Demand (COD_T)	0,20768	kg
			Total Suspended Solids (TSS)	0,07096	kg

The table 2 presents the input and output data of the corrugating stage in the corrugated box production process. In the corrugating stage, kraft and fluting medium roll paper are fed into the corrugator machine, which forms the flutes (waves) through a process of heating and pressing. This stage requires 575 kg each of kraft liner paper and fluting medium paper, along with auxiliary materials such as starch, borax, caustic soda, and polyvinyl alcohol. The process consumes 58.19 kWh of electricity and 200 liters of water. The outputs include 1,150 kg of single-wall corrugated carton box sheets and environmental emissions comprising 0.0506 tons of carbon dioxide and 160 liters of wastewater containing 0.104 kg of BOD_5, 0.208 kg of COD, and 0.071 kg of TSS.

Table 3. Life Cycle Inventory of the Printing Stage

Printing Stage					
Input			**Output**		
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**
Single-Wall Corrugated Carton Box Sheets	1150	kg	Printed Colored Corrugated Carton Box Sheets	1150	kg

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Printing Stage					
Input			**Output**		
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**
Electricity	30	kWh	Carbon Dioxide (CO_2)	0,0261	ton
Flexo-Ink	6	liter	Limbah Cair	60	liter
Water	100	liter	Biochemical Oxygen Demand (BOD_5)	0,03906	kg
			Chemical Oxygen Demand (COD_T)	0,07788	kg
			Total Suspended Solids (TSS)	0,02661	kg

The table 3 presents the input and output data for the printing stage in the production of corrugated carton boxes. At this stage, designs, company logos, product information, and other visual elements are printed directly onto the surface of the cardboard. A total of 1,150 kg of single-wall corrugated sheets are processed using 30 kWh of electricity, 6 liters of flexographic ink, and 100 liters of water. The process yields the same amount of printed carton sheets and generates emissions of 0.0261 tons of carbon dioxide along with 60 liters of wastewater. The wastewater contains key pollutants including 0.03906 kg of biochemical oxygen demand (BOD_5), 0.07788 kg of chemical oxygen demand (COD_t), and 0.02661 kg of total suspended solids (TSS), indicating a potential environmental impact on water quality from the printing process.

Table 3. Life Cycle Inventory of the Creasing Stage

Creasing Stage					
Input			**Output**		
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**
Printed Colored Corrugated Carton Box Sheets	1150	kg	Cut and Fold-Line Marked Corrugated Carton Box	1000	kg
			Trim Waste	150	kg
Electricity	9,99	kWh	Carbon Dioxide (CO_2)	0,0086913	ton

The table 4 presents the input and output data for the creasing stage in the corrugated carton box production process. Once the corrugated board is formed, the sheet is processed by a slitter machine. This machine performs two functions simultaneously: slitting (cutting the board width according to order specifications) and creasing (creating fold lines on the board). Subsequently, the board is processed in the slotter machine to create slots or openings that serve as flaps when the carton box is folded. A total of 1,150 kg of printed colored corrugated carton sheets are processed to produce 1,000 kg of fold-line marked carton boxes, accompanied by 150 kg of trim waste. This process consumes 9.99 kWh of electricity and results in carbon dioxide (CO_2) emissions amounting to 0.0086913 tons.

Table 4. Life Cycle Inventory of the Folding Stage

Folding Stage					
Input			**Output**		
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**

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Folding Stage					
Input			Output		
Creased Corrugated Carton Box	1000	kg	Carton Box	1000	kg
Lem	6	kg			
Electricity	1,575	kWh	Carbon Dioxide (CO_2)	0,00137025	ton

The table 5 presents the input and output flows in the folding stage of the carton box production process. This stage involves forming the basic box structure by folding the board along the previously created creasing lines. This process can be carried out using a folder-gluer machine. A total of 1,000 kg of creased corrugated carton box serves as the primary input material, accompanied by the consumption of 6 kg of adhesive and 1.575 kWh of electricity. This process yields 1,000 kg of finished carton boxes as the main output, along with 0.00137025 tons of carbon dioxide (CO_2) emissions resulting from energy consumption.

Table 5. Life Cycle Inventory of the Finished Goods Storage Stage

Finished Goods Storage Stage					
Input			Output		
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**
Carton Box	1000	kg	Carton Box (Bundling)	1000	kg
Strapping Band	2	kg	Strapping Band Waste Trimmings	200	gr
Diesel	0,6	liter	Nitrogen Oxide(NOx)	0,0050592	kg
			Methane (CH_4)	0,0000128	kg
			Non-Metal Volatil Organic Compound (NMVOC)	0,001264	kg
			Carbon Monoxide (CO)	0,0050592	kg
			Dinitrogen Monoxide (N_2O)	0,0000512	kg
			Carbon Dioxide (CO_2)	0,935968	kg
Finished Goods Transport Capacity	0,4	tkm	Finished Goods Transport Capacity	0,4	tkm
Electricity	2	kWh	Carbon Dioxide (CO_2)	0,00174	ton

The table 6 presents the input and output flows during the finished goods storage stage. The completed carton boxes are then stacked and bundled according to standard unit quantities using plastic strapping bands. After the boxes have been manufactured and passed quality control inspection, they are packaged in a flat form (not yet assembled into a 3D shape) and arranged on pallets. A total of 1,000 kg of carton boxes are bundled using 2 kg of strapping band, resulting in 200 grams of trimming waste. The process requires 0.6 liters of diesel fuel and 2 kWh of electricity, contributing to greenhouse gas and air pollutant emissions, including 0.935968 kg of CO_2 from diesel and 0.00174 tons of carbon dioxide (CO_2) from electricity. Additional emissions such as Nitrogen Oxide (Nox), methane (CH_4), non-metal volatil organic compound (NMVOC), carbon monoxide (CO), and dinitrogen monoxide (N_2O) are also generated in small quantities. The recorded transport capacity for finished goods in this stage is 0.4 tkm.

Table 6. Life Cycle Inventory of the Finished Goods Delivery to Customer Stage

Finished Goods Delivery to Customer					
Input			**Output**		
Input	**Quantity**	**Unit**	**Output**	**Quantity**	**Unit**
Forklift Transport Capacity	0,1	tkm	Forklift Transport Capacity	0,1	tkm
Truck Transport Capacity	184	tkm	Truck Transport Capacity	0,1	tkm
Diesel	92,4	liter	Nitrogen Oxide (NOx)	1,460844	kg
			Methane (CH4)	0,003696	kg
			Non-Metal Volatil Organic Compound (NMVOC)	0,36498	kg
			Carbon Monoxide (CO)	1,460844	kg
			Dinitrogen Monoxide(N_2O)	0,014784	kg
			Carbon Dioxide (CO_2)	270,2607	kg

After undergoing a series of production processes, the completed carton boxes stored in the finished goods warehouse are prepared for the delivery stage. The table 3.7 presents the input and output associated with the delivery of finished goods to customers. This process involves the use of a forklift with a transport capacity of 0.1 tkm and a truck with a transport capacity of 184 tkm. To support these transport operations, 92.4 liters of diesel fuel are consumed. The combustion of diesel results in the emission of several air pollutants, including 1.460844 kg of nitrogen oxides (NOx), 0.003696 kg of methane (CH_4), 0.36498 kg of non-metal volatile organic compounds (NMVOC), 1.460844 kg of carbon monoxide (CO), 0.014784 kg of nitrous oxide (N_2O), and 270.2607 kg of carbon dioxide (CO_2).

The subsequent phase of life cycle assessment (LCA) is the life cycle impact assessment (LCIA), which evaluates the scale of environmental impacts arising from production processes. LCIA comprises four stages: characterization, normalization, weighting, and single-score calculation (Sonia & Purwaningsih, 2024). This study employs the Eco-Indicator 99 LCIA method, an endpoint-oriented approach that assesses environmental impacts across three damage categories: human health, ecosystem quality, and resource depletion (Piasecka et al., 2020).

A Sankey diagram (or process flow diagram) provides a visual representation of material and energy flows within a system, incorporating a cut-off filter to quantify the environmental contributions of each process or product life cycle stage. The arrow thickness in the diagram corresponds to the flow magnitude; thicker arrows indicate processes with greater adverse environmental impacts (Rasyid & Anggriani, 2024).

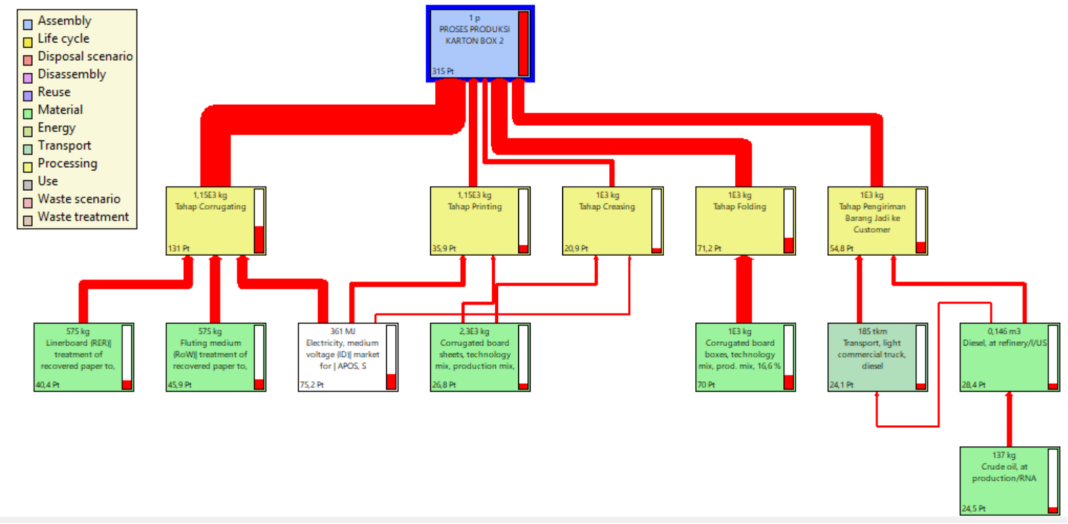


Figure 1. Sankey Diagram

The results of the Sankey diagram indicate that the production process of 1 ton of carton boxes generates a total environmental impact value of 315 pt, with the most significant contributing process being the corrugating stage, accounting for 131 pt or 41.4%. This is attributed to the use of raw materials such as kraft liner roll paper and fluting medium paper, as well as electrical energy during the corrugating process. Followed by folding (22.6%), transportation (17.4%), printing (11.4%), and creasing (6.63%). The significant impact of the corrugating stage is primarily attributed to the consumption of key raw materials such as kraft liner and fluting medium, as well as the use of electricity that still heavily relies on fossil-based sources. The printing and folding stages also contribute substantial impacts due to the use of chemicals, energy consumption, and waste generation. Transportation emissions are mainly driven by diesel combustion, while the recycling process of carton waste also carries a notable environmental burden. Overall, this visualization highlights that the primary sources of environmental impact in the carton box production process are fossil-based energy consumption, the intensity of water and raw material usage, and emissions resulting from transportation and waste processing activities.

The first stage of data processing in LCA measurement is characterization. Characterization involves identifying and grouping factors that potentially cause environmental impacts into several categories based on the Eco-Indicator 99 method (Sonia & Purwaningsih, 2024).

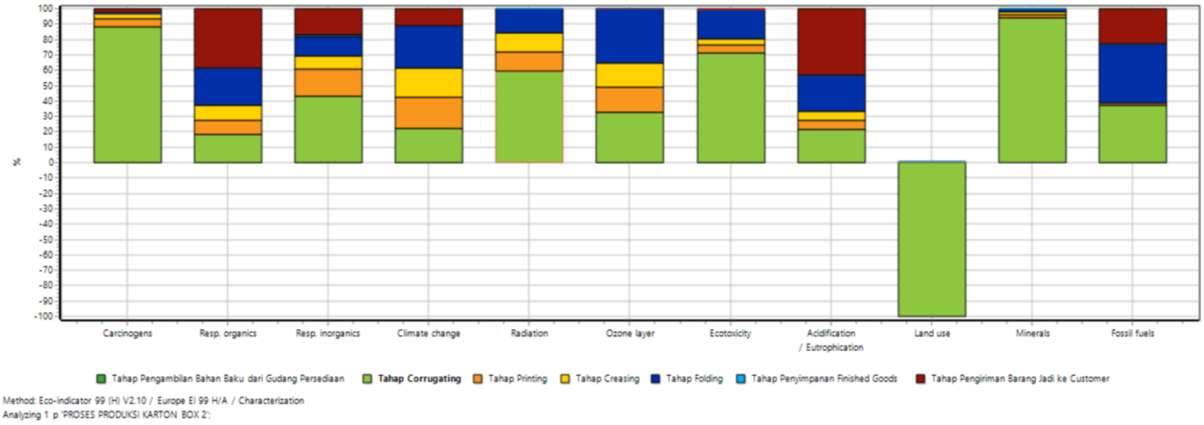
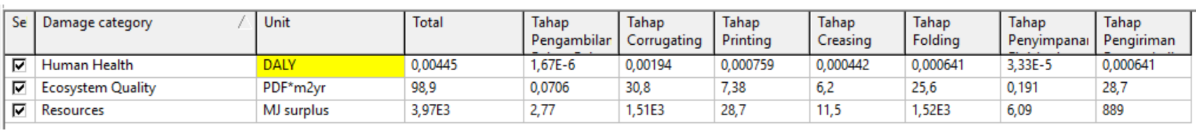


Figure 2. Characterization

This stage will present the values generated from each process for the damage category. The impact indicators measured using Eco-Indicator 99 include carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels (Irawati & Kurniawati, 2020).



Se	Damage category	Unit	Total	Tahap Pengambilar	Tahap Corrugating	Tahap Printing	Tahap Creasing	Tahap Folding	Tahap Penyimpanai	Tahap Pengiriman
☑	Human Health	DALY	0,00445	1,67E-6	0,00194	0,000759	0,000442	0,000641	3,33E-5	0,000641
☑	Ecosystem Quality	PDF*m2yr	98,9	0,0706	30,8	7,38	6,2	25,6	0,191	28,7
☑	Resources	MJ surplus	3,97E3	2,77	1,51E3	28,7	11,5	1,52E3	6,09	889

Figure 3. Damage Assessment

Damage assessment is the evaluation of damage caused by the 11 aforementioned impacts, which are then classified into three impact categories: human health, ecosystem quality, and resources. The output of the damage assessment shows a total impact of 0.00445 DALY (Disability-Adjusted Life Years) for the human health category, meaning the loss of 0.00445 years of healthy life per individual due to disability or premature death. For the ecosystem quality category, the impact is 98.9 PDF·m²·yr (Potentially Disappeared Fraction of species per square meter per year), indicating the loss of 98.9 species per m² annually. Meanwhile, the resources category yields 3970 MJ Surplus, representing the amount of energy lost due to the extraction of natural resources.

Following the characterization stage, the next step is normalization, where the overall impacts are compared, simplified, and standardized using the same measurement basis. This stage aims to obtain comparable values for each type of impact, facilitating further interpretation (Sonia & Purwaningsih, 2024).

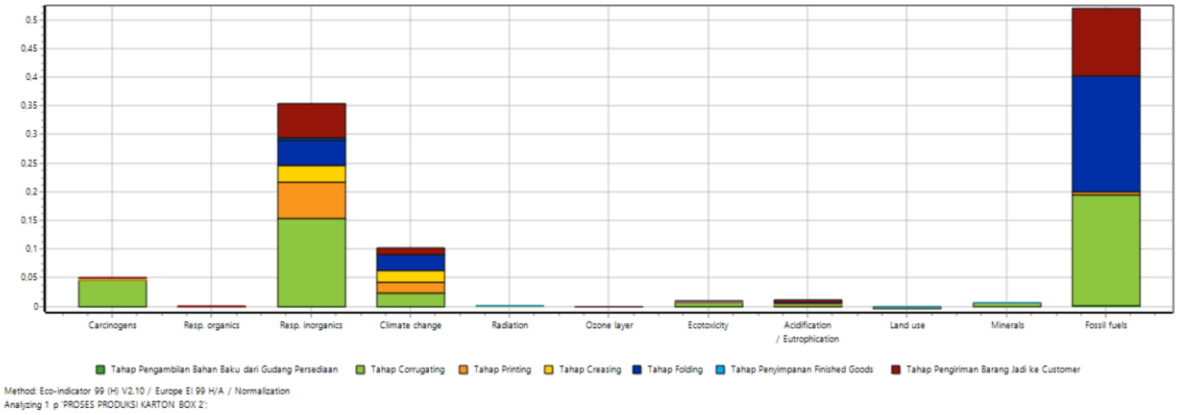


Figure 4. Normalization

The normalization stage reveals the most dominant impacts throughout the carton box production process. Based on the graph, it is evident that fossil fuels, resp. inorganics, and climate change are the most significant impacts generated by the carton box production process. The normalization results table indicates that the impact category with the highest total value is fossil fuels at 0.52, followed by resp. inorganics at 0.354, and then climate change at 0.102.

Weighting is the stage of assigning weights to each environmental impact category. The weighting factors vary depending on the method used and the urgency level of the impact category. This stage aims to establish relative unit values among the impact categories, as comparing all types of environmental impact potentials requires a relative assessment to ensure uniform units, measured in Pt (Points) (Sonia & Purwaningsih, 2024).

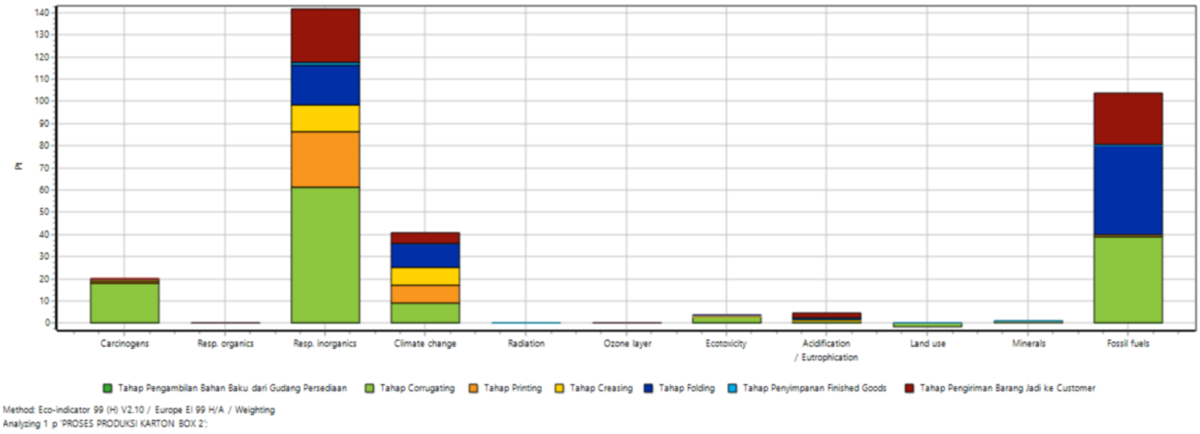


Figure 5. Single Score

The single score stage aims to classify the impact category values of each process or activity. Based on the single score values, it is possible to determine which processes or activities contribute the most to environmental impact or damage (Sonia & Purwaningsih, 2024). In the single score stage, all impact categories are grouped according to damage categories. Following the Eco-Indicator 99 method, the impact categories are classified into three damage categories: human health, ecosystem quality, and resources.

Under the human health category, there are six impact categories: carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, and ozone layer depletion. The ecosystem quality category consists of three impact categories: ecotoxicity, acidification/eutrophication, and land use. Meanwhile, the resources category includes two impact categories: fossil fuels and minerals. This stage presents the resulting values of each process in relation to the respective damage categories.

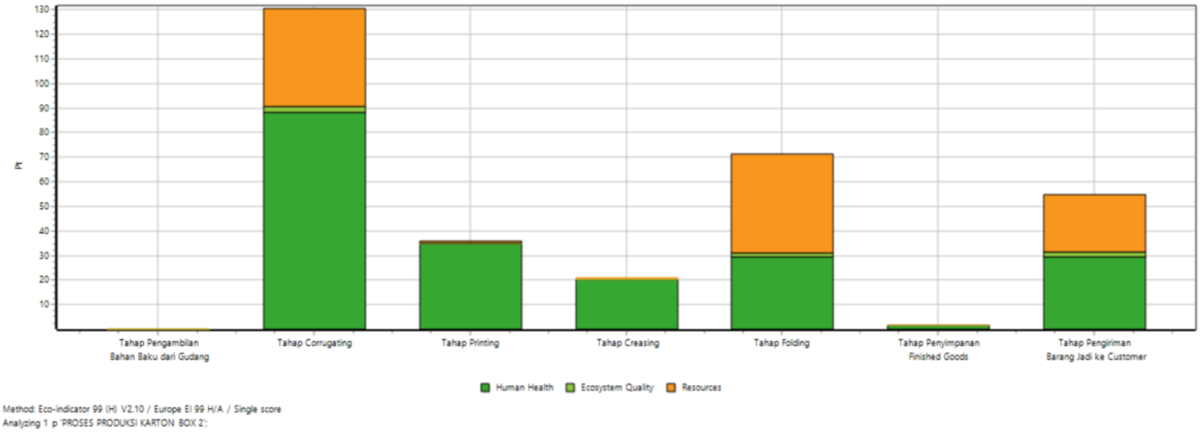


Figure 6. Single Score

The single score graph above illustrates the impact category classification into three damage categories: human health, ecosystem quality, and resources. The most dominant process affecting human health, ecosystem quality, and resources is the corrugating stage, with 203 Pt for human health, 6.92 Pt for ecosystem quality, and 105 Pt for resources.

The final step of LCA is interpretation. This interpretation is conducted to identify, review, and reevaluate the results of the calculations performed to ensure each stage is properly integrated. The environmental impact assessment in this study adopts a gate-to-gate approach, encompassing activities from raw material delivery, carton box production processes (corrugating, printing, creasing, folding), finished goods storage, to the delivery of finished products to customers. Using the Eco-Indicator 99 (E) method, the identified environmental impacts include: The assessment is carried out through the stages of characterization, normalization, weighting, and single scoring to provide an overview of the environmental impact in the carton box production process per batch (1 ton). The assessment reveals that the highest impacts in carton box production are inorganic respiratory effects and fossil fuel consumption, with the most significant contributing processes being the corrugating, folding, and delivery to customer stages.

The results of the LCA calculation will be used to determine the environmental cost. Eco-cost refers to the expenditure required to quantify the magnitude of environmental impact (Susanto et al., 2022). Below is the eco-cost calculation for the carton box production process. For conversion, 1 USD equals IDR 18,432 as of May 3, 2025.

Table 7. Corrugated Carton Box Production Eco-Cost

Damage Category	**Unit**	**Result**	**Conversion Factor**	**Eco-Cost (€)**	**Eco-Cost (IDR)**
Human Health	DALY	0,00445	74000	329,3	6.069.658
Ecosystem Quality	PDFm2yr	98,9	1,4	138,46	2.552.095
Resources	MJ Surplus	3970	0,00411	16,3167	300.750
Total Eco-Cost per Batch Production					8.922.503

The calculation of Net Value is conducted using the Cost-Benefit Analysis (CBA) method, an evaluation approach to compare the costs incurred with the benefits generated. The net value is obtained by subtracting the company's profit from the selling price with the production cost or cost of goods manufactured. The production cost of carton boxes per production batch can be seen in the following table 9.

Table 8. Corrugated Carton Box Production Cost per Batch

Cost Componen	**Cost**
Raw Material Cost	IDR35.000.000
Direct Labor Cost	IDR10.000.000
Fuel Cost	IDR3.000.000
Total Production Cost per Batch Production	IDR48.000.000

From the total production cost, the company sets the selling price of the carton box product at IDR60,000,000 per ton (per production batch). Thus, the net value calculation for each production batch is as follows:

Net Value = Selling Price – Production Cost

= IDR60.000.000 – IDR48.000.000

= IDR12.000.000

The net value is then used to calculate the Eco-Efficiency Index (EEI). The Eco-Efficiency Index measures the economic and environmental performance of an industry or company by considering resource efficiency and environmental impact. A product is considered sustainable if the EEI value is >1, while a product with an EEI between 0 and 1 is deemed affordable. Conversely, a product with an EEI < 0 is classified as unsustainable and unaffordable. The following is the EEI calculation for carton box production:

$$EEI = \frac{Net\ Value}{Eco\ Cost} = \frac{IDR12.000.000}{\text{IDR8.922.503}} = 1{,}34$$

For this carton box product, the eco-efficiency index is 1.34, which falls into the category of values above 1, indicating that the product is affordable and sustainable.

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The Eco-cost Value Ratio (EVR) is a metric used to measure the environmental efficiency of a product by comparing its environmental impact cost (eco-cost) to its economic value (net value). The following is the EVR calculation for carton box production:

$$EVR = \frac{Eco - cost}{Net\ Value} = \frac{IDR10.489.334}{\mathrm{IDR}8.922.503} = 0{,}74$$

The carton box production yields an EVR of 0.74. A lower EVR indicates better environmental efficiency, meaning the product is more viable for production, as a more efficient production process results in lower negative environmental impacts. The Eco-cost Value Ratio (EVR) calculation is used to determine the Eco-Efficiency Ratio (EER) (Susanto et al., 2022). The Eco-Efficiency Ratio (EER) is the final step in measuring a product's eco-efficiency level, aimed at assessing the efficiency of its production process (Sari & Mahdiy, 2025). The following is the EER calculation for carton box production:

$$EER = (1 - EVR) \times 100\%$$

$$EER = (1 - 0{,}74) \times 100\%$$

$$EER = 25{,}6\%$$

The eco-efficiency ratio (EER) of 25.6% in the carton box production at PT XYZ indicates a relatively low level of environmental efficiency. This result warrants a thorough critique by taking into account several key factors and comparisons with previous studies. According to a study by Susanto et al. (2022) on the stamped batik industry, a lower EER of 15.1% compared to PT XYZ was attributed to the high impact of respiratory inorganics and fossil fuels findings that are consistent with this study, in which the corrugating stage accounted for 41.4% of emissions due to electricity use and paper-based raw materials. Based on the calculations, the carton box product's eco-efficiency ratio is 25.6%, indicating that the production process's eco-efficiency level remains relatively low and requires improvement.

Based on the Life Cycle Assessment (LCA), the three production stages with the highest emissions in carton box manufacturing are corrugating (forming corrugated carton box), folding (folding and gluing), and shipping. The corrugating stage generates high emissions due to raw material use (kraftliner and fluting medium roll paper) and electricity consumption, while folding contributes through cutting and printing processes, and shipping emissions stem from diesel-fueled trucks.

PT XYZ, as a producer of corrugated cardboard, faces the challenge of balancing productivity with environmental sustainability. A study by Fahmi et al. (2024) in the tofu industry revealed that energy-intensive production processes increased eco-costs by up to 34%, while Kresnanggara and Purwaningsih (2024) found that raw material substitution in the batik industry could reduce eco-costs by 40%. These findings serve as a basis for evaluating PT XYZ's production practices, particularly in the corrugating stage, which contributes 41.4% of the total environmental impact. This reinforces the conclusions of Fahmi et al. (2024) and Kresnanggara and Purwaningsih (2024) regarding the trade-off between production efficiency and sustainability. The Eco-Efficiency Index (EEI) value of 1.34 indicates economic advantage but highlights the need for environmental optimization, particularly through energy and raw material substitution. Specifically, the low Eco-Efficiency Ratio (EER) of PT XYZ (25.6%) is influenced by three main issues: the dependence on fossil fuels, particularly during the transportation; water inefficiency in the corrugating (200 liters/ton) and printing processes, contributing to water stress impact; and the unutilized solid cardboard waste.

Given the relatively low eco-efficiency value of 25.6%, improvements are necessary to minimize both production and environmental costs. Recommended enhancements include: Substituting fossil fuels with renewable energy (e.g., biofuels or Diesel power) to reduce

Carbon Dioxide (CO_2) and greenhouse gas emissions. These findings reinforce the study by Fahmi et al. (2024) regarding the linear relationship between renewable energy and eco-efficiency, while also highlighting a distinctive aspect at PT XYZ: high transportation emissions due to long distribution distances. Therefore, in addition to energy substitution, logistics route optimization emerges as a key recommendation (Susanto et al., 2022). Furthermore, sourcing raw materials from environmentally certified suppliers, such as those with Forest Stewardship Council (FSC) certification, to ensure sustainability and reduce deforestation. Studies (Bogra & Bakhsi, 2020) show that FSC-certified pulp reduces deforestation by 30% compared to non-certified sources. In addition, optimizing production machinery, including replacing outdated equipment and modifying exhaust systems, which has been proven to reduce emissions by 71% (Ketrin & Rosariawar, 2023). However, the study by Sonia & Purwaningsih (2024) on traditional jenang production by SMEs in Kudus achieved an EER of 54% through the optimization of organic waste processing, indicating that utilizing solid carton waste (such as scrap boxes) as recycled material could serve as a viable solution to improve the EER at PT XYZ. These measures are expected to enhance production efficiency while mitigating environmental impacts.

Conclusion

Based on the Life Cycle Assessment (LCA) using the Eco-Indicator 99 method in SimaPro software, the production of 1 ton of cardboard boxes generates an environmental impact of 315 Pt, with the largest contributions coming from the corrugating, folding, and delivery stages. The most dominant impact category was human health (203 Pt), followed by resource depletion and ecosystem quality degradation. The calculated eco-cost per production batch was Rp8,922,503, yielding an eco-efficiency index of 1.34, indicating that the production process is both environmentally friendly and economically viable. However, the eco-efficiency ratio of 25.6% remains relatively low, suggesting the need for improved energy efficiency and emission reduction strategies. To enhance sustainability, the following improvements are recommended replacing fossil fuels with renewable energy sources, selecting environmentally responsible suppliers, and upgrading or modifying machinery to improve efficiency and reduce emissions.

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