

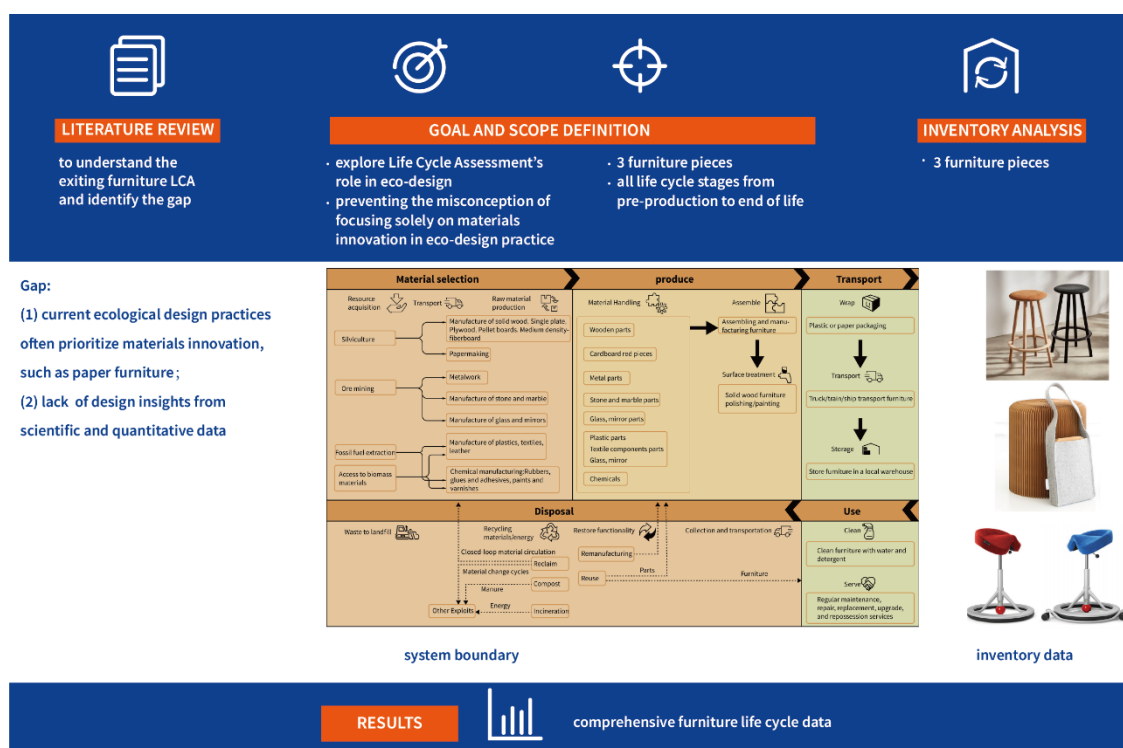
Furniture Product Eco-Design Based on Life Cycle Assessment

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GRAPHICAL ABSTRACT



The comparison of the life cycle Environmental impact of three benches (single score results in mpt)



- (1) By comparing the material types and their environmental impacts on the three pieces of furniture, it becomes evident that selecting renewable materials, like paper, does not invariably dictate the final product's environmental impact.
- (2) By comparing the lifespans and environmental impacts of the three pieces of furniture, it becomes evident that for non-energy-consuming products, such as furniture, extending their use phase can enhance their environmental performance.
- (3) By comparing the functional units and their environmental impacts on the three pieces of furniture, it becomes apparent that the environmental impact of the three products increases with the rise in material weight consumed per functional unit.

Furniture Product Eco-Design Based on Life Cycle Assessment

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This study aimed to quantify the environmental impacts associated with furniture products' life cycle, and to explore Life Cycle Assessment's role in eco-design. The goal was to overcome any misconception of focusing solely on materials innovation in eco-design practice. Three furniture products made up of different materials (paper, plastic, and mixed materials) were assessed using product Life Cycle Assessment (LCA) methodology with Simapro 9.1.1.1 software and the Ecoinvent 3.5 database. The process followed a defined scope and objectives, with inventory analysis, impact assessment, and interpretation of results. The study's quantitative environmental data revealed that eco-design should extend beyond a focus on material renewability and recyclability, traditionally prioritized by designers. It highlighted the importance of prioritizing furniture product life extension, material reduction, and energy reduction, though with varying degrees of priorities. In addition, the data served as a basis for proposing targeted eco-design improvement strategies. The paper concluded that quantitative product environmental data obtained from the product LCA can provide a clear reference for eco-design, which is of great importance in reducing the adverse environmental impact of products.

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Keywords: Eco-design; Life Cycle Assessment; Sustainable design; Environmental impact

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INTRODUCTION

Sustainable development is one of the core issues facing mankind in the 21st century. Efforts related to sustainability will affect the continuation of human civilization and are becoming an essential element in national decision-making. Sustainable development is an approach aimed at meeting the needs of the present generation while not compromising the ability of future generations to meet their own needs. Defined by fairness, continuity, and shared responsibility, the concept of sustainability serves as the compass for the future development of the design world, which is a common pursuit of current designers, residents, and even society as a whole (Liu 2018; Liu 2022). Sustainable product design (or ecological design, or life cycle design) can serve as a critical driver or fundamental aspect. Ecodesign, which is also known as ecological design or design for the environment (DfE), is a design approach that integrates environmental considerations into the development of products, services, or systems throughout their entire life cycle (Brezet

and Hemel 1997; Charter and Tischner 2001). Data shows that about 80% of the environmental impact of products is determined during the design stage (Charter and Tischner 2001; European Commission 2020; Design Council 2022). It follows that ecological design can play a pivotal role in reducing the environmental impact of products, and designers play a key role in this process. Sustainable development is the primary pathway to achieving human development that is not only constrained by resources availability and environmental conditions but also significantly influenced by the evolving societal needs and advancements in production technologies (Liu *et al.* 2022). Through incorporating the concept of sustainable development into the entire product design life cycle, it is possible to assess the potential environmental impact furniture throughout its life cycle. This aids in identifying and reducing factors that could negatively affect future environmental requirements, thereby accelerating the achievement of the sustainable development goals and promoting the sustainable development of the furniture manufacturing industry (Li and Zhao 2023; Yang and Vezzoli 2024).

An important starting point for sustainable product design is to consider the ecological environment encompassing the relationship between people and nature (Jia 2014). Numerous factors influence a product's environmental impact, motivating researchers to propose sound eco-design (or sustainable design) strategies to guide the design process. The need for design approaches compatible with sustainability has led to the emergence of sustainable design.

However, current ecological design practices often prioritize materials innovation, such as paper furniture. While materials selection is crucial throughout a product's life cycle (encompassing raw material acquisition, production, distribution, use, and end-of-life), focusing solely on this aspect can lead to the environmental burdens transfer, not elimination. For example, using renewable materials such as kraft paper reduces resources consumption but it may compromise the product's durability, necessitating increased production and potentially greater pollution. Even given a comprehensive list of eco-design guidelines, designers will encounter multiple design choices that conflict with each other and need to navigate trade-offs to achieve the best solution. Without scientific quantitative data as a reference, making informed decisions about eco-design trade-offs becomes a significant challenge for designers.

Life Cycle Assessment (LCA) quantifies the environmental impact of a product, material, process, or activity throughout its entire life cycle. As one of the most commonly used tools for assessing environmental impacts from a systemic perspective (Panameño *et al.* 2019), LCA provides a reliable basis for product (re)design, preventing environmental burdens from being shifted or hidden within the design process.

The furniture industry, a crucial contributor to environmental pollution, is a key target for the circular economy. Firstly, the paper explores the application of LCA in furniture design. Subsequently, the research employs the LCA method to acquire quantitative environmental impact data for three furniture items. This data enables the identification of these product's environmental hotspots, and in turn, informs the development of crucial principles for sustainable design enhancements that will maximize the environmental performance of these evaluated furniture. This research aims to: i) offer a paradigm for using LCA to quantify environmental impact throughout the furniture life cycle, and ii) propose key areas for eco-design improvement and design strategies based on the experimental study.

Research Review

Life Cycle Assessment is a method used by researchers to assess the environmental impacts of furniture at different levels, including materials, components, and individual items, or even furniture of different categories or different business models.

From a material perspective, wood-based panels such as particleboard and fiberboard are commonly used in furniture production. Data from the European Union show that the average Swedish furniture piece contains 70% wood, 15% filler material, 10% metal, and 5% other materials (Donatello *et al.* 2017). Studies have shown that standard particleboard can have a lower impact than fiberboard (Bovea and Vidal 2004; González-García *et al.* 2009), particularly when considering factors such as phenol-formaldehyde resin production and energy consumption (González-García *et al.* 2009). One key raw material for wood-based panels is the surface material. An environmental assessment of four different wood surface finishing coatings (two wax-based coatings and two UV-hardened UV lacquers) showed that 100% UV lacquers were the most environmentally friendly option (Gustafsson and Börjesson 2007). Looking beyond traditional materials, LCA can also be used for new materials development and evaluation. Biocomposite materials made from hemp fibers and polylactic acid have shown better environmental performance due to their low resource consumption and biocompatibility (Smoca 2019).

Furniture production processes evaluation is another key area. Environmental assessments of the wood production process showed that the sawmill (*i.e.*, raw material acquisition) was the step with the highest adverse environmental impact (AEI) (Phungrassami and Usubharatana 2015). However, assessments of tree felling techniques indicate that the selection between traditional or advanced technology should be contingent upon the specific characteristics of the investigated area, such as geology and topography. It is noted that no single technique can be unequivocally considered as the most environmentally friendly (Mirabella *et al.* 2014a). In the European Union, furniture waste constitutes over 4% of the total municipal solid waste (MSW) annually, of which approximately 80 to 90% is incinerated or sent to landfill, while only a small proportion is recycled (Donatello *et al.* 2014). Notably, a significant amount of furniture is discarded before reaching the end of its functional lifespan. This premature disposal often arises from factors such as office relocation, renovations that render existing furniture unsuitable, expansion of workspace or personnel, and shifts in interior or corporate design. As a result, furniture that remains structurally sound is frequently discarded for aesthetic reasons. The frequent replacement of office furniture exacerbates the generation of solid waste and contributes to the growing demand for landfill space (Besch 2005). Landfilling can lead to methane emissions and groundwater contamination, while incineration poses risks of air pollution and the production of toxic ash (Ulrich and Eppinger 2012).

On furniture product level, LCA can be employed to evaluate individual furniture pieces, pinpoint environmental hotspots, and inform improvement strategies. Research indicates that typical environmental concerns across a furniture item's life cycle encompass various stages such as the production of wooden boards and electricity consumption (González-García *et al.* 2012), solid wood panel production, and iron part machining (Mirabella *et al.* 2014b), as well as transportation distances coupled with the production of primary materials such as medium-density particleboard (Medeiros *et al.* 2017).

Comparing the results of LCAs for different furniture items can aid in selecting more environmentally friendly options (Yang *et al.* 2025). For instance, wardrobes crafted from hybrid-modified ammonium lignosulfonate/wood fiber composites exhibit superior

environmental performance compared to traditional medium-density fiberboard (MDF) wardrobes. Environmental hotspots identified in the LCA of composite wardrobes include raw material supply, energy requirements, and transportation (Li *et al.* 2019). In another study by Gamage and Boyle (2006), LCA was conducted on two types of office chairs, revealing that chairs with aluminum bases have a higher AEI on global warming indicators, with the extrusion/refining of raw materials being a key hotspot in the life cycle. A comparison of 11 seating solutions demonstrated that minimizing energy and materials can enhance environmental performance, while increasing the use of recycled materials and renewable energy sources are favorable strategies (Askham *et al.* 2012). Panameño *et al.* (2019) conducted a comparative environmental assessment of a chair and a redesigned version to inform design enhancements. Additionally, studies have compared the AEI of various business models, confirming that adaptive remanufacturing is an environmentally friendly and economically viable strategy (Krystofik *et al.* 2018).

The research described above has validated the feasibility and effectiveness of conducting product LCA at various levels, including materials (components) or processes, products, and models. This article adheres to scientific LCA methodology to evaluate the environmental performance of three seating stools. Through comprehensive comparisons and analysis, it aims to pinpoint the environmental hotspots of each furniture piece and propose improvement strategies. Existing research primarily focuses on comparing the environmental impacts of materials or production process. As previously mentioned, contemporary ecological design practices often highlight material innovation, such as paper-made furniture. However, few studies systematically assess how paper compares with other commonly used materials in environmental terms. This study addresses this gap through a quantitative evaluation, challenging the assumption that using paper—whether recycled or renewable—necessarily constitutes sustainable design.

EXPERIMENTAL

Research Methods

The product LCA methodology is a structured, comprehensive approach widely employed internationally to quantify the AEI of a product (goods or services) throughout its life cycle (European Commission and Joint Research Center 2010), covering various stages from raw material acquisition, production, distribution, transportation, and use to end-of-life treatment (Vezzoli and Manzini 2008). It is based on analyzing the resource input and waste output during the life cycle of a product, service, or organization, used to calculate the AEI (ISO 14040 2006; ISO 14044 2006). This article adheres to the LCA process delineated in ISO 14040 and ISO 14044, which encompasses: i) goal and scope definition, ii) life cycle inventory analysis, iii) impact assessment, and iv) results interpretation (ISO 14040 2006; ISO 14044 2006). These steps were undertaken to conduct a comprehensive impact assessment of three seating furniture pieces. This assessment utilized the EF method (Environmental Footprint method) and was carried out using SimaPro version 9.1.1.1 software, employing the Cut-off System Model of Ecoinvent version 3.5. The EF method considers 14 environmental indicators and yields a single score result. The Cut-off System Model is a specific section or model within the Ecoinvent database utilized for conducting a Life Cycle Evaluation. It serves to exclude or cut-off data from certain systems, thereby facilitating a more accurate analysis of specific environmental impacts. This model aids researchers in gaining a better understanding of

the environmental performance of a product or process. The cut-off system model was selected for this study because of its simplicity, transparency, and its common use in product environmental declaration (Saade et al. 2019). This system model applies a straightforward yet fundamental approach to distinguish between primary and secondary use stages (Wernet et al. 2016). In the cut off model, recyclable materials are cut off from the original product system, meaning they are removed burden-free from the producing activity, and no impacts or benefits are allocated to them (Wernet et al. 2016). Instead, the full environmental burdens of waste treatment is attributed to the activity that generate the waste. Consequently, recycled materials and energy recovered from incineration become burden-free resources for subsequent consuming activities, i.e. recycled aluminum in pre-production stage in this study.

Defining Evaluation Objectives and Scope

The life cycle of products entails the utilization of various materials and processes, with material innovation often serving as a starting point for sustainable design. This article takes furniture products as a case study, selecting seating benches for indoor use crafted from different materials (paper, wood, plastic, and metal). The goal is to assess and compare their AEI .

Three benches made from (1) paper, (2) wood, and (3) plastic and metal were chosen for the AEI evaluation. This decision was made for different reasons. Firstly, these materials represent typical groups in the furniture industry. Secondly, there are significant disparities in the production methods. Therefore, evaluating and comparing them can provide more comprehensive data, enhancing our understanding of the overall AEI of various material selections for a product. Lastly, this selection aligns with the fundamental principles of sustainable design, emphasizing the consideration and mitigation of AEI during product design to promote more sustainable manufacturing and usage practices.

The objectives of this study are outlined as follows: firstly, to identify the environmental hotspots throughout the life cycle of three seating benches; secondly, to compare the AEI of three benches; thirdly, to propose improvement strategies, and finally to elucidate the key role of LCA in product eco-design. This assessment spans all stages of the bench's life cycle, encompassing raw material acquisition, production, distribution, transportation, and use to end-of-life treatment.

The primary activities during the raw material acquisition phase encompass resource extraction, transportation, raw material processing, and production, all of which consume energy and generate environmental waste. In the production phase, main activities include material handling, component production, furniture assembly, and surface treatment (e.g., polishing, painting, etc.). Other production-related activities, such as design, research and development, production planning, and management, are excluded from the evaluation. Distribution and transportation processes primarily involve packaging, transportation, and product storage. The use phase involves daily cleaning, maintenance, component replacement, and upgrades. The end-of-life phase encompasses furniture disposal after use, including collection, transportation, functional recovery (e.g., remanufacturing or reuse), recycling (materials and energy), and landfilling, among other methods. This study conducted “cradle to cradle” LCA analysis. The system boundary refers to Fig. 1, which was developed based on the authors’ field investigation of the furniture industry and desk research.

Another crucial step in conducting an LCA is defining the functional units of a product. The functional unit serves as a reference unit within a product system to quantify its performance (ISO 14040 2006). In the environmental assessment of products, the object of evaluation is not solely on the product itself, but the functions provided by the product. In this article, the functional unit of the evaluated object is defined as a stool that provides one user with one year of use, based on the typical frequency of use.

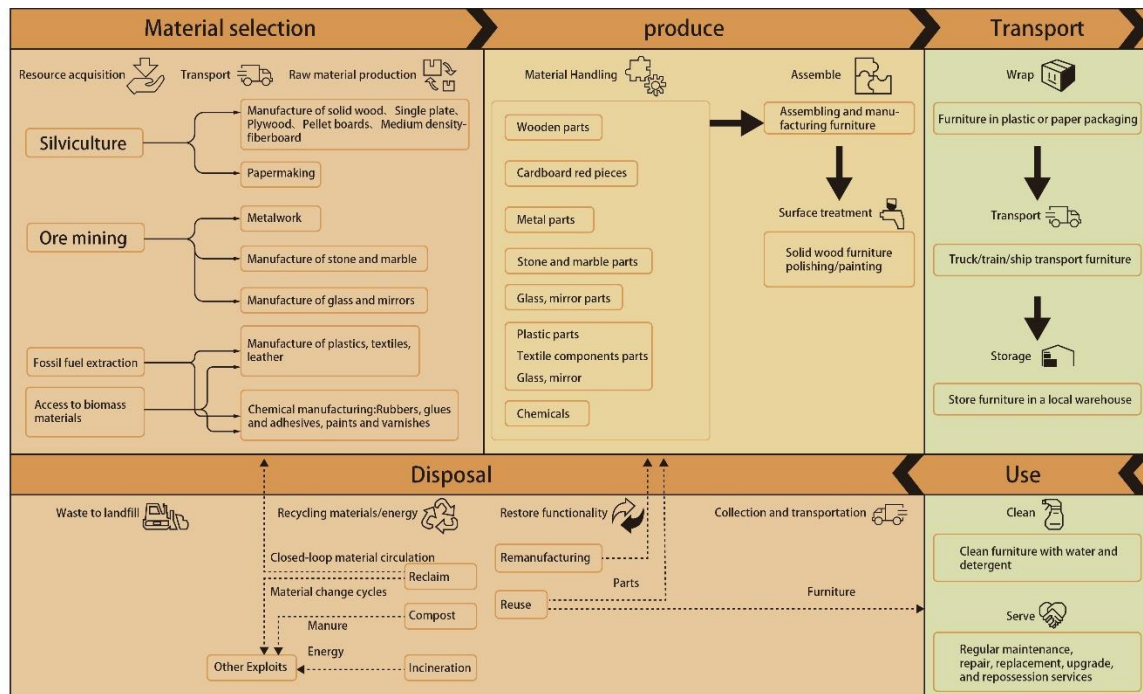


Fig. 1. The system boundary of general furniture

Life Cycle Inventory Analysis

The primary sources for the life cycle inventories of the three seating benches mentioned above are as follows: data for product 1-molo are sources from information published on the product's official website, while data for product 2-OVO and product 3-Backapp are obtained from their respective Environmental Product Declaration (Benchmark 2009; Back 2016). Assumptions for missing information are made in accordance with ISO 14040 (2006), ISO 14044 (2006), and the Product Classification Rules.

The Life Cycle Inventory data encompasses resource inputs across the product's life cycle. Data for the raw material acquisition phase was sourced from the furniture production company, including its official website and environmental statement. Drawing from the inventory of the raw material acquisition phase, this paper makes assumptions about the processes involved in the production phase, guided by the Product Classification Rules.

The transportation stage included environmental assessment necessities data collection on various factors, such as the weight of the product, packaging materials and their weight, transportation means, and transportation distance, *etc.* The following priorities are adopted for sourcing data: i) utilizing actual means of transportation and distance obtained from "The Environmental Product Declaration" issued by a third party; ii) in the absence of relevant data from the producer, hypothetical data provided in "The

Product Environmental Declaration”; iii) If both of the above sources lack data, general assumptions outlined in “The Product Classification Rules” issued by the 'International Product Environmental Declaration System Project' are employed, such as assuming transportation by freight trucks over a distance of 1000 km.

The use scenarios considered in this study involve vacuum cleaner cleaning and wet rag wiping, with the use of detergents not being addressed. Specifically, two scenarios are outlined: i) vacuum cleaner cleaning of the fabric part: it is assumed that a standard vacuum cleaner (with a power rating 900 W) is utilized for cleaning, lasting 20 s once a month. Consequently, an annual consumption of 0.06 kWh of electricity is estimated for cleaning the fabric components. ii) Wet rag wiping for cleaning the non-fabric part. According to the "Product Environmental Footprint Classification Rules - Office Chair (Draft)", it is estimated that 1.5 L of water are consumed per year for each seating stool (Irene 2018).

Because all products originate from the European region, the treatment options at the disposal stage adhere to the general assumptions set forth by the European Union for the end-of-life phase of household goods. The assumptions suggest that 55% of the furniture is disposed of in landfill as solid waste, and 45% is subject to incineration (Castellani *et al.* 2021).

Given that the functional unit (as described earlier) serves as the object of the product life cycle evaluation, this paper converts the functional unit to the product lifetime. The Molo has a lifetime of 1 year, necessitating one Molo seating stool for each realized functional unit; the OVO boasts a design lifetime of 100 years and requires 1/100th of a seating stool for each realized functional unit; and the Backapp boasts a stated lifetime of 15 years and necessitating 1/15th of a seating stool for each functional unit. Specific product life cycle inventory data are delineated in Table 1.

Table 1. The Life Cycle Inventory of Molo (per Functional Unit, 1 Stool)

Molo Picture	Life Cycle Inventory				
	Raw Material Acquisition Stage	Producti on Stage	Distribution and Transportation Stage	Use Stage	Disposal Stage
	Kraft paper: 2.9 (kg)		Automobile carrier	Clean the vacuum cleaner	55% landfill; 45% incineration
	Wool felt: 0.9 (kg)	Spinning	1000 (km)	0.06 (Kwh/year)	
			0.9 (kg) Kraft paper packaging		

The production of an OVO bench involves the consumption of 4.65 kg of solid wood, 0.05 kg of wood wax oil, and 0.02 kg of glue. Considering that the bench is designed to have a lifespan of 100 years, the life cycle inventory values should be divided by 100 when calculating the AEI of the bench for the defined functional unit (1 year). Specific product life cycle inventory data are detailed in Table 2.

Table 2. The Life Cycle Inventory of OVO (per Functional Unit, 1/100 Stool)

OVO Picture	Life Cycle Inventory				
	Raw Material Acquisition Stage	Production Stage	Distribution and Transportation Stage	Use Stage	Disposal Stage
	Solid wood: 0.0465 (kg) (86.11 (cm ³)) Wax oil: 0.0005 (kg) Glue: 0.0002 (kg)	Electric saw: 10 min/100	Automobile carrier	Water: 1.5 (L)	55% landfill; 45% incineration
			104(km)		

The production of a Backapp bench involves the use of 2.234 kg of steel, 2.821 kg of aluminum, 1.855 kg of polypropylene plastic, and 0.2 kg of fabric. Given that the bench is designed with a life cycle of 15 years, the life cycle inventory values should be divided by 15 calculating the AEI of the bench for the defined functional unit (1 year).

Table 3. The Life Cycle Inventory of Backapp (per Functional Unit, 1/15 Stool)

Backapp Picture	Life Cycle Inventory				
	Raw Material Acquisition Stage	Production Stage	Distribution and Transportation Stage	Use Stage	Disposal Stage
	Steel: 0.1489 (kg) Aluminium: 0.1881 (kg) Polypropylene plastics: 0.1237 (kg) Fabric: 0.0133 (kg)	Steel extrusion; Aluminum extrusion; Plastic injection molding	Automobile Carrier: 1000 (km) Kraft paper: 0.0222 (kg)	Water: 1.5 (L) Clean the vacuum cleaner: 0.06 (KwH)	55% landfill; 45% incineration

Comparison of the AEI of Three Pieces of Furniture

The environmental impact values for three pieces of furniture across five stages are presented in Table 4. These values represent the single score outcomes of assessing the AEI across 19 environmental categories, encompassing climate change, ozone depletion, ionizing radiation, photochemical ozone formation, respiratory inorganics, non-carcinogenic effects on human health, carcinogenic effects on human health, acidification of terrestrial and freshwater, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, freshwater ecotoxicity, land use, water resource scarcity, resource use (energy), resource use (minerals and metals), climate change (fossil), climate change (biogenic), and climate change (land use and transformation). Across all three pieces of furniture, the highest AEI is observed during the raw material acquisition stage, followed by the production stage. The AEI during the distribution and disposal stages is relatively similar and lower, while the adverse impact during the use stage tends to be negligible. The assessment results indicate that Stool 1-Molo exhibits the highest AEI, followed by Stool 3-Backapp, with Stool 2-Ovo demonstrating the lowest AEI. Specifically, the AEI of Stool 1-Molo is 2.4 times greater than that of Stool 3-Backapp and 121 times greater than that of Stool 2-Ovo, as shown in Table 4.

Comparing the AEI of the three stools at various stages of their life cycle, it is observed that the Molo stool surpasses 50% of the total AEI in the raw material acquisition stage, with some AEI evident in other stages as well. Conversely, OVO stool demonstrates minimal AEI across all stages of its life cycle. Meanwhile, the Backapp stool exhibits an overall AEI throughout its life cycle that is less than half of what the Molo stool generates, with the primary AEI occurring in the raw material acquisition stage, constituting approximately 80% of the total AEI of the stool.

Table 4. The Comparison of the Life Cycle AEI of Three Benches (Single Score Results in mpt)

Unit: mpt	Raw Material Acquisition	Production	Distribution and Transportation	Use	End-of-Life Processing	Total Value
Molo	0.70	0.22	0.16	0.00	0.12	1.21
OVO	0.0028	0.0019	0.0001	0.0006	0.0000	0.01
Backapp	0.41	0.08	0.01	0.00	0.01	0.51

Analysis of Environmental Hotspots for Each of the Three Pieces of Furniture

For seating stool 1, the raw material acquisition stage highlights the cushion material (viscose) and stool material (corrugated cardboard) as the main contributors to AEI. Following this, during the production phase, spinning exerts a partial AEI. In the transportation stage, the AEI of transportation is comparable to that of packaging materials. Additionally, the electricity consumed for cleaning during use demonstrates a partial AEI. During the end-of-life phase, the landfill of waste cardboard has a higher AEI than material incineration.

For seating stool 2, the raw material acquisition phase highlights the preparation of the sawn timber as the primary contributor to AEI. Additionally, in the production phase, the sawmilling process imposes a relatively significant environmental burden. The water consumption for cleaning the furniture during use also demonstrates a partial effect, while other processes have minimal AEI.

For seating stool 3, the raw materials acquisition stage highlights the preparation of aluminum, steel, textiles, and polypropylene as significant contributors to AEI. During the production stage, the processing of these materials also exerts a relatively large AEI. Notably, during the waste disposal stage, the AEI of burning polypropylene is significantly higher than that of disposing of other materials. The AEI amounts generated by other processes are relatively minor.

Research Conclusions

Life Cycle Assessment offers comprehensive insights into environmental pollution data and aids in identifying pollution sources. In this study, the LCA method was employed to assess three pieces of furniture. Through cross comparing the inventory data and AEI data of these three pieces of furniture, several key findings emerged:

(1) By comparing the material types and their AEI on the three pieces of furniture, it becomes evident that selecting renewable materials, such as paper, does not invariably dictate the final product's AEI. Among the three pieces of furniture examined in this paper, Stool 1-Molo predominantly composed of renewable kraft paper exhibits the largest AEI. Conversely, Stool 3-Backapp, constructed from a blend of materials including steel,

aluminum, plastic, and fabric, demonstrates a moderate AEI. Finally, Stool 2-Ovo crafted from wood showcases the smallest AEI.

(2) By comparing the lifespans and AEI of the three pieces of furniture, it becomes evident that for non-energy-consuming products, such as furniture, extending their use phase can reduce their AEI. Among the three pieces of furniture analyzed in this paper, Stool 1-Molo with a lifespan of only 1 year, exhibits the largest AEI. In contrast, Stool 3-Backapp, with a lifespan of 15 years, demonstrates a moderate AEI. Finally Stool 2-Ovo boasting a lifespan of 150 years, showcases the smallest AEI.

(3) By comparing the functional units and their AEI on the three pieces of furniture, it becomes apparent that the AEI of the three products increases with the rise in material weight consumed per functional unit. Stool 1-Molo consumes 3.8 kg of material per functional unit, resulting in the largest AEI. In contrast, Stool 3-Backapp consumes 0.474 kg of mixed materials per functional unit, leading to a moderate AEI. Finally, Stool 2-Ovo consumes 0.0465 kg of material per functional unit, resulting in the smallest AEI.

DISCUSSION

Based on the data from the product LCA, improvements can be made in the following areas to reduce the AEI of the three pieces of furniture:

(1) For product 1-Molo, enhancing the durability of the product should be the primary focus. Considering the life cycle environmental impact of this model, particular attention should be given to the raw material acquisition stage, which contributes the most to environmental impact. In addition, it is essential to avoid high-impact materials if not compromising the durability of the product, such as by reconsidering the choice of the cushion material. Additionally, the Molo also exhibits higher environmental impacts during transportation compared to other products. Therefore, reducing packaging materials and optimizing the mode and route of transportation should be considered.

(2) Product 2-OVO demonstrates low AEI due to its provision of various services aimed at enhancing durability. This suggests that product providers can explore extending product life by offering services such as refurbishment, reuse, and remanufacturing.

(3) Product 3-Backapp exhibits the highest environmental impacts during the raw material acquisition stage, particularly with aluminum causing the most significant environmental impacts. Therefore, the consideration of using recycled aluminum instead of virgin aluminum is recommended. Additionally, steel components contribute significantly to environmental impacts suggesting a potential replacement of non-structural steel components with alternative materials during the design process. Moreover, polypropylene components exhibit a notable impact and should be replaced with plastics of lower environmental impact, while avoiding the incineration of polypropylene.

The design process should prioritize the functional unit of the product. Upon comparing the environmental impacts of the three benches, which furniture 1-molo is constructed with the least amount of material, its short 1-year life span results in the highest material consumption per functional unit. Consequently, it generates the greatest environmental impact among the three benches. In contrast, Furniture 3-Backapp, despite being composed of the most materials and having a complex material composition, boasts a longer lifespan of 15 years. Consequently, it consumes less material and energy per functional unit compared to furniture 1, yet still demonstrates superior environmental properties. Furniture 2-OVO comprising a relatively large variety of materials, with low

AEI due to its service-based approach, allowing for a lifetime of 100 years. With the same functional units, it consumes the least amount of material and energy.

Through analyzing the overall impacts of the three pieces of furniture, several common design strategies emerge. Across the five life cycle stages, all three products exhibit their greatest environmental impacts at the raw material acquisition stage, underscoring the importance of reducing impacts at this stage without comprising product lifespan. Strategies such as reducing materials usage, opting for renewable/recyclable materials, among others, can effectively mitigate environmental risks. The production phase's impact can be mitigated using renewable energy sources and enhanced production efficiency. While the transportation phase generally has a lower environmental impact, optimizing transportation routes and minimizing packaging materials can further reduce AEI. Although impact during the usage phase tends to approach zero, significant improvements can be made by offering maintenance, repair, refurbishment, and upgrading services to extend product life and thus reduce consumption per functional unit. Impacts associated with incineration and landfill during the disposal stage can be minimized or even eliminated through material recycling and furniture reuse initiatives. Last but not least, design interventions should aim to extend furniture lifespan and facilitate materials life extension (*i.e.* recycling, energy recovery, *etc.*), and avoidance of the throw-away culture. Strategies such as modular design and design for disassembly are particularly effective in facilitating these goals.

This research acknowledges some limitations. The end-of-life stage is modelled based on an average scenario, assuming that 55% of furniture is landfilled as municipal solid waste, while the remaining 45% is incinerated (Castellani *et al.* 2019). In practice, however, end-of-life treatment varies significantly depending on the type of furniture and regional waste management practices. Therefore, when assessing the environmental impact of specific furniture items, it is recommended to use real-life cycle data rather than rely solely on average or screening-level assumptions.

CONCLUSIONS

Considering the rapid degradation of the contemporary ecological environment, environmentally friendly design plays an increasingly important role in the process of sustainable development. This research aimed at creating products or projects that seamlessly integrate with environment considerations. The following design strategies are recommended:

1. Different types of products or even the same type products (such as furniture considered in this research) with different characteristics have varying impacts on the environment throughout their life cycles. In product design, it is essential to select appropriate sustainable strategies based on the characteristics of the product type. This may involve product and materials life extension, reducing materials and energy consumption, using renewable materials and energy.
2. Product life cycle assessment (LCA) is an effective method that can assist designers in obtaining a comprehensive understanding of a product's environmental impact throughout its entire life cycle. This approach enables the quantification of environmental effects at each stage, facilitating the identification of stages with the

greatest impact. Consequently, designers can pinpoint which design strategies will yield the most efficient outcomes.

3. Based on the results of the product LCA, designers can formulate improvement strategies to reduce the product's environmental impact. This may entail adopting more environmentally friendly manufacturing processes, utilizing more durable materials, enhancing product repairability, or encouraging users to prolong the product's lifespan. Additionally, it can spur innovation in discovering greener materials and production methods.

In contrast to previous studies, this research compares the same type of furniture—a stool—made from paper and from other common materials, including wood, plastic, and composites. The results clarify that the trend of using paper, although renewable and recyclable, is not necessarily the most sustainable option or the highest priority in sustainable design. Some contemporary design practices—particularly those involving paper furniture assumed to be eco-friendly—do not meet the fundamental criteria of sustainability.

As future considerations, product sustainability extends beyond just the environmental aspects. It also encompasses social and economic considerations. Designers must take a holistic approach to consider these aspects within the product LCA to ensure that the design is truly comprehensive in its sustainability. Furthermore, addressing end-of-life challenges remains a critical area for future inquiry, particularly through innovations in business models, sustainable product–service systems, service design, and emotionally durable design.

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