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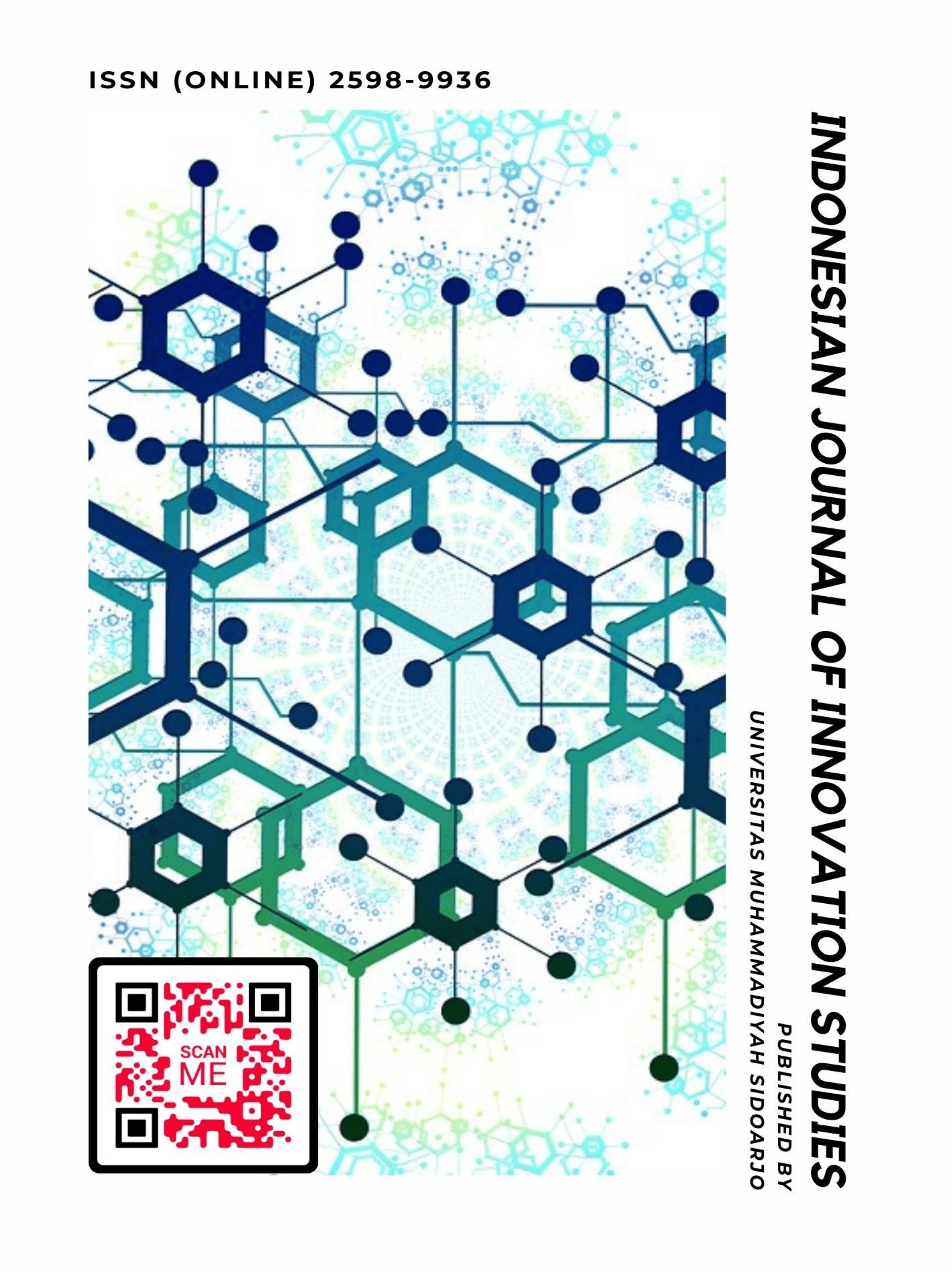

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Life Cycle Assessment of Strandkorb Beach Chair Production

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Abstract

General Background: Wooden furniture production relies on raw materials, auxiliary inputs, and energy-intensive operations that may generate substantial environmental pressures. **Specific Background:** This study assessed strandkorb beach chair production using a gate-to-gate Life Cycle Assessment with SimaPro 9.0 and ReCiPe 2016 (H), covering production stages from raw material use to final factory processes. **Knowledge Gap:** Although Life Cycle Assessment has been applied in manufacturing and furniture studies, limited work has examined wooden beach chair production by identifying detailed process-level hotspots for practical company improvement. **Aims:** The study aimed to evaluate environmental burdens from strandkorb beach chair production and determine the production stages contributing most substantially to those burdens. **Results:** The analysis showed that marine ecotoxicity, freshwater ecotoxicity, and freshwater eutrophication were the most significant midpoint categories, indicating pressure on aquatic ecosystems. At the endpoint level, the total score reached 53.5 Pt, with human health contributing 31.8 Pt, resources 12.9 Pt, and ecosystems 8.77 Pt. The wood kiln drying stage was the main hotspot, contributing 37.1 Pt overall, including 21.7 Pt to human health, 8.43 Pt to ecosystems, and 6.94 Pt to resources, mainly due to high electricity and fuelwood consumption. **Novelty:** This study provides a gate-to-gate ReCiPe 2016 assessment of strandkorb beach chair production and identifies kiln drying as the critical process hotspot. **Implications:** The findings support energy efficiency, kiln operation optimization, low-VOC finishing materials, and more sustainable supplier selection as priorities for cleaner production.

Highlights:

- Aquatic toxicity categories showed the highest comparative importance.
- Human health recorded the largest endpoint score at 31.8 Pt.
- Energy use and finishing chemicals became priority areas for improvement.

Keywords: Beach Chair, Environmental Impact, Life Cycle Assessment, ReCiPe 2016

Introduction

The manufacturing industry is one of the key sectors contributing to Indonesia’s economic development. Among its various subsectors, the wooden furniture industry holds a strategic position due to its ability to generate value-added products while also offering significant opportunities in the global market [1]. According to data from the Ministry of Trade in collaboration with the Indonesian Furniture and Handicraft Industry Association (HIMKI), the value of Indonesia’s furniture exports increased from approximately USD 2.46 billion in 2023 to USD 2.5 billion in 2024. Export distribution in 2024 indicates that the United States was the main destination market, accounting for 53.2% of total exports, followed by Japan (6.04%), the Netherlands (4.48%), Germany (3.73%), and Belgium (2.87%). The existence of this industry not only contributes to foreign exchange earnings through exports but also creates employment opportunities and drives production supply chains from upstream to downstream. On the other hand, as it relies heavily on the utilization of natural resources, the development of the wooden furniture industry cannot be separated from concerns regarding environmental sustainability. This condition also opens up opportunities for wooden furniture companies such as PT XYZ, which produces beach chairs for export.

PT XYZ is an export-oriented manufacturer of wooden furniture, whose flagship product is the strandkorb beach chair, sold internationally, particularly in Germany. The company uses a "make to order" production system, whereby production is carried out only after receiving customer orders. This production system enables the company to adjust its capacity in line with market demand, however, production activities still generate various forms of waste, including solid waste, liquid waste, and emissions resulting from energy consumption, which have not yet been fully managed in an optimal manner. At present, environmental issues have gained increasing attention at both global and national levels, requiring companies to place greater emphasis on the sustainability of their production processes [2]. Therefore, a comprehensive evaluation of environmental impacts is essential as a basis for formulating control strategies and improving resource-use efficiency, as well as serving as an initial step toward the development of a more standardized environmental management system, thereby ensuring the long-term sustainability of the company’s operations [3].

One approach that can be adopted by companies to assess waste generation and emissions arising from production processes is the implementation of Life Cycle Assessment (LCA). LCA is a scientific method used to identify energy use and emissions across all stages of a product’s life cycle, starting from raw material extraction, manufacturing processes, use, maintenance, and ending with post-consumption waste management [4]. This method is an international standard regulated under ISO 14040 and ISO 14044. In this study, the scope of the analysis is limited to the stages from initial raw material utilization to the final production processes within the factory, referred to as a gate-to-gate system boundary. LCA can be applied to identify the sustainability of natural resource utilization, assess environmental pollution burdens, and evaluate as well as implement environmental improvement strategies [5].

A study conducted by Hidayatulloh et al. [6] applied the Life Cycle Assessment method with a gate-to-gate approach to evaluate emissions generated along the supply chain processes of seasoning flour products. The results indicated which production stages contributed most significantly to environmental emissions, primarily due to high electricity consumption and transportation activities. These results demonstrate that life cycle analysis is effective in identifying key sources of environmental impacts and providing a basis for improving production processes towards greater sustainability. Similarly, in a study by Lestari and Pulansari [7], a life cycle analysis approach was applied to the cradle-to-gate system in the furniture industry, enabling a comprehensive assessment of the pollution potential at each stage of the production process. Based on the results of these studies, life cycle analysis is considered an appropriate method for this study, as it can provide a comprehensive overview of the potential environmental impacts arising from the beach chair manufacturing process at PT XYZ.

Previous studies have applied LCA in various manufacturing sectors, including the furniture industry, but studies that specifically analyze the environmental impacts of wooden furniture production remain limited. In addition, only a few studies have examined the contribution of each production stage in detail to identify environmental hotspots as a basis for practical improvement recommendations at the company level. Therefore, this study offers novelty through a gate-to-gate analysis of strandkorb beach chair production using the ReCiPe 2016 (H) method to identify environmental hotspots and provide more practical process improvement recommendations.

The use of life cycle analysis in this study will allow the company to obtain a quantitative overview of the contribution of each production stage to environmental impact. This analysis is necessary because wooden furniture production processes involve not only the primary raw material of wood but also energy and additional materials that can potentially generate emissions and waste. Having clear and measurable results will allow the company to determine which stages of production contribute most significantly to environmental impacts, which will serve as a basis for setting priorities for improvement. The application of this method to strandkorb-type beach chair production is expected to deliver relevant information to support effective environmental impact control.

Method

A. Production Process Flow

The beach chair manufacturing process at PT XYZ involves several distinct stages for each component and subcomponent of the product. Each component undergoes specific production stages based on its specifications, after which all components are assembled in the pre-assembly stage and subsequently processed to produce the finished product. Figure 1 shows the beach chair manufacturing process at PT XYZ, from the initial processing stage to assembly and final finishing.

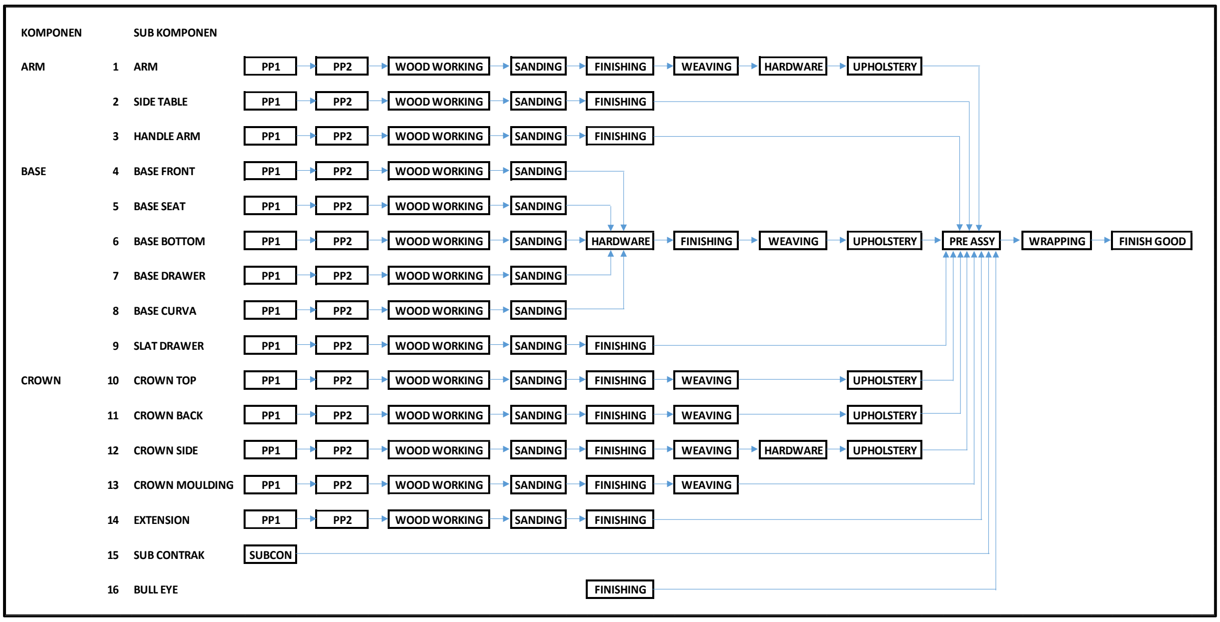


Figure 1. Production Process Flow of Beach Chair at PT XYZ

B. Life Cycle Assessment Method

Life Cycle Assessment (LCA) is an analytical method used to evaluate environmental aspects and potential environmental impacts throughout the life cycle of a product in accordance with applicable international standards. This approach encompasses upstream stages, including raw material acquisition, followed by production and use phases, and extends to downstream stages such as disposal or waste management. Life cycle analysis (LCA) helps quantify the environmental impact of a product or activity, including emissions, waste generation, and resource consumption, and enables comparisons between products or processes that perform similar functions [8]. The LCA method used in this study focuses on understanding the environmental impacts of each process in the supply chain for the production of strandcorb beach chairs. According to ISO 14040 and ISO 14044, LCA consists of four main stages:

1. Goal and Scope Definition

This initial stage serves to clearly define the objectives of the LCA study as well as the scope of the analysis. At this stage, the functional unit is determined as the basis for comparison. Subsequently, the system boundary is established to define the extent of the product life cycle to be assessed. In general, the scope of LCA is classified into four categories which include cradle-to-gate, gate-to-gate, cradle-to-grave, and cradle-to-cradle [9].

2. Life Cycle Inventory (LCI)

This stage represents the most detailed phase of data collection. All inputs, including energy, raw materials, and water, as well as outputs in the form of air emissions, liquid waste, and solid residues, are quantitatively collected. The data are typically obtained from company operational records, field surveys, or secondary databases such as Ecoinvent [10].

3. Life Cycle Impact Assessment (LCIA)

After the inventory phase is completed, the collected data are translated into potential environmental impacts through LCIA. This process involves classification, which groups material and energy flows into specific impact categories, followed by characterization using models such as ReCiPe or TRACI. The analysis results can be further enhanced through normalization and weighting to enhance interpretability and comparability. Environmental impact assessment helps identify "hotspots" in the system, defined as process steps that contribute most significantly to environmental impacts [11].

4. Interpretation

This stage represents the final evaluation phase, in which the results of the Life Cycle Inventory and Life Cycle Impact Assessment are reanalyzed to generate conclusions that can serve as a basis for recommendations. Through this interpretation, hotspots can be identified and practical recommendations can be formulated. The interpretation stage can be used to link analytical results with tangible strategies toward sustainability [12].

C. Data Assumptions and Validation

In this study, several assumptions were applied to ensure model consistency. The production process was assumed to operate under normal conditions in accordance with the company's standard operating procedures, while the quality of wood raw materials and supporting materials was considered relatively uniform. The inventory data were compiled from company production records, field observations, and interviews with relevant personnel. To improve data reliability, cross-checking was carried out between operational records and field information, and the input-output data were adjusted to the functional unit of one strandkorb beach chair product.

D. ReCiPe 2016 Method

The ReCiPe 2016 method is one of the Life Cycle Impact Assessment approaches that is widely used in environmental research, as it is capable of linking Life Cycle Inventory data, including emissions and resource use, to environmental impact categories. ReCiPe 2016 presents results at two levels, namely the midpoint level, which consists of 18 impact categories such as global warming, acidification, and eutrophication, and the endpoint level, which aggregates impacts into three main areas of protection, namely human health, ecosystem quality, and resource scarcity [13]. A study by Hardiansyah et al. [14] emphasizes that the use of both levels in the ReCiPe 2016 method is capable of providing detailed technical insights while simultaneously facilitating the communication of results to decision-makers, thereby demonstrating the relevance of ReCiPe 2016 for application across various industrial sectors. This finding indicates that ReCiPe 2016 functions not only as an analytical tool but also as an effective communication bridge between technical assessments and strategic considerations in environmental management.

E. SimaPro Software

SimaPro is a software developed by PRé Sustainability and has been widely recognized as one of the supporting tools for Life Cycle Assessment. This software has been applied extensively in both academic research and industrial practice [15]. Its primary function is to collect, analyze, and monitor the environmental impacts of a product or service [16]. Through SimaPro, users are able to construct systematic and transparent models to perform complex LCA analyses in accordance with ISO 14040 standards. Each stage of the life cycle, from material use, production processes, transportation, reuse, recycling, and disposal, can be modeled in detail to provide a comprehensive understanding of environmental impacts.

Users can also add new materials and processes to the database to meet specific analytical requirements. SimaPro also supports the use of parameters or additional variables, allowing for model adjustments without compromising the consistency of results. These capabilities make SimaPro an effective and flexible tool for various life cycle impact assessment applications. One of SimaPro's key advantages is its integration with international databases such as Ecoinvent, enabling quantitative analysis and providing a broader perspective on a product's environmental footprint [17]. Several studies in the furniture sector have utilized SimaPro to conduct LCA and quantify environmental impacts of production processes, including a study by Yang et al. [18], which analyzed 25 types of furniture using SimaPro version 9.1.1.1 and the Ecoinvent 3.7 database.

Results and Discussion

A. Goal and Scope Definition

The goal and scope definition stage represents the initial step in the implementation of Life Cycle Assessment and serves to establish the research objectives as well as the system boundaries applied in the study. The objective of this research is to identify and evaluate the environmental impacts generated by each stage of the strandkorb-type beach chair production process at PT XYZ. The analysis is conducted to determine the process stages that contribute the most significantly to environmental impacts (hotspots), so that the results of the study can be used as a basis for formulating recommendations for more environmentally friendly production process improvements. The functional unit applied in this study is one unit of strandkorb-type beach chair product. The determination of this functional unit aims to ensure that all analyzed inputs and outputs are based on a consistent reference, allowing the environmental impact assessment results to be interpreted in a consistent and representative manner for a single unit of product. The scope of the study is defined using a gate-to-gate system boundary, which includes all production stages from the initial use of raw materials to the final manufacturing processes within the factory. In addition, this study employs the ReCiPe 2016 (H) environmental impact assessment method, which is analyzed at both the midpoint and endpoint levels using SimaPro software.

B. Life Cyle Inventory

At this stage, material inputs and energy consumption for each process unit in the strandkorb-type beach chair production process are analyzed. Furthermore, the LCI stage involves the identification of outputs, including intermediate products, final products, and potential emissions and wastes generated during the production process.

Table 1. Life Cycle Inventory of Kiln Drying Process

Kiln Dry					
Input			Output		
Materials	Quantity	Unit	Materials	Quantity	Unit
Wood (Pine)	0,25	m^3	Wood (Pine)	0,2241	m^3
Fuelwood	0,125	m^3	CO_2 Emissions (Fuelwood)	108,76	kg
Water	0,094	m^3	Water Vapor	194,20	kg
Electricity	63	kWh	CO_2 Emissions (Electricity)	54,81	kg

Table 1 summarizes the Life Cycle Inventory of the kiln drying process. At the kiln drying stage, wet pine wood is loaded into the kiln with an initial volume of 8 m^3 per batch. The wood undergoes a drying process for 14 days using a kiln chamber machine. During this stage, fuelwood and water are used as supporting inputs for chamber operation. Fuelwood serves as a thermal energy source to support the drying process, with a requirement of 4 m^3 per batch, while water is used as part of the supporting system with a consumption of 3 m^3 per batch. Throughout this process, a reduction in wood volume occurs due to water evaporation and material losses. Based on a drying yield of 90%, the volume of dried wood produced from one kiln drying batch is 7.2 m^3. This dried wood is subsequently used as the main raw material for the following production stages. Considering the PPIC data on dried wood requirements per beach chair unit, which amount to 0.2241 m^3, one kiln drying batch is capable of producing approximately 32 units of beach chairs. Consequently, the required volume of wet wood per unit product is 0.25 m^3 per unit.

Table 2. Life Cycle Inventory of Pre-Production Process

Pre-Production					
Input			Output		
Materials	Quantity	Unit	Materials	Quantity	Unit
Wood	0,2241	m^3	Wood	0,1503	m^3
			Wood offcuts	0,0738	m^3
Electricity	8,06	kWh	CO_2 Emissions (Electricity)	7,01	kg

Table 2 summarizes the Life Cycle Inventory of the pre-production process. The main input at the pre-production stage consists of pine wood obtained from the previous kiln drying process, with a volume of 0.2241 m^3. This wood is used as the raw material to be processed during the cutting and initial shaping stages according to the requirements of the product components. In addition to material inputs, the pre-production stage also requires electrical energy to operate the production machines used in the wood cutting process. These production machines include a cross-cut saw, a single rip saw, and a blower.

Table 3. Life Cycle Inventory of Woodworking Process

Woodworking					
Input			Output		
Materials	Quantity	Unit	Materials	Quantity	Unit
Wood	0,1503	m^3	Semi-Finished Product 1	1	unit
Screw	75	pcs			
Electricity	18,36	kWh	CO_2 Emissions (Electricity)	15,98	kg

Table 3 summarizes the Life Cycle Inventory of the woodworking process. At the woodworking stage, the materials used consist of wood obtained from the previous process with a volume of 0.2241 m^3, along with supporting components in the form of screws used in the forming and initial assembly of product components. The wood is processed through several activities, including surface leveling, further cutting, and profile shaping in accordance with the specified design requirements. The woodworking process requires electrical energy to operate various production machines used sequentially during these activities. Based on the production data, the machines utilized at this stage include a jointer, planer, band saw, radial arm saw, double shaper, head router, stroke sander, push drill, blower, panel saw, drum sander, hand bor, and grinder.

Table 4. Life Cycle Inventory of Sanding Process

Sanding					
Input			**Output**		
Materials	**Quantity**	**Unit**	**Materials**	**Quantity**	**Unit**
Semi-Finished Product 1	1	unit	Semi-Finished Product 2	1	unit
Sandpaper	3,5	sheet	Sandpaper Waste	3,5	sheet
Electricity	0,72	kWh	CO_2 Emissions (Electricity)	0,63	kg

Table 4 summarizes the Life Cycle Inventory of the sanding process. At the sanding stage, the inputs used consist of a semi-finished product obtained from the woodworking process and sandpaper amounting to 3.5 sheets with dimensions of 25 cm × 25 cm as consumable materials. The wood is sanded to smooth the surface and remove irregularities prior to entering the subsequent processing stages. The sanding process requires electrical energy to operate the hand sander and grinder machines.

Table 5. Life Cycle Inventory of Hardware Process

Hardware					
Input			**Output**		
Materials	**Quantity**	**Unit**	**Materials**	**Quantity**	**Unit**
Semi-Finished Product 2	1	unit	Semi-Finished Product 3	1	unit
Screw	32	pcs			
Drawer	4	pcs			
Electricity	0,84	kWh	CO_2 Emissions (Electricity)	0,73	kg

Table 5 summarizes the Life Cycle Inventory of the hardware process. At the hardware stage, the inputs used include the semi-finished product obtained from the previous sanding process, along with supporting components consisting of drawers and screws. These components are used in the installation and reinforcement of product parts to ensure compliance with the specified design and functional requirements. The hardware process requires electrical energy to operate equipment such as a hand drill and a compressor.

Table 6. Life Cycle Inventory of Staining Process

Staining					
Input			**Output**		
Materials	**Quantity**	**Unit**	**Materials**	**Quantity**	**Unit**
Semi-Finished Product 3	1	unit	Semi-Finished Product 4	1	unit
Paint	1,3	l	Volatile Organic Compounds	1,024	kg
Thinner	1,19	l			
Electricity	11,4	kWh	CO_2 Emissions (Electricity)	9,92	kg

Table 6 summarizes the Life Cycle Inventory of the staining process. At the staining stage, the inputs used include the semi-finished product obtained from the previous hardware process, as well as coating materials in the form of paint and thinner, which are applied to provide color and surface protection to the wood in accordance with product specifications. The staining process requires electrical energy to operate the spray booth and compressor used during paint application. The emissions recorded at this stage include Volatile Organic Compounds (VOCs), which are solvent-based chemical substances that readily evaporate into gases at room temperature and originate from the use of paint and thinner.

Table 7. Life Cycle Inventory of Weaving Process

Weaving					
Input			**Output**		
Materials	**Quantity**	**Unit**	**Materials**	**Quantity**	**Unit**
Semi-Finished Product 4	1	unit	Semi-Finished Product 5	1	unit
Stapler	1750	pcs			
Synthetic Rattan	3,3	kg	Rattan Offcuts	500	g
Electricity	11,56	kWh	CO_2 Emissions (Electricity)	10,05	kg

Table 7 summarizes the Life Cycle Inventory of the weaving process. At the weaving stage, the main component used is the wooden frame that has been processed in the previous stages, along with synthetic rattan as an additional material.

The synthetic rattan is applied to form the woven structure on the seat and backrest in accordance with the product design. In addition, a stapler is used as a supporting tool to fasten and secure the rattan so that it is properly attached to the wooden frame during the weaving process. The weaving activities require electrical energy to operate supporting equipment such as a hand drill and a compressor.

Table 8. Life Cycle Inventory of Upholstery Process

Upholstery					
Input			Output		
Materials	**Quantity**	**Unit**	**Materials**	**Quantity**	**Unit**
Semi-Finished Product 5	1	unit	Semi-Finished Product 6	1	unit
Foam	3	pcs			
Fabric	2,26	m	Fabric Offcuts	0,2	m
Electricity	5,61	kWh	CO_2 Emissions (Electricity)	4,88	kg

Table 8 summarizes the Life Cycle Inventory of the upholstery process. At the upholstery stage, the components used consist of the wooden frame that has been processed in the previous stage, cushioning materials in the form of three pieces of foam, and fabric upholstery used to cover the seat and backrest surfaces with dimensions of 2.26 × 1.8 meters. The foam functions as a filling material to enhance product comfort, while the fabric is applied as an outer layer that forms the final appearance of the seating area. Upholstery activities utilize electrical energy to operate supporting equipment such as a hand drill and a compressor.

Table 9. Life Cycle Inventory of Pre-Assembly Process

Pre-Assembly					
Input			Output		
Materials	**Quantity**	**Unit**	**Materials**	**Quantity**	**Unit**
Semi-Finished Product 6	1	unit	Finished Product	1	unit
Screw	75	pcs			
Handle	2	pcs			
Electricity	1,32	kWh	CO_2 Emissions (Electricity)	1,15	kg

Table 9 summarizes the Life Cycle Inventory of the pre-assembly process. At this stage, product components begin to be assembled so that the chair form can be recognized for inspection before proceeding to the next stage. The inputs used include the wooden frame, handles, and screws, which are installed to connect the main components. At this stage, the assembly is not yet fully permanent; rather, it aims to ensure that all components can be properly fitted and do not encounter issues when advanced to the packaging process. Electrical energy is consumed during pre-assembly activities to support operators in installing and tightening components. Equipment such as a hand drill, compressor, and strapping band is used to facilitate faster and more orderly assembly.

Table 10. Life Cycle Inventory of Wrapping Process

Wrapping					
Input			Output		
Materials	**Quantity**	**Unit**	**Materials**	**Quantity**	**Unit**
Finished Product	1	unit	Product Ready for Shipment	1	unit
Cardboard	1	pcs			

Table 10 summarizes the Life Cycle Inventory of the wrapping process. At the wrapping stage, the fully assembled product is prepared for the packaging process. The materials used at this stage consist of the finished product and cardboard as a protective medium. The cardboard is used to wrap the product in order to protect it from impacts and potential damage during storage and transportation. The output of the wrapping stage is a packaged product that is ready for shipment to consumers. At this stage, no changes occur in the form or function of the product, as the activities performed are limited to packaging. The wrapped product is recorded as the final output of the production process.

Table 11. Life Cycle Inventory of Product Storage Stage

Product Storage Stage					
Input			Output		
Materials	**Quantity**	**Unit**	**Materials**	**Quantity**	**Unit**
Electricity	4	kWh	CO_2 Emissions (Electricity)	3,48	kg

Table 11 summarizes the Life Cycle Inventory of the product storage stage. The product storage stage is conducted after the wrapping process is completed, during which the packaged beach chair products are placed in the storage warehouse prior to shipment to customers. At this stage, no changes occur in the form of the product nor are additional materials introduced; however, storage activities remain part of the production system flow analyzed in the Life Cycle Inventory (LCI). Activities at the product storage stage include the arrangement of finished products, transfer of products to the warehouse area, and storage for a certain period in accordance with the shipping schedule. During this process, electricity consumption primarily arises from warehouse lighting requirements, without the involvement of major production machinery.

C. Life Cyle Impact Assessment

The Life Cycle Assessment phase focuses on assessing potential environmental impacts based on the results of the life cycle inventory. During this phase, all input and output flows collected within the production system are further analyzed and converted into impact categories reflecting the environmental pressures arising from production activities. The LCIA process is conducted to explain the relationships between inventory flows, impact generation mechanisms, and potential environmental consequences occurring within defined system boundaries. This study utilizes the ReCiPe 2016 (H) impact assessment method. This method allows for impact analysis at two levels: an intermediate level, which represents potential impacts across 18 specific environmental categories, and a final level, which represents impacts on key protection areas, including human health, ecosystem quality, and natural resources.

1. Characterization

The characterization stage aims to quantitatively assess the potential environmental impacts of the beach chair production system for each impact category. At this stage, all Life Cycle Inventory data are converted using the characterization factors of the ReCiPe 2016 Midpoint (H) method, which covers 18 environmental impact categories.

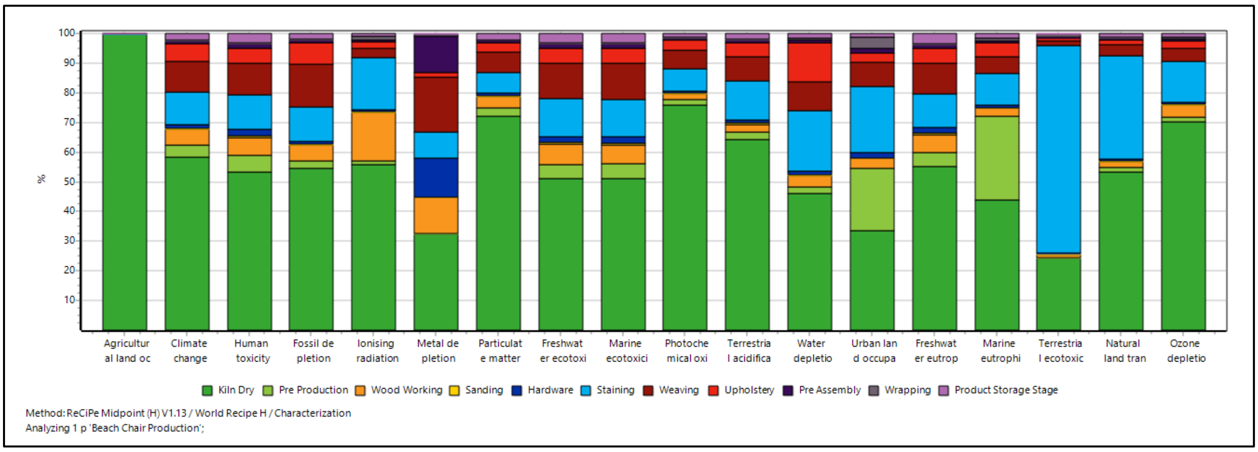
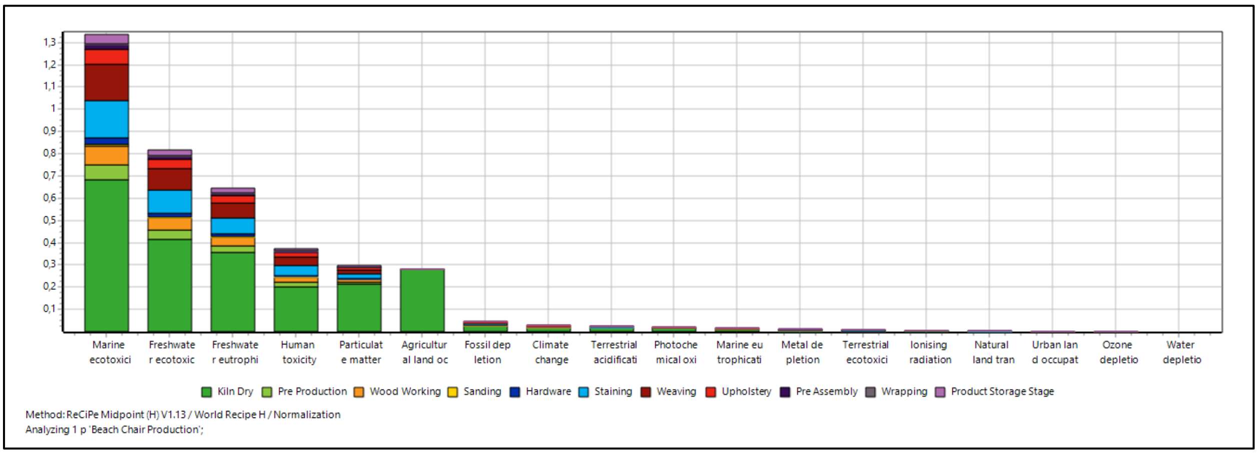


Figure 2. Characterization Results of the Beach Chair Production Process

Based on the characterization results presented in Figure 2, a total of 18 environmental impact categories were assessed, namely: agricultural land use, climate change, human toxicity, fossil fuel depletion, ionizing radiation, metal depletion, particulate matter generation, freshwater ecotoxicity, marine ecotoxicity, photochemical oxidant generation, terrestrial ecosystem acidification, water resource depletion, urban land use, freshwater eutrophication, marine eutrophication, terrestrial ecosystem ecotoxicity, natural land transformation, and ozone depletion. The analysis results show that the kiln-drying process is consistently the dominant factor in almost all environmental impact categories. The dominance of the kiln-drying process is particularly evident in several categories, reflecting its high energy consumption, which significantly influences the overall environmental impact. In addition, the staining and weaving processes also make significant contributions to some impact categories; However, their contribution remains lower than that of the kiln-drying process. Other production processes contribute relatively little to the overall environmental impact.

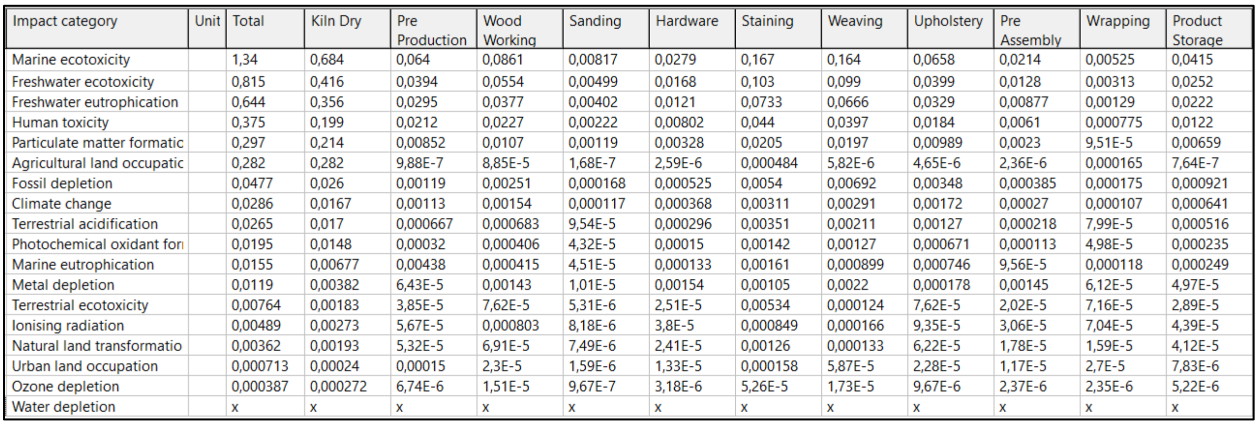
2. Normalization

The normalization stage is applied to enable comparison of the characterization results by standardizing the impact values across environmental categories. At this stage, all Life Cycle Inventory data are converted using the normalization factors of the ReCiPe 2016 Midpoint (H) method, which covers 18 environmental impact categories. Through normalization, differences in magnitude among impact categories can be directly compared, thereby allowing the identification of the most prominent environmental impact categories within the beach chair production system.



Method: ReCiPe Midpoint (H) V1.13 / World Recipe H / Normalization
Analyzing 1 p 'Beach Chair Production';

Figure 3. Normalization Results of the Beach Chair Production Process



Impact category	Unit	Total	Kiln Dry	Pre Production	Wood Working	Sanding	Hardware	Staining	Weaving	Upholstery	Pre Assembly	Wrapping	Product Storage
Marine ecotoxicity		1,34	0,684	0,064	0,0861	0,00817	0,0279	0,167	0,164	0,0658	0,0214	0,00525	0,0415
Freshwater ecotoxicity		0,815	0,416	0,0394	0,0554	0,00499	0,0168	0,103	0,099	0,0399	0,0128	0,00313	0,0252
Freshwater eutrophication		0,644	0,356	0,0295	0,0377	0,00402	0,0121	0,0733	0,0666	0,0329	0,00877	0,00129	0,0222
Human toxicity		0,375	0,199	0,0212	0,0227	0,00222	0,00802	0,044	0,0397	0,0184	0,0061	0,000775	0,0122
Particulate matter formatic		0,297	0,214	0,00852	0,0107	0,00119	0,00328	0,0205	0,0197	0,00989	0,0023	9,51E-5	0,00659
Agricultural land occupatic		0,282	0,282	9,88E-7	8,85E-5	1,68E-7	2,59E-6	0,000484	5,82E-6	4,65E-6	2,36E-6	0,000165	7,64E-7
Fossil depletion		0,0477	0,026	0,00119	0,00251	0,000168	0,000525	0,0054	0,00692	0,00348	0,000385	0,000175	0,000921
Climate change		0,0286	0,0167	0,00113	0,00154	0,000117	0,000368	0,00311	0,00291	0,00172	0,00027	0,000107	0,000641
Terrestrial acidification		0,0265	0,017	0,000667	0,000683	9,54E-5	0,000296	0,00351	0,00211	0,00127	0,000218	7,99E-5	0,000516
Photochemical oxidant fori		0,0195	0,0148	0,00032	0,000406	4,32E-5	0,00015	0,00142	0,00127	0,000671	0,000113	4,98E-5	0,000235
Marine eutrophication		0,0155	0,00677	0,00438	0,000415	4,51E-5	0,000133	0,00161	0,000899	0,000746	9,56E-5	0,000118	0,000249
Metal depletion		0,0119	0,00382	6,43E-5	0,00143	1,01E-5	0,00154	0,00105	0,0022	0,000178	0,00145	6,12E-5	4,97E-5
Terrestrial ecotoxicity		0,00764	0,00183	3,85E-5	7,62E-5	5,31E-6	2,51E-5	0,00534	0,000124	7,62E-5	2,02E-5	7,16E-5	2,89E-5
Ionising radiation		0,00489	0,00273	5,67E-5	0,000803	8,18E-6	3,8E-5	0,000849	0,000166	9,35E-5	3,06E-5	7,04E-5	4,39E-5
Natural land transformatio		0,00362	0,00193	5,32E-5	6,91E-5	7,49E-6	2,41E-5	0,00126	0,000133	6,22E-5	1,78E-5	1,59E-5	4,12E-5
Urban land occupation		0,000713	0,00024	0,00015	2,3E-5	1,59E-6	1,33E-5	0,000158	5,87E-5	2,28E-5	1,17E-5	2,7E-5	7,83E-6
Ozone depletion		0,000387	0,000272	6,74E-6	1,51E-5	9,67E-7	3,18E-6	5,26E-5	1,73E-5	9,67E-6	2,37E-6	2,35E-6	5,22E-6
Water depletion		x	x	x	x	x	x	x	x	x	x	x	x

Figure 4. Normalization Data Results of the Beach Chair Production Process

Based on the normalization results presented in Figure 3 and Figure 4, marine ecotoxicity and freshwater ecotoxicity emerge as the two environmental impact categories with the highest comparative importance, with values of 1.34 and 0.815, respectively. Both categories are associated with the potential impacts of toxic substances on aquatic ecosystems, including marine and freshwater environments, and are influenced by similar production processes within the beach chair manufacturing system. The largest contribution to both categories primarily originates from the kiln drying process, which exhibits the highest electricity consumption within the production system. The extensive use of electricity by the kiln chamber imposes environmental burdens from the upstream energy generation supply chain, which is strongly associated with the release of toxic substances into aquatic environments. This high contribution is closely related to the operational practice at PT XYZ, where the kiln chamber is operated continuously for 14 days per batch and requires substantial electricity and supporting inputs during the drying process.

In addition, the staining process contributes significantly through the use of finishing chemicals and the emission of volatile organic compounds (VOCs), while the weaving process further reinforces these impacts through the use of synthetic materials and electricity consumption at this stage. This result is also relevant to the operational conditions at PT XYZ, where the staining stage involves the use of paint, thinner, spray booth equipment, and compressor support, all of which contribute to VOC emissions and electricity consumption. Likewise, the weaving stage is carried out using synthetic rattan and electricity-supported tools such as hand drills and compressors, which explains its additional contribution to the ecotoxicity-related impact categories.

Although influenced by similar processes, the difference in normalized values between marine ecotoxicity and freshwater ecotoxicity is attributable to differences in the receiving environments. In the marine ecotoxicity category, toxic emissions are associated with marine ecosystems, which are considered to have higher global sensitivity compared to freshwater ecosystems, resulting in the highest level of importance within the analyzed system. Meanwhile, the remaining impact categories exhibit relatively lower normalization values, indicating a lower comparative importance of the beach chair production system with respect to these categories. Nevertheless, all impact categories still contribute to the overall environmental burden of the production system.

3. Weighting

The weighting stage aims to aggregate the normalization results into major damage groups by considering the relative importance of each impact category. At this stage, each impact category is assigned a specific weighting factor so that its contribution can be accumulated using the ReCiPe 2016 Endpoint (H) method, which consolidates the impacts into three damage categories, namely human health, ecosystems, and resources.

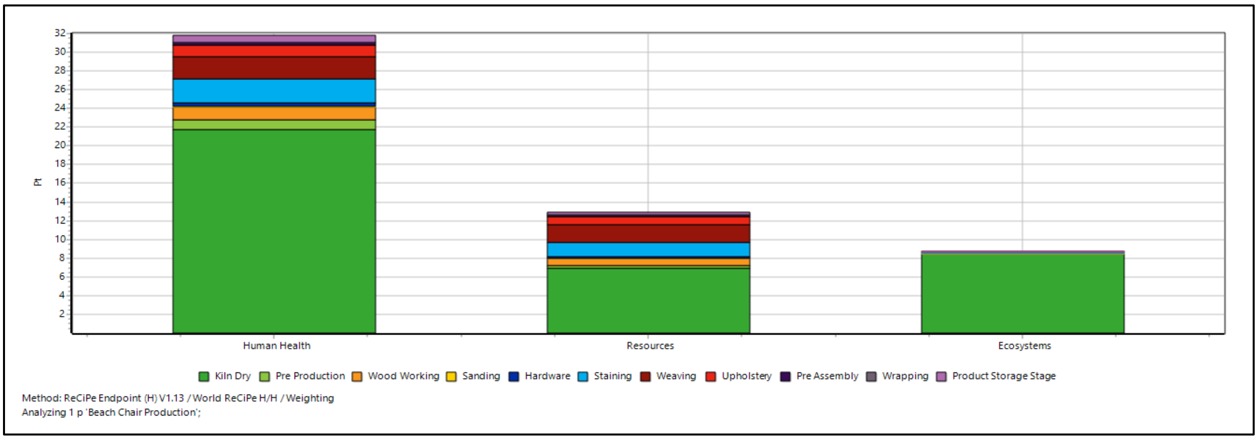
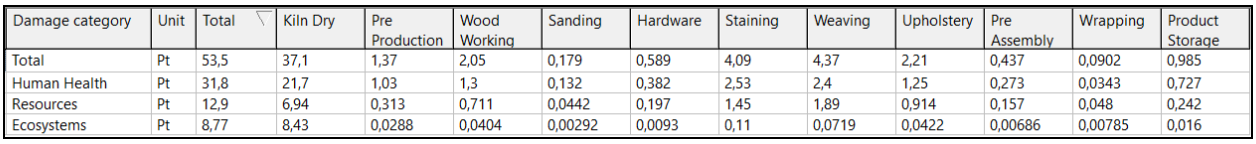


Figure 5. Weighting Results of the Beach Chair Production Process



Damage category	Unit	Total	Kiln Dry	Pre Production	Wood Working	Sanding	Hardware	Staining	Weaving	Upholstery	Pre Assembly	Wrapping	Product Storage
Total	Pt	53,5	37,1	1,37	2,05	0,179	0,589	4,09	4,37	2,21	0,437	0,0902	0,985
Human Health	Pt	31,8	21,7	1,03	1,3	0,132	0,382	2,53	2,4	1,25	0,273	0,0343	0,727
Resources	Pt	12,9	6,94	0,313	0,711	0,0442	0,197	1,45	1,89	0,914	0,157	0,048	0,242
Ecosystems	Pt	8,77	8,43	0,0288	0,0404	0,00292	0,0093	0,11	0,0719	0,0422	0,00686	0,00785	0,016

Figure 6. Weighting Data Results of the Beach Chair Production Process

Based on the weighting results presented in Figure 5 and Figure 6, the total environmental impact score of the beach chair production system amounts to 53.5 Pt, reflecting the cumulative potential damage to the environment and human health arising from all analyzed production processes. The human health damage category contributes the largest share, with a score of 31.8 Pt, accounting for approximately 59% of the total impact score. The dominance of this category is primarily influenced by the kiln drying process, which serves as the main contributor, accounting for 21.7 Pt of the potential human health impacts. This indicates that the operational reliance of PT XYZ on kiln-based wood drying makes this stage the most critical source of health-related environmental burden, since its intensive energy use amplifies the upstream emissions associated with electricity generation. The ecosystems damage category records a total score of 8.77 Pt, indicating a lower contribution compared to the human health category, yet remaining significant in overall environmental impact formation. Nearly the entire contribution to this category is dominated by the kiln drying process, with a value of 8.43 Pt. Contributions from other processes are relatively minor and do not exert a dominant influence on the ecosystems category. Furthermore, the resources damage category yields a total score of 12.9 Pt, reflecting pressure on resource availability resulting from the analyzed production system. The largest contribution to this category once again originates from the kiln drying process, with a score of 6.94 Pt, indicating substantial resource pressure due to its association with fossil-based material use and energy consumption.

D. Interpretation

The interpretation stage is conducted to interpret and evaluate the results of the Life Cycle Impact Assessment, which includes the characterization, normalization, and weighting stages, as well as to identify the key environmental impacts of the analyzed beach chair production system. Based on the characterization results, all impact categories indicate that environmental contributions arise from a combination of energy consumption, material use, and chemical application across various production stages. However, the impact magnitudes at this stage remain specific to each category and do not yet fully reflect the relative importance of each impact category within the overall production system. The normalization results provide a more comparative analysis, highlighting impact categories with the highest importance relative to others. At this stage, the most critical impact categories are marine ecotoxicity and freshwater ecotoxicity, followed by freshwater eutrophication, human toxicity, and particulate matter formation. The dominance of these categories indicates that the beach chair production system exerts significant environmental pressure on aquatic ecosystems, freshwater environmental quality, and human health, particularly through mechanisms related to ecotoxicity, eutrophication, and atmospheric pollutant emissions.

In a subsequent weighting step, the various intermediate impact categories are converted into three main final damage categories: human health, ecosystems, and resources. The analysis shows that human health represents the damage category with the largest contribution, followed by resources and ecosystems. This finding indicates that, overall, the potential impact of the beach chair production system is more pronounced in terms of human health than in terms of ecosystem integrity and resource availability. Overall, the analysis results indicate that the kiln-drying process is the most influential production step, with the greatest environmental impact within the beach chair production system in terms of human health, ecosystems, and resource use. The consistent dominance of this process across the characterization, normalization, and weighting stages confirms that environmental improvement efforts should prioritize energy efficiency enhancement and operational optimization of the kiln chamber.

These findings are consistent with previous studies in the furniture sector. Earlier research has shown that the production stage contributes the greatest environmental impact, mainly due to high electricity consumption during the manufacturing process [7]. A similar pattern was also found in other furniture studies, in which the pre-production and production stages were identified as the main environmental hotspots [18]. In this study, the kiln-drying stage also emerged as the main environmental hotspot, reinforcing that production stages with high energy consumption play a dominant role in shaping the overall environmental burden. In addition, controlling the use of chemicals during the staining process is also a critical aspect for reducing potential impacts on human health and the environment.

E. Recommendation

1. Improvement of Energy Consumption Efficiency

Based on the results of the normalization and weighting stages, a substantial portion of the environmental impacts is attributable to energy consumption during the production processes, particularly the kiln drying stage, which represents the largest contributor. Improving energy consumption efficiency can be implemented primarily in the kiln drying process and is also relevant to other electricity-intensive processes such as weaving, staining, woodworking, and related stages. One of potential improvement strategy is the application of a hybrid wood drying method, which combines natural air drying with kiln chamber drying. In this approach, wood is initially dried naturally until reaching an intermediate moisture content, followed by kiln drying to achieve the final required specifications. This method has been widely applied in the wood processing industry, as it can significantly reduce kiln operating time and electricity consumption. However, the implementation of this strategy may face practical challenges, such as the need for additional space for air drying, longer processing time, and possible adjustments to production scheduling. In addition, the company may consider sourcing wood from suppliers that provide semi-dried wood, particularly for pine wood, which is commonly traded in such conditions.

a. Management of Chemical Use

The next proposed improvement focuses on the staining process, which involves the use of chemical substances that contribute significantly to environmental impacts in the marine ecotoxicity and freshwater ecotoxicity categories. The analysis results indicate that this process also contributes to the human health and particulate matter formation categories through emissions of volatile organic compounds (VOCs). Improvements may be achieved through the selection of finishing materials with lower VOC content (low-VOC coatings) and the optimization of application methods to enhance material use efficiency. Nevertheless, replacing conventional finishing materials with low-VOC alternatives may require additional costs, product quality testing, and operator adaptation to new application methods.

b. Selection of Materials and More Sustainable Suppliers

The selection of alternative materials with lower environmental impacts may serve as an effective improvement strategy. The company may consider using synthetic materials with recycled content, selecting suppliers that implement more environmentally friendly production practices, and re-evaluating material specifications to ensure that they do not exceed the functional requirements of the product. More selective supply chain management can also help reduce environmental burdens at upstream stages, which, as demonstrated by the LCA results, contribute significantly to the total environmental impacts of the production system. Despite its potential benefits, this strategy may be constrained by the limited availability of environmentally preferable suppliers, higher material prices, and the need to ensure consistent quality and supply continuity.

Conclusion

Based on the Life Cycle Assessment results using the ReCiPe 2016 (H) method for the strandkorb-type beach chair, this study is able to identify the production process stages that contribute most significantly to environmental impacts. The analysis results indicate that the most dominant environmental impacts originate from processes with high energy consumption intensity, particularly the kiln drying process, which therefore acts as the primary hotspot within the production system. Furthermore, the results demonstrate that environmental pressures are not limited to a single impact but encompass multiple environmental aspects, particularly those related to human health, aquatic ecosystems, and resource use. These findings support the idea that efforts to reduce environmental impacts should focus on production stages characterized by significant energy and auxiliary material consumption, particularly the kiln-drying process, as well as other processes associated with energy consumption and chemical use in the beach chair manufacturing system. These findings also relevant for company policy because it identifies the production stage that should be prioritized in environmental management and cleaner production initiatives. However, this study is limited to a gate-to-gate system boundary and does not cover the upstream raw material extraction stage, product distribution, product use, or end-of-life stage. Therefore, the results only represent the environmental impacts within PT XYZ's production system. Even so, these findings still provide useful input for prioritizing energy efficiency improvements and sustainability-oriented production strategies. For future research, broader system boundaries beyond the gate-to-gate approach may be considered to capture environmental impacts more comprehensively across upstream and downstream stages. Furthermore, incorporating economic and social aspects may provide a more comprehensive sustainability assessment of strandkorb beach chair production.

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