LIFE CYCLE ASSESSMENT OF FURNITURE PRODUCTS: A CASE STUDY OF A CHAIR

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

BESTE DİNGİL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
EARTH SYSTEM SCIENCE

AUGUST 2024

Approval of the thesis:

LIFE CYCLE ASSESSMENT OF FURNITURE PRODUCTS: A CASE STUDY OF A CHAIR

submitted by **BESTE DİNGİL** in partial fulfillment of the requirements for the degree of **Master of Science in Earth System Science, Middle East Technical University** by,

Prof. Dr. Naci Emre Altun
Dean, **Graduate School of Natural and Applied Sciences**

Prof. Dr. İsmail Ömer Yılmaz
Head of the Department, **Earth System Science**

Prof. Dr. Ülkü Yetiş
Supervisor, **Earth System Science, METU**

Prof. Dr. Niğmet Uzal
Co-Supervisor, **Civil Engineering, Abdullah Gül Uni.**

Examining Committee Members:

Assist. Prof. Dr. Sema Sevinç Şengör
Environmental Engineering, METU

Prof. Dr. Ülkü Yetiş
Environmental Engineering, METU

Prof. Dr. Gökşen Çapar
Water Management Institute, Ankara University

Date: 02.08.2024

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Last name : Beste Dingil

Signature :

ABSTRACT

LIFE CYCLE ASSESSMENT OF FURNITURE PRODUCTS: A CASE STUDY OF A CHAIR

Dingil, Beste
Master of Science, Earth System Science
Supervisor: Prof. Dr. Ülkü Yetiş
Co-Supervisor: Prof. Dr. Niğmet Uzal

August 2024, 128 pages

Furniture products have long been integral to human daily life, serving not only functional needs but also enhancing comfort and aesthetic appeal in various living spaces. However, due to the harmful effects of furniture production, the industry is under immense pressure, highlighting the critical need for sustainable practices to mitigate potential damage to the environment and human health. Life Cycle Assessment (LCA) serves as a crucial method for evaluating the environmental hotspots of processes by examining the entire life cycle of products.

This study encompasses the cradle-to-grave LCA of a dining chair, based on actual and country-specific production data from Türkiye. The assessment was conducted using SimaPro 9.2.0.2 software with the Ecoinvent 3.7.1 and the U.S. Life Cycle Inventory (USLCI) databases, interpreting results across midpoint and endpoint impact categories using the ReCiPe 2016 Hierarchist method.

The endpoint single score results indicated that the manufacturing stage has the highest environmental impact throughout the chair's life cycle, followed by packaging. Within the manufacturing phase, the veneer joining and upholstering stages were identified as the main contributors due to the use of urea-formaldehyde (UF) resin and woven cotton, respectively. Furthermore, scenario analysis demonstrated that recycling packaging material and the final product notably reduces environmental impacts compared to incineration. Additionally, substituting non-woven fabrics for woven textiles emerges as a promising alternative in upholstered furniture. It is concluded that the proposed alternatives, when combined, can reduce the environmental impacts of a chair product by up to 48%, highlighting significant improvement opportunities in the industry.

Keywords: Furniture, Dining Chair, Ecodesign, Life Cycle Assessment, Environmental Impacts

ÖZ

MOBİLYA ÜRÜNLERİNİN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ: BİR SANDALYE ÜZERİNE ÖRNEK ÇALIŞMA

Dingil, Beste
Yüksek Lisans, Yer Sistem Bilimleri
Tez Yöneticisi: Prof. Dr. Ülkü Yetiş
Ortak Tez Yöneticisi: Prof. Dr. Niğmet Uzal

Ağustos 2024, 128 sayfa

Mobilya ürünleri uzun zamandır insanın günlük yaşamının ayrılmaz bir parçası olmuştur. Yalnızca işlevsel ihtiyaçlara hizmet etmekle kalmamış, aynı zamanda çeşitli yaşam alanlarında konforu ve estetik çekiciliği de artırmıştır. Bununla birlikte, mobilya üretiminin zararlı etkileri nedeniyle sektör büyük bir baskı altındadır ve bu durum, çevreye ve insan sağlığına gelebilecek olası zararları azaltmak için sürdürülebilir uygulamalara olan kritik ihtiyacı vurgulamaktadır. Yaşam Döngüsü Değerlendirmesi (YDD), ürünlerin tüm yaşam döngüsünü inceleyerek süreçlerin çevresel sıcak noktalarını değerlendirmek için önemli bir yöntem olarak kullanılmaktadır.

Bu çalışma, Türkiye'deki gerçek ve ülkeye özgü üretim verilerine dayanarak bir yemek sandalyesinin beşikten mezara YDD'sini kapsamaktadır. Değerlendirme, SimaPro 9.2.0.2 yazılımı aracılığıyla Ecoinvent 3.7.1 ve U.S. Life Cycle Inventory (USLCI) veri tabanları kullanılarak gerçekleştirilmiş ve sonuçlar ReCiPe 2016 Midpoint ve Endpoint etki kategorilerinde Hierarchist yöntemi ile yorumlanmıştır.

Endpoint tek puan sonuçları, üretim aşamasının sandalyenin yaşam döngüsü boyunca en yüksek çevresel etkiye sahip olduğunu ve bunu paketlemenin izlediğini göstermiştir. Üretim aşamasında, ahşap papel birleştirme ve döşeme işlemleri, sırasıyla üre-formaldehit (ÜF) reçine ve dokuma pamuk kullanımı nedeniyle ana katkıyı oluşturan aşamalar olarak belirlenmiştir. Ayrıca senaryo analizi, paketleme malzemesinin ve nihai ürünün geri dönüştürülmesinin, yakmaya kıyasla çevresel etkileri önemli ölçüde azalttığını ortaya koymuştur. Ek olarak, dokuma olmayan kumaşların dokuma tekstillerle ikame edilmesi, döşemeli mobilyalarda gelecek vaat eden bir alternatif olarak öne çıkmıştır. Önerilen alternatiflerin bir araya getirildiğinde bir sandalye ürününün çevresel etkilerini %48'e kadar azaltabileceği sonucuna varılmıştır ve bu da sektördeki önemli iyileştirme fırsatlarının altını çizmektedir.

Anahtar Kelimeler: Mobilya, Yemek Sandalyesi, Ekotasarım, Yaşam Döngüsü Değerlendirmesi, Çevresel Etkiler

To the beautiful and resilient Stemless Gentian, flourishing amidst the heights of the Alpine peaks

ACKNOWLEDGEMENTS

I would like to extend my deepest gratitude to my supervisor, Prof. Dr. Ülkü Yetiş, whose exceptional problem-solving skills have made this endeavor remarkably smooth for me. Her profound knowledge and ability to impart it have been a constant source of inspiration since my undergraduate studies. I am also sincerely thankful to my co-supervisor, Prof. Dr. Niğmet Uzal, whose reassurance has consistently motivated me to keep moving forward. I greatly value the opportunity to have worked with her and to benefit from her insights and guidance.

A special acknowledgment is owed to İstikbal Mobilya staff, especially to Yasin Tokyay and Ali Şenyürek, for being the key contributors to this study. I am deeply grateful for their willingness to provide the essential data and share their expertise.

I am thankful to Büşra Özeş for her emotional support and for always sharing in my joy. My gratitude also goes to Alper Al for encouraging me by expressing his pride in my accomplishments. I would also like to thank İdil Kayan, representing all my workmates, for making the office moments enjoyable during these intense times.

My heartfelt thanks go to my partner, Ozan Erel, for being an unwavering companion along this entire journey. His mentorship and shared experiences were invaluable, challenging me to reach the best version of myself with love and a playful spirit.

I wish to express my greatest appreciation to my mother, Meral Dingil, who has stood by me through every challenge. Carrying a piece of her within me provides immense strength wherever I go. I am eternally grateful for the countless sacrifices she has made for my education. Additionally, a big thank you goes to my sister, Özge Dingil, and my aunt, Fadime Demirel, for their continuous support and belief in me.

Lastly, I am profoundly grateful to my father, Dr. Gürbüz Dingil, who, although no longer with us, continues to inspire me with his diligence and perseverance. Guided by his words that "the essence of life is to love and work," I strive to embody his vision of finding happiness and humanity by living with purpose and passion.

TABLE OF CONTENTS

CHAPTERS

APPENDICES

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

APOS	Allocation at the Point of Substitution
BIFMA	Business and International Furniture Manufacturers Association
DfE	Design for the Environment
EoL	End-of-Life
FE	Freshwater Ecotoxicity
FET	Freshwater Eutrophication
FPMF	Fine Particulate Matter Formation
FRS	Fossil Resource Scarcity
FSC	Forest Stewardship Council
GTP	Customs Tariff Position
GW	Global Warming
HCT	Human Carcinogenic Toxicity
HNCT	Human Non-Carcinogenic Toxicity
IR	Ionizing Radiation
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
ME	Marine Ecotoxicity
MET	Marine Eutrophication
MRS	Mineral Resource Scarcity
MSDS	Material Safety Data Sheet
MUF	Melamine Urea-Formaldehyde
OFHH	Ozone Formation: Human Health
OFTE	Ozone Formation: Terrestrial Ecosystems
PE	Polyethylene

PEFC	Programme for the Endorsement of Forest Certification
PES	Polyester
PF	Phenol-Formaldehyde
PP	Polypropylene
PUR	Polyurethane
SITC	Standard International Trade Classification
SOD	Stratospheric Ozone Depletion
SPP	Solar Power Plant
TA	Terrestrial Acidification
TE	Terrestrial Ecotoxicity
UF	Urea-Formaldehyde
USLCI	U.S. Life Cycle Inventory
VOCs	Volatile Organic Compounds
WC	Water Consumption

CHAPTER 1

INTRODUCTION

1.1 General

The furniture industry, a vital part of the global economy, is engaged in producing durable goods for various uses, including storage, hanging, supporting, lying, sitting, working, and eating (Medeiros et al., 2017). This industry involves the manufacturing and distribution of furniture products, with an annual market value exceeding USD 500 billion. Nonetheless, the industry's extensive demand for raw materials results in the harvesting of millions of trees each year, leading to an average annual deforestation rate of 15 billion trees, highlighting its substantial environmental impact (Sakib et al., 2024).

Furthermore, a diverse range of waste, including sawdust, wood chips, residual solvents, and adhesive particles, is generated during the common manufacturing process of a furniture product. Without a robust commitment to sustainable practices, cleaner production, and waste minimization, these side effects can pose severe threats to the environment, as well as to health and safety (Rinawati et al., 2018).

Moreover, global markets have become more complex, differentiated, and demanding. Consumers are increasingly concerned with a wide range of non-traditional issues, such as environment, safety, sustainable products, fair labor or trade practices. Consequently, there is a growing demand for reassurance about how products are being made, where they are sourced from, what the environmental consequences of their production and use are, and how they are disposed of at the end of their life cycle (González-García et al., 2011). Thus, conducting studies on furniture from a life cycle environmental impact perspective is imperative. Such research will guide companies in expediting their entry into the international market for green furniture products (Wang et al., 2016). Consequently, providing impact assessment tools and product environmental declarations has become increasingly essential for manufacturers to sustain their market presence (Gamage & Boyle, 2006).

Ecodesign, also known as Design for the Environment (DfE), is a highly researched area within the furniture industry. It integrates all environmental aspects of the life cycle into the design process, considering every production step and material selection that impacts environmental performance (Linkosalmi et al., 2016). The Life Cycle Assessment (LCA) method is subsequently utilized to quantify environmental impacts, facilitating the evaluation of the feasibility of developing more sustainable furniture products. Integrating DfE and LCA methodologies offers a practical approach to implement Ecodesign practices, as this integration enables a thorough assessment of both qualitative and quantitative environmental impacts associated with furniture production (Septiani et al., 2022).

Especially after the 2010s, there has been an increase in LCA studies on furniture. It should be noted that LCA studies of engineered wood products also contribute to furniture LCAs. As a result, there is a wealth of suggestions for future research on the topic in the literature, which can help identify gaps in the literature. However, since furniture covers wide variety of product groups, each LCA study serves different purposes with different production models, and it is not possible to arrive at a generic conclusion for all furniture.

Furniture LCA studies to date suggest that environmental impacts are primarily caused by the manufacturing phase. Among these, processes involving textiles have been found to be prominent (Wang et al., 2016; Linkosalmi et al., 2016; Mermertas et al., 2018; Ali et al., 2024). Moreover, finishing processes, where chemicals are applied to make furniture products protective against external factors and appealing to users, have been identified as another hotspot (Medeiros et al., 2017; Hartini et al., 2019; Purwaningsih et al., 2021). Most studies, however, did not include the use and End-of-Life (EoL) phases within their system boundaries and conducted cradle-to-gate LCAs. Some of the studies have suggested that excluding these phases is not critical, as furniture functions without requiring additional resources during the use phase (Gamage & Boyle, 2006; Wang et al., 2016). Additionally, uncertainty regarding EoL data has led to its omission from the assessment (Wang et al., 2016). On the other hand, some studies recommended the addition of several life cycle stages, such as packaging, transportation, use, and EoL for a complete LCA (Gamage & Boyle, 2006; Mirabella et al., 2014; Iritani et al., 2015; Rinawati et al., 2018).

It is important to note that the success of LCA studies is directly linked to an inventory established with actual and country-specific data. In this context, LCA studies conducted in cooperation with the sector by acquiring the bill of materials and utilizing the datasets from the literature as minimally as possible are of great importance in order to obtain accurate results and provide feasible recommendations. Unfortunately, there is a notable scarcity of LCA studies focused on furniture specific to Türkiye, constituting a deficiency for sector participants seeking self-improvement and requiring guidance.

1.2 The Objective and Scope of the Study

The aim of this study is to analyze the environmental impacts and hotspots of a dining chair through LCA and scenario analysis, providing valuable insights to investigate the improvement potential of the chair and make informed decisions to promote eco-friendly furniture innovation. The chosen product, the chair, is among the most commonly utilized and purchased furniture items, as seating around a table is essential in family households. The manufacturing processes for this chair are comparable to those of other furniture items, as it is categorized as standard wooden furniture. Thus, the results of the environmental impact assessment serve as the basis for identifying hotspots of a wooden furniture product. On top of that, scenario development contributes to the furniture industry by providing them with alternative options during manufacturing processes.

The system boundaries of the study include the extraction and production of the raw materials, their transportation to the production factory, the utilization of them for processing and assembly, the production of packaging material, the packaging of the product, the management of wastes generated during production, the transportation of final product to the distributors, the use phase and the EoL of the product. In short, the system boundary of the LCA study is defined as cradle-to-grave. The functional unit is defined as a single dining chair measuring 920 x 740 x 470 mm, designed to offer stable and sturdy seating for indoor use in a household setting.

The data necessary for the inventory analysis in the LCA methodology were mainly collected from a company with a long-standing market presence and significant global export activities, ensuring comprehensive and high-quality data. Additionally, literature sources were utilized to supplement the provided data when there were deficiencies. The inventory of the LCA was established using the existing libraries of Ecoinvent 3.7.1 and the U.S. Life Cycle Inventory (USLCI) databases. The life cycle impact assessment (LCIA) was carried out via SimaPro 9.2.0.2 software using ReCiPe 2016 methodology at both midpoint and endpoint levels with a Hierarchist perspective.

The results of this study are anticipated to make a significant scientific contribution by presenting the environmental impacts of chair production through a comprehensive examination of the product's entire life cycle. This approach minimizes the exclusion of any stages from the system boundary, even if their impact is relatively minor. In this way, the study will represent a complete cradle-to-grave LCA, as most of the literature recommends. Moreover, the inventory for the LCA was primarily developed using very comprehensive data provided by a well-known company. Given the scarcity of LCA studies on furniture in Türkiye, a country-specific inventory will be crucial for the industry. This is especially important as the industry will face increasing obligations for cleaner production due to the widespread implementation of sustainability efforts in government policies. Beyond the mandated regulations, scenario studies will particularly provide valuable guidance for companies seeking to enhance customer trust and produce environmentally friendly products.

This thesis study consists of six chapters. In Chapter 1, the objectives and scope of the study is presented. Chapter 2 provides background information on the furniture industry, sustainable production in the furniture industry, and the LCA. Following this chapter, a literature review on existing furniture LCA studies is given in Chapter 3. Chapter 4 includes the methodology employed during this LCA study by explaining the study approach, data collection, scenario development, and LCA methodology. The results of the studies conducted are provided in Chapter 5, along with the interpretation of the outcomes. In Chapter 6, a conclusion of the study is summarized. Finally, recommendations for the sector and the literature are presented in Chapter 7.

CHAPTER 2

BACKGROUND

2.1 Furniture Industry

2.1.1 Furniture Products

Furniture is defined as all functional and aesthetically pleasing objects of use made of different materials to meet the basic social and cultural needs of people for daily life, such as working, sitting, resting, eating, storing, and displaying their belongings safely and comfortably (Üst, 2015). Furthermore, furniture serves multiple purposes and covers many product groups. The primary uses of furniture include providing enclosed storage space, offering surface area for storage, providing seating, and functioning as bedding. Although its purpose seems basic, furniture exhibits complexity in many aspects. For instance, materials utilized in furniture production extend beyond wood-based materials. From wood to metals, plastics, textiles, leather, and glass, furniture products are manufactured by obtaining raw materials from many different sectors (Wenker et al., 2018).

Furniture can be categorized based on its place of use (indoor and outdoor), the material used in production (wood, metal, plastic, marble, glass), the style influenced by the geographical region (English, Italian, Scandinavian), and the specific spaces it is designed for (kitchen, living room, bedroom, office, etc.) (TOBB, 2017).

Comprehensive classification systems are also used for international trade analysis and customs clearance statistics regarding furniture products. Two classification systems are mainly used for furniture. The Harmonized Commodity Description and Coding Systems (Harmonized System) is used for detailed data, while the Standard International Trade Classification (SITC) is used for aggregated data (Ticaret

Bakanlığı, 2021). The codes and product descriptions of furniture under SITC are given in Table 2.1.

Table 2.1. Furniture Product Descriptions by SITC Codes

SITC Code	**Product Description**
821.1	Furniture for sitting (whether or not of the type that can be turned into a bed), their parts and components
821.2	Bedding and similar items
821.3	Furniture made of metal (not elsewhere classified)
821.5	Wooden furniture (not elsewhere classified)
821.7	Furniture made of other materials (not elsewhere classified)
821.8	821.3, 821.5, and 821.7 group furniture parts and components
872.4	Furniture used in medicine, surgery, dentistry, and veterinary medicine, their parts and components

The Customs Tariff Statistical Position, based on the International Harmonized System, is utilized in Türkiye for the classification of goods. Furniture product descriptions as per the Customs Tariff Position (GTP) codes adapted from the Harmonized System are given in Table 2.2.

Table 2.2. Furniture Product Descriptions by GTP Codes

GTP Code	**Product Description**
9401	Furniture for seating, their parts, and components
9402	Furniture used in medicine, surgery, dentistry, and veterinary medicine, their parts and components
9403	Other furniture, parts, and components
9404	Bedsteads, bedding, and similar items

2.1.1.1 Manufacturing of Furniture Products

Manufacturing furniture on an industrial scale involves advanced technology and is largely automated. Processes are intricate due to the interconnection of machines and the establishment of manufacturing lines with large dimensions by plant equipment. The manufacturing process for furniture involves multiple phases, and the operations differ according to the type of furniture. Furthermore, the production processes in a furniture manufacturing facility are mainly affected by the degree of prefabrication of the supplied semi-finished products (Wenker et al., 2018). The production of typical wooden furniture can be summarized as in Figure 2.1.

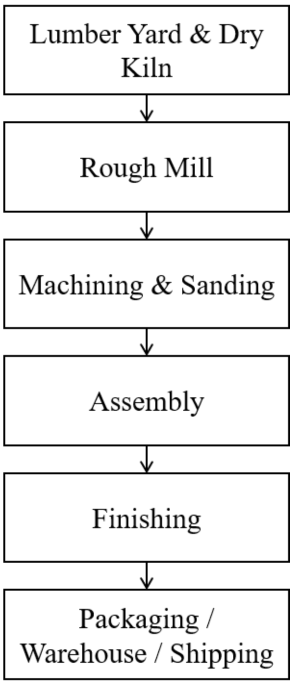


Figure 2.1. Production Flow of Furniture (Csanády et al., 2019)

The lumber yard serves as a facility for storing raw materials, which are categorized based on their origin and size. Additionally, it functions as a place for air drying the lumber. The rough mill transforms dried lumber boards into panels with particular proportions through planing, cutting, gluing, and processing. The rough-cut lumber is taken to the machining area, where it is turned into parts with the desired forms, profiles, and dimensions for furniture production. Occasionally, a sanding machine is employed to achieve a uniform panel thickness or modify its dimensions (Csanády et al., 2019; Prak & Myers, 1981).

The individual parts are assembled in accordance with the design and prototypes. Adhesives and joints are frequently utilized in this process. The most encountered adhesives include urea-formaldehyde (UF), phenol-formaldehyde (PF), polymeric diphenyl-methane diisocyanate, hot melt, and polyvinyl acetate. The finishing process includes the application of several coatings, like stains, lacquers, varnishes, etc., to achieve the intended aesthetic of the final product. Upholstered furniture is made using additional materials such as textiles, leather, and plastics. The sewing section closely resembles a clothing manufacturer (Csanády et al., 2019; Prak & Myers, 1981).

2.1.2 Market Overview of the Furniture Industry

2.1.2.1 Furniture Industry Worldwide and in EU Countries

The USA, Germany, and Italy are the leading developed countries in world furniture production. However, there has been a notable trend in the past few years towards developing nations instead of developed ones, primarily driven by the availability of cheaper labor and favorable tax rates (Koridze, 2022). Developing countries realized 46.7% of the world's production in 2020. Among these, China, Poland, Vietnam, and Mexico are the countries showing rapid growth in recent years (Sanayi Genel Müdürlüğü, 2020). As reported in the World Furniture Outlook 2018 by CSIL (Centro Studi Industria Leggera), a furniture research institution in Milan, worldwide furniture production in 2017 amounted to USD 420 billion. Notably, China contributed approximately 40% of the total global production (Xiong et al., 2020).

At the same time, the European furniture industry holds a solid global reputation due to its exceptional quality, which encompasses both technical and aesthetic aspects.

It has a significant position as a key participant in the international market of wooden furniture (González-García et al., 2011; Ticaret Bakanlığı, 2021). The Union ranks second in the global furniture market, accounting for 26% of the world's manufacturing, as seen in Figure 2.2. The European market leads in innovative design, sustainable production practices, efficient utilization of natural resources, and the incorporation of cutting-edge technologies in manufacturing (Koridze, 2022).

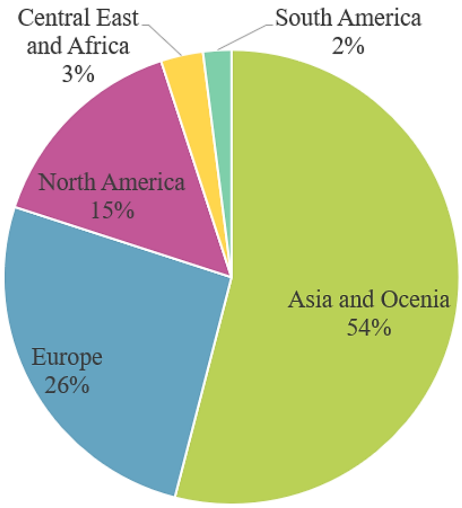


Figure 2.2. Furniture Production Rates by Region

2.1.2.2 Furniture Industry in Türkiye

The furniture sector is one of the oldest and most developing sectors in Türkiye and has started to gain momentum, especially since the 1970s. In recent years, world-class production facilities have been established in the sector. However, the sector is mainly oriented towards the domestic market and consists of primarily atelier-type, small-scale factories, which work with traditional methods (Terece et al., 2020).

The furniture industry in Türkiye is primarily concentrated in specific regions with high market activity and abundant forest resources. The major furniture manufacturing regions, based on their respective contributions to overall production, include Istanbul, Ankara, Bursa, Kayseri, Izmir, and Adana (Ticaret Bakanlığı, 2021). Furthermore, the share of Türkiye's furniture sector in the entire timber production is 20% (Ministry of Economy, 2018), and it has a vital place with its use of other forest industry products as raw materials, the added value it creates, the number of workplaces, and the employment effect (Yazıcı & Karayılmazlar, 2001).

One of the critical points worth mentioning is that the sector is insufficient in raw materials since about 40% of the annual need for primary raw materials and other auxiliary materials used in production are imported products. Raw materials for furniture production are supplied from neighboring northern countries as well as African, American, and Asia Pacific countries (Sanayi Genel Müdürlüğü, 2021). This is regarded as an essential obstacle to developing the furniture sector in Türkiye.

Another crucial aspect is the increasing costs in the furniture sector in Türkiye, which are becoming more and more noticeable. It is well known that the primary mode of transport used in the sector is road transportation. One of the reasons for the increase in costs is transportation-related damage to furniture (TOBB, 2017). This stands out as a preventable and improvable issue in the sector.

In addition, furniture manufacturers often use a second mode of transportation to reach railway facilities, and this transshipment necessity also affects transportation costs. It should be noted that road transportation increases costs by 20% compared to rail (Sanayi Genel Müdürlüğü, 2021). The expansion of railway networks will have a profoundly positive influence on transportation, particularly within the furniture sector, where its utilization is extensive. Research indicates that while the environmental impact of highway construction is less significant than that of railway construction, the operation of railway systems is more eco-friendly compared to highway operations (Dimoula et al., 2016).

Another important point is that the furniture industry faces limitations in process efficiency and material reduction, necessitating technological and managerial innovations to address these challenges (Medeiros et al., 2017). The spread of automation in large enterprises in the Turkish furniture industry affects production costs in facilities as it causes more energy emissions (Sanayi Genel Müdürlüğü, 2020). Therefore, efforts to optimize costs and reduce environmental impacts without bypassing innovations in the sector must be emphasized, which requires a multifaceted approach that points to sustainable production.

2.2 Sustainable Production in the Furniture Industry

Demand for sustainable interior products, including environmentally friendly furniture, is increasing worldwide. Consumers usually consider several conventional factors, including price, quality, branding, and availability, when making a purchase decision. Nevertheless, many consumers are progressively expressing apprehension regarding a diverse array of non-conventional subjects, including the environment, safety, and sustainable production (González-García et al., 2011).

A report dated 2010 revealed that in a survey of a representative sample of Italian customers, one-third of respondents were willing to pay a 10% premium for furniture with environmentally sustainable properties compared to regular options (Mirabella et al., 2014). A decade later, a 2020 study in the United States revealed that 76% of Americans would also pay more for environmentally friendly furniture (Grand View Research, 2022). A significant increase is observed in consumer preference for sustainability over the years. Therefore, it is crucial to conduct a thorough assessment of this industry in order to enhance the environmental sustainability of the entire supply chain.

Bianco et al. (2021) suggest that the furniture sector has the potential to contribute to achieving the objective of limiting global warming to 2°C by 2050, as outlined in the Paris Agreement. In addition, the widespread promotion of zero-waste policies is also driving greater adoption of sustainable connections in the home design industry.

One important point to note here is that the furniture industry is also influenced by different sectors. For instance, as the building industry strives towards achieving net-zero energy buildings, the significance of furniture becomes apparent too, since furniture contributes to approximately 10% of the overall impact of global warming (Medeiros et al., 2017). Specifically, the choice of materials can significantly impact reducing the effects of climate change.

The widespread utilization of wood as a raw material in the furniture industry indirectly contributes to climate change since trees generate oxygen and sequester carbon dioxide (Purwaningsih et al., 2021). Conversely, research has demonstrated that wood, particularly when sourced from sustainable forests, is regarded as a sustainable consumer good due to its lower environmental impact compared to other materials used in furniture, such as metals and plastics, and its status as a favorable renewable material requiring minimal resource input for extraction (Wang et al., 2016; Mirabella et al., 2014).

Understanding the adverse effects of the materials commonly employed in a particular industry on the environment is crucial for companies to enhance their products and production methods regarding environmental sustainability. This awareness will facilitate their entry into the growing market for eco-friendly products (González-García et al., 2011).

Within the worldwide furniture and wood products market, the shifting expectations and changing preferences of consumers have resulted in a significant burden being placed on businesses (Morris & Dunne, 2004). In order to differentiate their products from those of competitors, the furniture industry has been compelled to implement innovative concepts and adopt distinct product strategies, taking into account all the aforementioned factors. In response to the increasing environmental awareness of consumers, manufacturers are trying to meet consumer demand by offering certified products.

Some furniture producers see incorporating environmental considerations in the early stages of their product's life cycle, such as design, manufacture, and commercialization, as a valuable opportunity to distinguish their offerings. They are exploring the implementation of sustainability principles and obtaining environmental accreditation through ecolabels. These certification schemes give producers the opportunity to promote their products while providing consumers with the necessary assurance and guarantee (González-García et al., 2011).

2.2.1 Sustainability Certification Schemes in Furniture Production

The Forest Stewardship Council (FSC), established in 1993, is a global non-profit entity dedicated to promoting environmentally sound, socially responsible, and economically feasible forest management practices worldwide. It aims to achieve this by implementing a global labeling system for forest products, ensuring that consumers can trust that the product originates from a responsibly managed forest (Morris & Dunne, 2004). FSC principles include conserving biodiversity, maintaining the integrity of large-scale ecosystems and landscapes, preserving rare and endangered ecosystems, meeting the basic needs of communities, and protecting important cultural, ecological, economic, or religious values (Forest Stewardship Council, 2023).

Another certification scheme is the Programme for the Endorsement of Forest Certification (PEFC). In 1999, PEFC emerged by various national forest stakeholders across Europe as an alternative to the FSC, addressing worries regarding the specific requirements and expenses associated with certifying forests owned by small-scale operators. The competitiveness between the FSC and PEFC has resulted in enhancements to both organizations' systems, reduced expenses related to certification, and the worldwide expansion of PEFC (Stringer, 2006).

One of the common certificates specific to the furniture industry is Level, which was developed by the Business and International Furniture Manufacturers Association (BIFMA). It is an impartial and reliable certificate that examines the environmental and social impacts of furniture production. The BIFMA Level certification consists of four pillars: materials, energy and atmosphere, human and ecosystem health, and social responsibility (Güneş & Demirarslan, 2020).

Although it addresses different product groups, GREENGUARD, which primarily covers furniture products, GREENGUARD certification ensures that products meet low emission standards to maintain indoor air quality by limiting volatile organic compounds (VOCs). Products are tested by independent laboratories within a week of manufacture, undergoing a 96-hour emissions assessment. The data obtained from these tests are then used to project the emission levels over several months (Zimmerman, 2005). This certification is particularly relevant for furniture used in sensitive environments such as child rooms, schools, and healthcare facilities, as maintaining air quality in these areas is critical.

Another scheme widely used in the furniture industry, the Cradle-to-Cradle Certification, is a non-governmental, multi-featured framework that assesses products based on five sustainability principles: material health, product circularity, air, and climate protection, water and soil stewardship, and social fairness (Llorach-Massana et al., 2015).

Europe's highly recognized certification, EU Ecolabel, is a voluntary program that promotes environmentally high-quality products and services. Its approach is comprehensive and addresses the primary environmental impacts of products throughout their entire life cycle, starting from the extraction of raw materials to their disposal (European Commission, n.d.). The EU Ecolabel criteria for furniture guarantees that any virgin wood used in furniture production comes from legally compliant and sustainably managed forests. It imposes strict restrictions on hazardous substances, limits harmful residues in upholstery, and ensures low formaldehyde emissions (Donatello et al., 2017).

In summary, ensuring the environmental responsibility of furniture products is undoubtedly very crucial. Extending this foundation, the Ecodesign concept enhances sustainability by incorporating environmental factors into the design process in order to reduce the environmental impact of products throughout their entire life cycle.

2.2.1.1 Ecodesign

Ecodesign is an approach in furniture design that takes into account the harmonious relationship between humans and nature, ensuring that the furniture blends well with its environment with the utilization of sustainability principles in the process of product design. The goal is to identify product modifications under economic, environmental, and social considerations that achieve cost and performance targets while minimizing pollution and waste throughout and beyond the life cycle of products (Çınar, 2005; Csanády et al., 2019).

Ecodesign, covered in The International Organization for Standardization (ISO) 14006:2011 (Environmental management systems—Guidelines for incorporating Eco-design), involves six defined steps: specifying product functions, assessing environmental impact, devising improvement strategies, setting environmental objectives, specifying products, and finding technical solutions. Identifying the phase with the greatest environmental impact is a crucial yet contentious step, as the standard does not indicate the preferred tool. While not mentioned in the standard, LCA is widely acknowledged as the most impartial and commonly utilized tool for evaluating a product's environmental profile (Navajas et al., 2017).

Additionally, there exists a European Eco-design Directive (Directive 2009/125/EC) that establishes ecological criteria for specific product categories, following the principles of sustainable design outlined in Eco-design. The Commission's strategy for achieving greater environmental sustainability and circularity in goods is centered on the proposal for a new Ecodesign for Sustainable Products Regulation, released in 2022. The proposal expands upon the current Ecodesign Directive, which now only encompasses energy-related products (European Commission, 2024). Presently, Members of the European Parliament want the Commission to prioritize furniture products in the scope of the proposed new regulation.

Bauer et al. (2018) introduced Ecodesign criteria encompassing durability, reusability, reparability, and recyclability. The suggested implementation of

Ecodesign specifications for furniture is outlined in the following manner: fitness for use, expected lifespan, provision of spare parts, design for disassembly, consumer information, bill of materials, and packaging.

The DfE concept enhances producers' attention to the complete life cycle of a product, encompassing the extraction of raw materials, manufacturing, distribution, use, and EoL. The LCA method is subsequently employed to quantify the environmental impacts in order to assess the feasibility of developing a more sustainable furniture product. The combination of the DfE and LCA methodologies provides a pragmatic approach to implementing Ecodesign practices since this approach allows for the comprehensive evaluation of the qualitative and quantitative environmental impacts of furniture (Septiani et al., 2022). In other words, Ecodesign strategies act as answers to the environmental impacts identified in the LCA study (González-García et al., 2012).

Thus, comprehensive environmental declarations are becoming increasingly essential in order to sustain commercial competitiveness in the furniture industry. The utilization of sustainable production strategies, cleaner technologies, and LCA has been widely accessible for a considerable period. These tools aid in assessing and reducing the environmental consequences of products, thereby facilitating the development of environmentally preferable products.

2.3 LCA

LCA is a tool used to evaluate the possible environmental burdens and impacts quantitatively at all phases of a product's life cycle, including resource extraction, manufacture, usage, and waste management. LCA offers an extensive assessment that takes into account all facets of the natural environment, human health, and resources (Lee & Inaba, 2004). The LCA method is used in the following areas (Hellweg & Milà Canals, 2014; Brusseau, 2019):

- In the development and improvement of a product or service by defining its relationship with the environment at different life cycle stages,
- Decision-making in strategic planning, priority setting, design of products and services, and redesign of existing designs in the public and private sectors,
- In public policymaking on environmental performance indicators, including measurement techniques,
- In developing marketing tools such as environmental declarations and environmental labeling.

The recognition of LCA had a significant surge in the 1990s. During that period, LCA was held in high regard; however, it frequently faced criticism for the results it provided (Finnveden & Potting, 2014). Several endeavors were made to standardize LCAs with the intention of achieving an unbiased and parallel outcome in studies.

ISO has incorporated well-established methods for evaluating LCA in its environmental management standards, 14000 series. ISO 14040 outlines the key concepts and structure and is specifically tailored for a managerial audience, while ISO 14044 provides practitioners with commonly used notions and guidelines for criteria (Pražanová et al., 2022). The work focused on method development and harmonization has enhanced the level of maturity and methodological strength of LCA.

As per ISO 14044, the LCA framework is conducted using four key steps, as depicted in Figure 2.3. It should be noted that LCA is described as an iterative process.

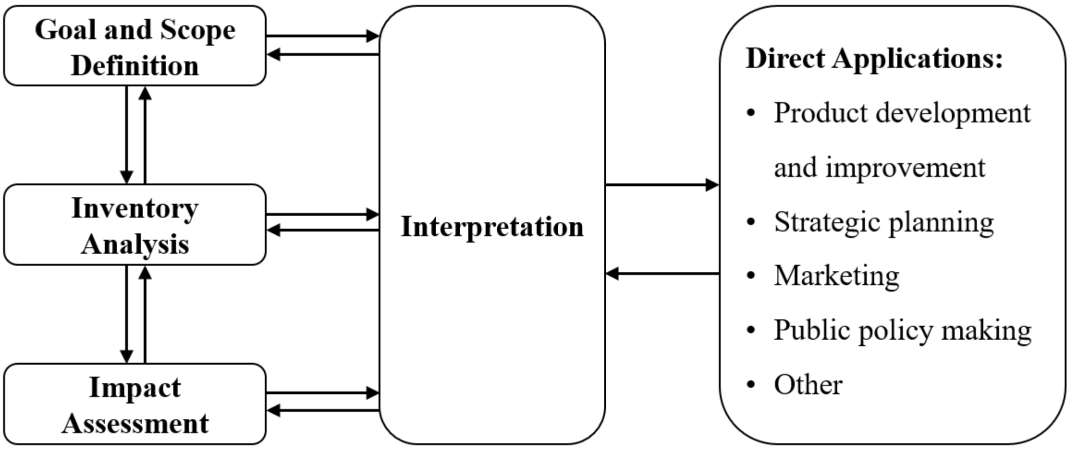


Figure 2.3. LCA Framework (ISO, 2006)

The goal and scope definition sets forth the aims of the assessment, the target audience for the study findings, the boundaries of the system being studied, the rules for allocation, the type of data to be gathered, and the parameters to be assessed. The life cycle inventory (LCI) analysis mainly involves gathering and examining data on the input and output flows related to the system being studied. During this stage, the system boundaries and allocation rules established in the goal and scope definition are implemented. The impact assessment is a process that converts the extensive input and output data collected through inventory analysis into clear information about the environmental impacts. Interpretation refers to evaluating the complete findings of the study, considering the intended goals, any constraints, data uncertainties, and the target audience (Keoleian & Spitzley, 2006).

2.3.1 Steps of LCA

2.3.1.1 Goal and Scope Definition

The initial stage of an LCA starts with the planning, as the goal and scope of the study are defined in a manner that enables the subsequent inventory analysis, impact assessment, and interpretation phases. The evaluation is defined concerning the system boundaries of the product and the periodical and technological nature of the processes within the product system (Hauschild et al., 2005).

The objective of the system is clearly defined using qualitative terms and quantified by a functional unit, which sets a reference for the LCA study. The functional unit serves as the foundation for the assessments and represents the system's performance measurement. The definition should encompass all relevant parts of the study's goals (Widheden & Ringström, 2007). This aligns with the essential comparison aspect of the majority of LCA applications. In order to ensure a valid comparison, it is crucial that the systems being evaluated offer identical functionality to the user (Jolliet et al., 2016).

The unit processes that will be included in the product system are specified while setting the system boundaries. Ideally, all processes related to the product should be covered. Nevertheless, due to limitations in data availability, financial constraints, and varying intended uses, achieving this goal might be unfeasible and impractical. Therefore, less essential procedures can be omitted from the product system (Lee & Inaba, 2004).

When establishing the boundaries of the system, it is crucial to differentiate between the foreground and background systems. The foreground system refers to the collection of processes that are immediately impacted by the analysis and contribute to the delivery of a specific functional unit as outlined in the goal and scope definition. The background system signifies the mechanism that provides energy and materials to the foreground system. Distinguishing between foreground and background systems is essential for determining the appropriate data to utilize. Precise process data should characterize the foreground system, whereas the background is typically depicted by data pertaining to a combination or a series of distinct technologies or processes (Azapagic, 1999).

A complete LCA should cover every phase, beginning with extracting raw materials and energy (cradle) and extending to the EoL processes. This approach is known as cradle-to-grave LCA. However, the system boundary may exclude subsequent steps, such as distribution, usage, and disposal, in order to compare different goods that serve comparable purposes. The term used to describe this boundary is a cradle-to-gate approach (Uddin & Wright, 2022). When the product's life cycle starts with the acquisition of the raw materials and ends with the completion of the manufacturing process, the approach is called gate-to-gate analysis. LCA can even be conducted cradle-to-cradle with the recovery of end products at the EoL stage.

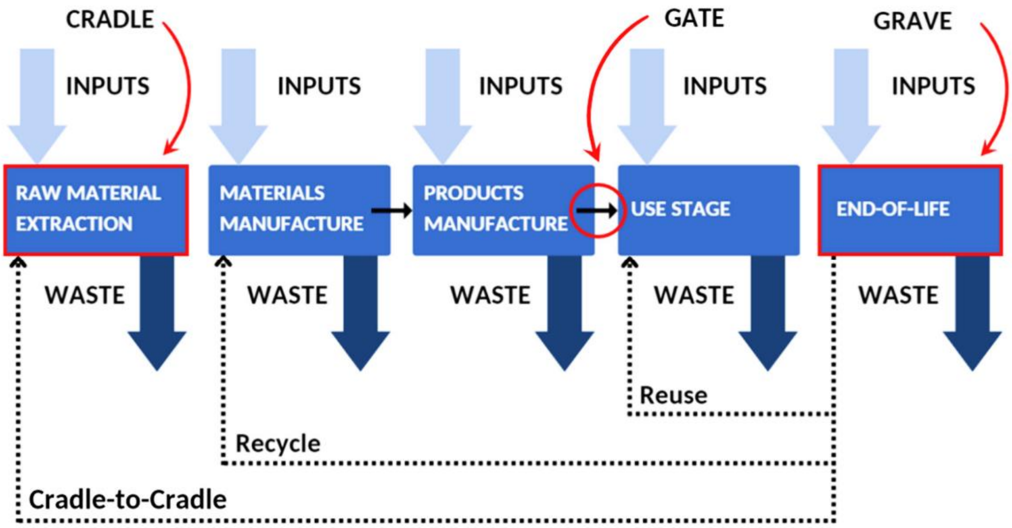


Figure 2.4. System Boundaries of a Product Life Cycle (Pražanová et al., 2022)

2.3.1.2 LCI Analysis

Following the scoping of the product system, the inventory analysis is performed by gathering information on the input and output of each process that functions in the system boundaries. Mass and energy balances are carried out to measure the environmental burdens and express them numerically. The burdens are shaped by resource use and the release of substances into the atmosphere, water bodies, and solid waste (Azapagic, 1999; Hauschild et al., 2005).

The EPA's 1993 publication, "Life-Cycle Assessment: Inventory Guidelines and Principles," together with its 1995 publication, "Guidelines for Assessing the Quality of Life Cycle Inventory Analysis," establish the structure for conducting an inventory analysis and evaluating the accuracy of the data and outcomes. These two publications outline the four stages of an LCI as below (Ram & Sharma, 2017):

1. Establish a flow diagram of the processes under evaluation
2. Formulate a strategy for gathering data
3. Collect data
4. Conduct an assessment and provide an analysis of the outcomes

Collecting data of sufficient quality and quantity is a comprehensive, time- and resource-intensive process. The level of precision and thoroughness of the data gathered is evident in all subsequent stages of the LCA process. However, constraints or new data requirements may arise during the data collection process that prevent the study from achieving its purpose. Data limits arise due to several factors, such as proprietary constraints, the need to combine information from multiple product systems, and the absence of a standardized monitoring system. This situation requires changes in data collection methods or the purpose and scope of the study. Since LCA is an iterative method, the purpose and scope of the LCA study can be changed depending on the new data requirements and constraints at this stage (Curran, 2013; Keoleian & Spitzley, 2006). Typical steps during the LCI stage, including data collection, are given in Figure 2.5.

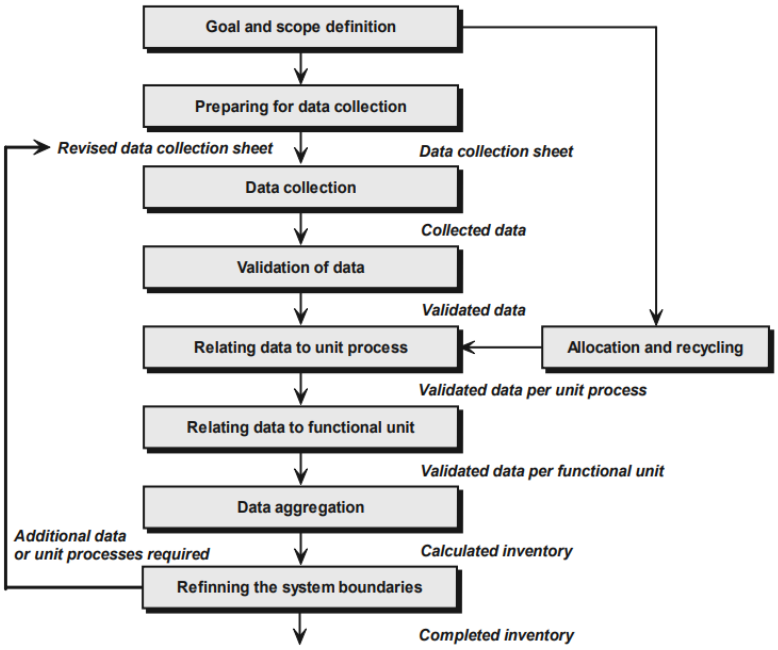


Figure 2.5. General Procedures of LCI (Lee & Inaba, 2004)

When data collection during LCI requires information on processes whose primary data are inaccessible, additional literature sources and pre-existing LCI databases are used to gather data. Since the publication of the ISO 14040 and ISO 14044 in 2006, many LCI-specific databases have been developed by various organizations, including some that are freely accessible to the public. However, not all sources are readily applicable for use in most life cycle studies since the dataset is presented for specific facilities rather than industry averages. On occasion, it may be required to make assumptions in order to integrate them into an industry sector (Curran, 2016).

Europe has been highly successful in developing databases that are accessible to the public. ELCD is widely regarded as the leading free database since it consolidates information from other industrial databases. According to Martínez-Rocamora et al. (2016), the GaBi Database and Ecoinvent come forward for their integrity, user-friendliness, and extensive resources, making them the most comprehensive LCA databases available. However, it is crucial to acknowledge that the study's goals significantly influence the choice of a suitable database.

The latest version of Ecoinvent includes three different system models. The main features and explanations that distinguish these models from each other are given below (Wernet et al., 2016).

- Allocation, cut-off by classification (Cut-off): Recyclable materials are entirely separated from the production process, so they become burden-free from the negative or positive effects being attributed to them.
- Allocation at the point of substitution (APOS): This model expands the product system to avoid allocation inside treatment systems for byproducts.
- Substitution, consequential, long-term: Various assumptions are employed to evaluate the ramifications of modifying a preexisting system. Substitution is used to replace the burdens on credit processes with the by-products produced within those processes.

2.3.1.3 Impact Assessment

The LCIA involves assessing the possible environmental and human health effects caused by the identified material and energy flows and releases specified during the LCI phase. An impact assessment must comprehensively evaluate the implications on the ecology and human health, as well as the degradation of natural resources. The aim here is to develop a connection between the product and its possible environmental consequences (Ram & Sharma, 2017).

LCIA takes a holistic view of environmental impacts. Essentially, it aims to simulate any potential harm to protected areas caused by the product system. The purpose of conducting an impact assessment for environmental changes is to determine the potential consequences of releases on protected areas accurately. This is achieved by utilizing the most reliable information regarding the cause-and-effect links between emissions and their impact on the environment (Hauschild et al., 2005).

According to ISO 14040, environmental impact categories can be converted into midpoint indicators, and each midpoint indicator can be converted into an endpoint.

Midpoint indicators represent the results of the impact categories, while endpoints represent the areas that need to be protected (Gültekin & Çelebi, 2016). Translating the midpoints into endpoints enhances the clarity of understanding the LCIA outcomes. Nevertheless, at every stage of aggregation, there is a growing level of uncertainty in the outcomes (Sakib et al., 2024).

A diagram illustrating the environmental processes that form the basis for modeling the effects and harm of LCIA is given in Figure 2.6 (Finnveden et al., 2009).

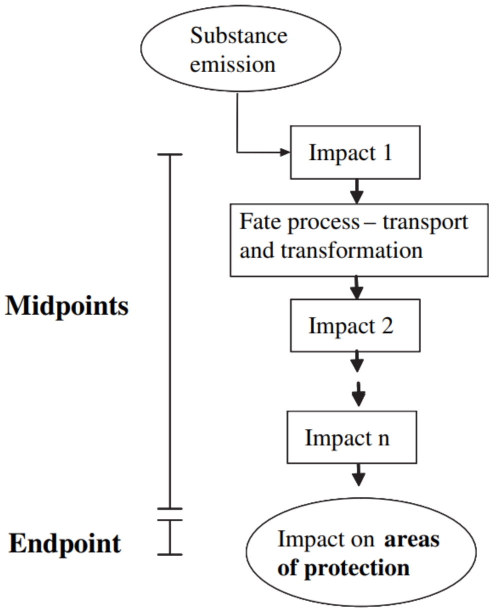


Figure 2.6. Schematic of LCIA Impact and Damage Modeling Processes

According to the ISO standard, the LCIA comprises the sub-phases of Impact Category Definition, Classification, Characterization, Normalization, Grouping, and Weighting. The first three elements are obligatory in distinguishing the objective aspects that are grounded in natural sciences from the subjective aspects that are determined concerning the context of the study. The remaining sub-phases are optional (Widheden & Ringström, 2007).

1. **Impact Category Definition and Classification (Mandatory):** The initial stage involves the selection of impact categories and their subsequent classification. In this context, the particular categories of environmental impacts that are pertinent to the study are established. For the majority of LCA studies, it is sufficient to simply adopt the categories that are already established (Hauschild et al., 2005).
2. **Characterization (Mandatory):** This stage requires assessing the quantification of environmental impacts resulting from every LCI parameter of the impact category. A characterization factor quantifies the added value of a certain parameter to the associated impact category, offering a realistic method for quantification. Due to characterization, it is possible to aggregate all emissions and material extractions in the same impact category, converting the data collected from the inventory into an overview of environmental impact scores since all quantified impacts become sharing an identical dimension or unit (Lee & Inaba, 2004).
3. **Normalization (Optional):** The normalization procedure quantifies the specific effect per functional unit with respect to the overall effect within that category. Therefore, it assesses the individual contribution of the product on the overall impact at a global, continental, or regional scale within a specific category. The results of the normalization are reported relative to these total reference values (Jolliet et al., 2016).
4. **Grouping (Optional):** This stage involves the process of sorting as well as prioritizing the indicators. For instance, the indicators might be grouped based on their global, regional, or local implications, or they can be prioritized as high, medium, or low-priority (Jolliet et al., 2016).
5. **Weighting (Optional):** Weighting converts category outcomes into an identical scale by applying factors that represent the relative significance of each category. Weighting factors are commonly employed to compute a total environmental impact value derived from the combination of characterization results to ease comparisons across different systems (Keoleian & Spitzley, 2006).

Specific tools are required to execute LCIA and its sub-phases. GaBi, openLCA, SimaPro, and Umberto are well-known tools that are used globally. There are notable disparities in the ease of use and the availability of databases. The findings of the study may differ based on the software tool selected by the user (Silva et al., 2017).

2.3.1.4 Interpretation

The last stage of LCA is a methodical approach to analyzing, measuring, verifying, and assessing the data derived from LCI and LCIA, with the aim of successfully presenting the findings (Curran, 2016). Interpretation is focused on discerning the potential for enhancing the efficiency of the system. Furthermore, it encompasses the identification of significant phases in the life cycle that contribute to the impacts, along with definitive suggestions (Azapagic, 1999). This phase of the LCA involves a thorough examination of the data, taking into account the uncertainties and assumptions that were made to get the outcomes (Brusseau, 2019).

During the LCI and LCIA, it is imperative to rely on assumptions, engineering estimates, and decision-making depending on the study subject. Every one of these choices must be integrated and represented in the final outcomes to effectively and thoroughly elucidate the findings derived from the data (Ram & Sharma, 2017).

The acquisition of a substantial quantity of information and data is necessary for any LCA study, and challenges in acquiring suitable data are frequently faced. It may be necessary to rely on literature data instead of site-specific data or single study data instead of national averages. Hence, the assessment of the resilience of outcomes and deductions made in an LCA study are integral components of the interpretation step (Widheden & Ringström, 2007). These evaluations may involve the tests indicated in Table 2.3.

Table 2.3. Overview of Tests Conducted for the Evaluation of Results

Type of Test	Purpose of Test
Completeness Check	It is ensured that the information and data required for the analysis are complete and accessible. This includes a check for data gaps in the LCI (Gültekin & Çelebi, 2016; Widheden & Ringström, 2007).
Sensitivity Analysis	The objective of conducting a sensitivity analysis is to evaluate the resilience of outcomes and their susceptibility to variations in data, assumptions, and models employed (Jolliet et al., 2016).
Consistency Check	It is an assessment of whether the assumptions, methods, and data in the study comply with the goal and scope definition (Gültekin & Çelebi, 2016).
Data Quality Requirements	The collected data needs to be evaluated against the previously established criteria to determine factors such as accuracy, comprehensiveness, representativeness, and data coherence (Lee & Inaba, 2004).

CHAPTER 3

LITERATURE REVIEW

In this part of the thesis, LCA studies on furniture were examined in detail to identify the gap in the literature. A road map was established by addressing the difficulties encountered during the literature studies. Based on these insights, a roadmap was established for the research, and the scope of the study was clearly defined. Since furniture refers to a wide range of products, LCAs of different products have been the subject of case studies in the literature. However, since the production processes of most products are similar, it has been observed that there are many common points in the studies. A number of studies are also conducted to examine the environmental impacts of the materials used in the furniture industry on the production process.

To assess the environmental impacts resulting from the materials and processes commonly employed in the production of wooden furniture, an LCA was performed on several types of wood-based boards, as well as surface and edge coverings. Prominent findings of the study indicated that the conventional particleboard exhibited a lower impact on the environment compared to the fiberboard, while the utilization of the low-density laminate showed greater ecological sustainability than the high-density laminate (Bovea & Vidal, 2004).

For the comparison of materials' environmental impacts, an LCA of a pair of different office seats was conducted, and it was reported that the seat made with aluminum had greater environmental impacts than the chair with a nylon base (Gamage & Boyle, 2006). Furthermore, it was revealed that the environmental consequences resulting from manufacturing can be mitigated by implementing appropriate EoL strategies, such as material recycling. It is worth mentioning that the data that could not be acquired in this study is attributed to the absence of pressure from the government or customers to disclose such information and the presence of confidentiality concerns in a competitive setting.

Also, this study of Gamage & Boyle (2006) did not consider transportation, packaging, and the usage phase. Only material parts that constitute more than 5% of the chair's mass were taken into account. The product functions without the need for electricity or water, and it is believed that no substantial repairs will be performed over its lifespan. The sole anticipated requirement was the cleaning, which involves wiping the surface to remove dust or markings and is anticipated to have minimal environmental impact.

Similarly, Wang et al. (2016) omitted the use phase from the system boundaries as furniture requires minimal energy input and maintenance information is inaccessible. In addition, due to the uncertainty of EoL data, this stage has also been omitted from the assessment.

Most research primarily examines the comparison of different substances or production processes. The objective of Wang et al.'s (2016) study is to determine the environmental effects and hot spots of three types of solid wood furniture: a beech wood desk, a white oak-and-fabric sofa, and a rubber wood wardrobe. The aim is to offer valuable information for selecting materials and making decisions regarding the development of eco-friendly furniture. While evaluating the environmental impact index in terms of mass unit, it is revealed that the sofa, which includes various components such as textile and upholstery materials, has the highest index.

To assess the use phase of the furniture and conduct a cradle-to-grave LCA, Medeiros et al. (2017) assumed a round-trip transportation of the final product from the factory to the consumer’s home during this stage and included the waste generated from packaging.

The scenarios involved evaluating various fuel consumption in transportation, shorter travel distances, or other forms of transportation to assess the possibilities for mitigating the impacts. Oceanic shipping exhibited reduced environmental impacts compared to both the base scenario and the fuel switch alternative. However, its implementation necessitates careful production planning because of time limitations. The ideal scenario turned out to involve the manufacturing and utilization of the wooden board in a closer vicinity.

For the evaluation of the global warming potential of furniture products and the development of Ecodesign methods in line with the results, the Spanish furniture industry was examined through the LCA of nine wood-based products. Based on the findings, implementing the suggested enhancement options leads to a significant decrease in greenhouse gas emissions, with up to 60% reductions. It was reported that the processes pertaining to the production of wood-based materials, along with energy generation, are crucial in nearly all evaluated products because manufacturers typically utilize electricity from the national power grid. The transportation of raw materials to the factory and the manufacturing of metals were also identified as the key factors (González-García et al., 2011).

A similar study was conducted to determine the stages that impact the environment most during the production of a children's furniture set and consequently establish Ecodesign guidelines. The research provided several alternatives, such as optimizing material usage, recycling wastes in manufacturing, utilizing renewable energy, minimizing materials used in packaging, and more. As shown by the findings, implementing any of the Ecodesign solutions would result in a substantial decrease in the environmental impacts of the childhood set. One of the most critical results showed that by generating 50% of the entire electricity needs through the proposed photovoltaic plant, reductions of up to 14% might be attained (González-García et al., 2012).

Recent research conducted by Sakib et al. (2024) confirms the significance of energy sources in the production process of furniture as well. The integration of solar and renewable energy sources in this study demonstrates the viability and potential advantages of including environmentally friendly practices in furniture production.

The result adds to the growing collection of research on using renewable energy and its contribution to mitigate adverse environmental impacts.

One limitation of the study conducted by González-García et al. (2012) was the inability to allocate energy and heat consumption specifically to each production stage (assembly, finishing, and packaging) due to the unavailability of data on energy consumption for individual stages, with only total energy use data being measured.

This is why the study conducted by Linkosalmi et al. (2016) stands out from others since the electricity consumption during every stage of the manufacturing was available, and all inputs of raw materials were also measured for the evaluation along with the waste generated in situ.

The primary emphasis was placed on the examination of greenhouse gas emissions. GWP was analyzed during the impact assessment as a demonstration of how the furniture industry may meet the climate targets set by the EU and to identify the key production stages that need to be addressed. When emissions are analyzed according to the emission-mass ratio for each individual material, they appear to be highly dependent on the substance. Textiles and plastics have a high ratio of emissions to mass, while metals exhibit a low ratio that is comparable to wood-based materials (Linkosalmi et al., 2016).

Another study that focused on the benefits of Ecodesign strategies emphasized that the design process accounts for 70% of the ultimate cost, functional needs, and environmental impacts of a product (Mirabella et al., 2014)In an effort to minimize the environmental impacts of furniture production, the effects of VOCs and formaldehyde emissions should be considered. Thus, the significance of the painting and preservative treatment stages is highlighted.

It was also reported that the assessment of enhancements resulting from the usage of certified wood was not possible due to the absence of established procedures since the LCA methodology does not include the capacity to measure the positive effects of using certified wood produced under certification mechanisms. The study noted that there are no inventories specifically dedicated to certified wood and no impact assessment categories and characterization factors that consider the lesser impacts associated with land use and biodiversity-related consequences.

The majority of current LCAs mainly concentrate on individual furniture items. These assessments employ a bottom-up methodology that relies on the bill of materials to construct the data inventory. The bottom-up technique involves initiating data collection from the selected functional unit, typically a particular product. Wenker et al. (2018) employed a top-down approach, which begins with an extensive view and then progressively breaks down the investigation into more specific parts. Data gathering was conducted on a corporate scale, wherein the company data were distributed proportionally based on the quantity of furniture manufactured. The top-down method guarantees comprehensive coverage and completeness of all material and energy flows at the organizational level. Accordingly, the declared unit was chosen to be 1 kg of furniture, including its packaging. The fundamental concept is that the functional unit offers environmental data per kg as a mutual and comparable base, which allows for comparing two pieces of furniture.

In an effort to use LCA with the aim of quantifying the environmental cost (eco-cost) associated with the materials used in the product and subsequently identifying the eco-efficiency level of the items, an analysis was carried out on a chair due to its status as the most extensively exported item (Rinawati et al., 2018). The study defined eco-efficiency as a corporate plan that prioritizes the reduction of natural resource consumption and the minimization of waste and environmental degradation, resulting in increased value. Nevertheless, finishing and upholstery procedures on the observed product were not analyzed in the scope of the study.

Hartini et al. (2019) also aimed to identify the eco-costs associated with the manufacturing process of a table, including roughing, construction, assembly, and finishing. Based on the results, the finishing process was identified as having the highest environmental impact value. The greatest environmental impact arose from metal depletion because of the industrial operations that rely on raw materials obtained through metal extraction, such as the utilization of paint.

In a similar study where an LCA of a dining table was conducted with the eco-cost method, Purwaningsih et al. (2021) recommended the reuse of wood waste that can minimize the influence of climate change and improve eco-efficiency. The second suggested strategy is to modify the material utilized during the finishing procedure, such as substituting water-based paint with wood paint. Iritani et al. (2015) also proposed the utilization of wood waste as a sustainable alternative for producing particleboard, which was identified through a comparative scenario analysis.

Unlike other furniture LCAs, where the standard practice is to express the functional unit in terms of quantity or mass, Iritani et al. (2015) chose the functional unit as 40 kg of stored goods/5 years with the reference flow of one wardrobe unit to depict both qualitative and quantitative characteristics of the goods storage. The findings revealed that the steps of raw materials supply and the distribution of the final product have the greatest environmental impacts. The impact categories of particularly high relevance were human toxicity, global warming, and acidification, collectively accounting for 68% of the overall impacts.

LCA studies for furniture in Türkiye have recently gained importance and are being demanded by manufacturers. To create local LCA data on a sofa sample produced in Türkiye and obtain a more precise assessment of sustainability efforts based on Türkiye's specific circumstances, Mermertas et al. (2018) conducted an LCA study. The results showed that the environmental impacts are largely caused by the extraction and processing of raw materials. Among the manufacturing stages, textile production, in particular, revealed a significant environmental impact.

Ali et al. (2024) performed an LCA on a wooden furniture set in Pakistan and compared the results with the study of Mermertas et al. (2018). The results were in line with each other and revealed that the greatest impacts on the environment were caused by the transportation of raw materials and textile use in production.

An LCA study was conducted by presenting a literature analysis specifically examining LCA methodologies used in the process of “Ecodesign”ing wooden furniture. A tool based on LCA was established specifically for the furniture sector, taking into account the primary materials and processes often employed. The tool underwent tests by investigating a case study of a wooden armchair. It enabled the quantification of the environmental impacts of the armchair and the assessment of potential improvements for the environmental sustainability of the product (Bianco et al., 2021).

To sum up, studies in this field have shown that not only LCA but also LCA on furniture is becoming increasingly important, and the research area is expanding. A significant number of studies limiting the system boundaries to the factory exit gate suggested that the cradle-to-grave model should be applied in future studies to examine the effects of the EoL stage in particular. This study addresses the entire life cycle of a chair, analyzing both the use and post-use phases. In addition, it presents a comprehensive result by performing the impact assessment at both midpoint and endpoint. In addition, it is evident that the studies are concentrated in countries where the furniture industry is emerging, as seen in Table 3.1. This study will pave the way for future LCA studies for different furniture products by presenting the chair product's environmental impacts and potential improvement options with reliable country-specific data in Türkiye, where furniture production has a significant sector volume.

Table 3.1. Summary of LCA Studies on Furniture

References	**Objective**	**Country**	**System Boundary**	**Database**	**Impact Method**	**Software**
Bovea & Vidal (2004)	LCA of wood-based boards, surface and edge coverings	Spain	cradle-to-gate	BUWAL 250 IDEMAT 96 IVAM	Eco-indicator 99 (EI99)	SimaPro 4.0
Gamage & Boyle (2006)	Comparative LCA of aluminum and nylon base office chairs	New Zealand	cradle-to-grave	Supplier	EI99	SimaPro 6.0
González-García et al. (2011)	Assessing GWP through LCA of nine indoor and outdoor wooden furniture	Spain	cradle-to-gate	IDEMAT (2001) Ecoinvent	CML 2 baseline 2000	SimaPro 7.1
González-García et al. (2012)	LCA of a wooden childhood furniture set	Spain	cradle-to-gate	IDEMAT (2001) Ecoinvent	CML 2 baseline 2000	SimaPro 7.3
Mirabella et al. (2014)	LCA of a wooden school desk	Italy	cradle-to-gate	Ecoinvent	ReCiPe 2008	SimaPro 7.2
Iritani et al. (2015)	LCA of a wooden wardrobe	Brazil	cradle-to-gate	GaBi	EDIP-97	GaBi 4.4
Wang et al. (2016)	Comparative LCA of three wooden furniture	China	cradle-to-gate	Ecoinvent	EI99	SimaPro 7.3
Linkosalmi et al. (2016)	Assessing GWP through LCA of eight furniture	Finland	cradle-to-gate	GaBi Ecoinvent KCL-ECO CPM LCA	CML 2001-2010	GaBi 4.0
Medeiros et al. (2017)	LCA of an office cabinet	Brazil	cradle-to-grave	Ecoinvent	ILCD 2011	SimaPro 8.0
Rinawati et al. (2018)	Eco-efficiency analysis through LCA of a chair	Indonesia	gate-to-gate	Ecoinvent	Eco-cost	SimaPro
Wenker et al. (2018)	LCA of storage furniture	Germany	cradle-to-gate	GaBi	CML	GaBi 6.0
Mermertas et al. (2018)	LCA of a sofa	Türkiye	cradle-to-grave	-	TRACI 2.1	GaBi 6.115
Hartini et al. (2019)	LCA of a wooden table	Indonesia	cradle-to-gate	-	Eco-cost EI99	SimaPro 8.4
Bianco et al. (2021)	Tool development through LCA of an armchair	Italy	cradle-to-gate	Ecoinvent	ILCD 2011	openLCA
Purwaningsih et al. (2021)	Eco-efficiency analysis through LCA of a dining table	Indonesia	gate-to-gate	-	Eco-cost	SimaPro
Ali et al. (2024)	LCA of a wooden furniture set	Pakistan	cradle-to-gate	Ecoinvent	CML 2 baseline 2000 CED	SimaPro 8.5
Sakib et al. (2024)	LCA of a pinewood table	Canada	cradle-to-grave	Ecoinvent GaBi	ReCiPe 2016	GaBi
This Thesis Study	LCA of a dining chair	Türkiye	cradle-to-grave	Ecoinvent USLCI	ReCiPe 2016	SimaPro 9.2.0.2

CHAPTER 4

METHODOLOGY

4.1 Study Approach

In this study, a cradle-to-grave LCA of a dining chair representing wood-based furniture products was conducted, and alternative scenarios that can reduce the chair's environmental impacts were evaluated. The LCA was carried out according to the standard methodology, which consists of goal and scope definition, LCI analysis, LCIA, and interpretation.

The first steps of this study consist of a comprehensive literature review to outline the framework of the study. LCA studies on furniture products to date are examined to gain insight into the methodology used. This is followed by a gap analysis of the literature, focusing on the potential contribution of the study. In line with the findings obtained from the literature review, the goal and scope of the study were determined along with the system boundary. As suggested by many literature works, system boundaries were drawn by including the use and post-use stages of the chair. One of the most critical steps of the study was to outline the data requirements during the LCI stage. The data collection process was initiated with careful consideration to prioritize actual, country-specific data over literature-based data.

Following the goal and scope definition, impact assessment was conducted using SimaPro 9.2.0.2 in combination with the Ecoinvent 3.7.1 and USLCI databases for the inventory analysis. The results were interpreted according to the midpoint and endpoint impact categories of the ReCiPe 2016 Hierarchist method. After that, six different scenarios were studied with the aim of reducing the environmental impacts resulting from the base scenario. The data collection process, scenario development, and LCA methodology are explained in detail in the following sections.

4.2 Data Collection

In developing the LCA inventory data for the chair, the primary inputs and outputs of each process step included in the product system were collected from a company. It was ensured that the company to be involved in the study was representative of the sector with its large production capacity.

The most produced and sold chair model was identified, and the choice was agreed upon with the company officials. A dining chair is one of the most widely used and sold furniture products, as seating around a table is a necessity in family households. This chair shares similar production processes with other furniture products since it is considered typical wooden furniture.

In order to collect the necessary data effectively, the information and documents to be requested from the company were determined beforehand, taking into account the suggestions given in the literature. After defining the data set required for the study, a site visit to one of the company's manufacturing facilities was organized to observe the production processes on-site in detail.

Processed forest products are used in the production of the wooden chair and production starts with the joining of thin layers of wood called veneers. Automation and machinery are used extensively to shape the various wood products used. It has been observed that it is difficult to collect and measure sawdust from wood in a controlled manner. Dyeing is distinguished as a stage where more chemicals are used since finishing processes are also involved here. Human labor seemed to be more prominent in the subsequent upholstering process. One of the noteworthy points here is that the disassembled furniture concept introduced to Türkiye by foreign brands has also been adopted by this company. During the data collection, another pioneering initiative mentioned by the company involves its investment plan to establish rooftop solar power plants (SPP) to fulfill the factory's electricity demand from renewable resources.

Inputs and outputs of all processes observed in the facility, along with their quantities, were received through dataset templates provided to the employees after the site visit. Information was also obtained from suppliers for various parts and raw materials used in producing the relevant product through the manufacturer. The data obtained revealed that the company's long-standing market dominance and considerable worldwide exporting have yielded extensive and high-quality data.

4.3 Scenario Development

Different scenario studies were carried out according to the results of the base scenario, which was created according to the current data provided by the company. The results obtained in the base scenario contribute to reporting which processes or materials cause the most significant environmental impacts on the chair and thus shed light on the furniture manufacturing industry. The subsequent scenario study provides an analysis of the opportunities for improvement in the sector. In this context, six different scenarios were developed, and it was assessed which of these scenarios has the potential to reduce environmental impacts more. Finally, a best-case scenario is created from the alternatives that give the best results in each scenario, and this is compared with the base-case. A detailed description of the scenarios is given in Section 5.2.

4.4 LCA Methodology

The LCA conducted for this study complies with the standardized framework established by ISO 14040. The LCA methodology consists of the following four phases: (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment and (4) Interpretation.

4.4.1 Goal and Scope Definition

This study aims to investigate the environmental impacts of a wooden chair through an LCA study by adopting a cradle-to-grave approach. In this scope, the production stages of the chair were analyzed, and the hotspots that accounted for the most significant environmental impacts were identified. Based on these hotspots, different scenario studies were carried out to achieve environmental sustainability in the entire life cycle of the chair.

Although the dining chair for which the LCA was conducted is mostly made of wood, the upholstering and dyeing processes require a wide range of raw materials. In addition, different kinds of plastic and metal materials are used to assemble and package all the individual parts.

While the warranty for spare parts on this chair is valid for ten years, research suggests that chair items generally have longer lifespans. This chair is designed to provide stable and solid seating for indoor use. This study sets the functional unit as one chair measuring 920 x 740 x 470 mm in a standard household. The back support and seating sections of the chair are provided in Figure 4.1.

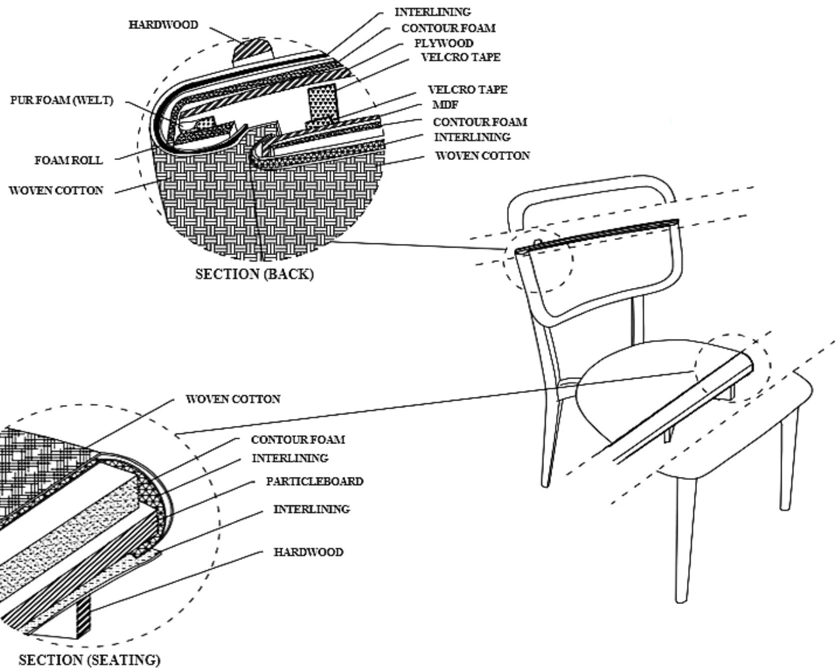


Figure 4.1. Section Views of the Studied Chair Product

The system boundary was established based on the determination of the aim and scope of the study, which is cradle-to-grave. Several life cycle stages have been excluded in many furniture LCA studies due to simplification or lack of data. This study examines the entire life cycle of the chair, minimizing the exclusion of stages from the system boundary, even if their impact is modest. In cases where data could not be obtained from the manufacturer, similar studies in the literature were taken as a basis, or if it was predicted that it would not have a major impact on the study, it was kept outside the system boundaries. The main exclusions in this study are the transfer of the final product from the retailer to the customer and the transfer of wastes. Figure 4.2 illustrates the system boundaries for the chair in general terms.

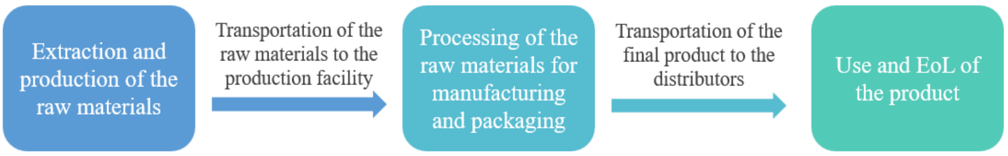


Figure 4.2. General System Boundary of the Chair

The process flow chart for the chair product starts with the extraction and processing of raw materials to be used in production processes and ends with the completion of the life cycle of the final product through waste disposal. According to the data provided by the company, the chair production processes of this particular facility are given as follows: veneer joining, machining, dyeing, upholstering, and assembly. The life cycle of the chair, including all its inputs and outputs within the system boundary, is given in Figure 4.3.

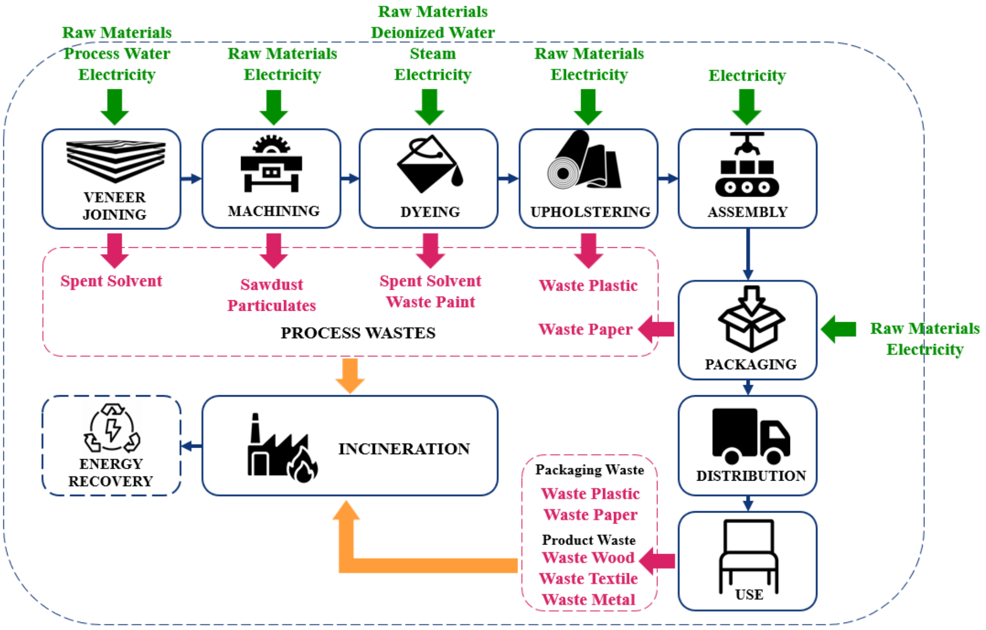


Figure 4.3. Detailed System Boundary of the Chair

Veneer joining involves applying adhesive to combine around 10-15 thin sheets of wood, each measuring a few millimeters in thickness. Subsequently, the molded veneers are transformed into functional wood, plywood, for further procedures. A powder press glue consisting of UF is mixed with deionized water to join the veneers. Machining involves various techniques and tools to shape woods into desired forms. In this stage, three more types of wood are utilized: hardwood, medium-density fiberboard (MDF), and particleboard. The dyeing process is characterized by its high degree of chemical intensity and employs steam, setting it apart as a distinct procedure within chair manufacturing. In upholstering, seating and back support components are crafted using polyurethane (PUR) foam, fabric, and structural joint elements. Assembly entails the conjoining of components from preceding stages, with the only input being electricity, necessary for the operation of automated machinery. This product is designed to be disassembled for various purposes, including minimizing the space required for transportation, providing convenience, mainly when delivering to international markets, and reducing production and packaging expenditures. Therefore, steel components like Allen wrench and screws are included in the packaging of the final product, composed of polyethylene (PE) packaging film and corrugated board box.

4.4.2 Inventory Analysis

Inventory analysis proposes an in-depth assessment of the material flows within the product system. These flows pertain to the introduction of raw materials, energy, and water, as well as the release of substances into the air, water, and land. As previously pointed out, the cradle-to-grave processes depend on manufacturing information obtained from the company under examination. The inventory study was conducted using SimaPro 9.2.0.2 software in conjunction with Ecoinvent database 3.7.1 and the USLCI database. Most foreground data is obtained by on-site measurement from company employees. The background inventory data referring to processes such as raw material extraction, plastic and metal production, textile manufacturing, and electricity generation are sourced from the Ecoinvent database 3.7.1, except for one input. The sheets that make up the plywood are called veneers in the industry and were selected through USLCI as they are not available in their raw form in the Ecoinvent database. All inputs and outputs entered into the SimaPro are summarized in Table 4.1 on a process basis with their quantities. Please see Table A. 1 for the detailed inventory data of all life cycle stages along with their source and transportation information.

Table 4.1. Summary of LCI Data for Each Process

Material Flow	**Quantity**	**Unit**
Veneer Joining		
Input		
Veneer	1,314	g
Glue (Powder Press)	1,814	g
Process Water	200	g
Electricity	1.307	kWh
Output		
Spent Solvent	573	g
Machining		
Input		
Hardwood	0.000790	m^3
MDF	0.000195	m^3
Particleboard	0.003974	m^3
Zamak Screws	14	g
White Glue	4	g
PUR Liquid Nail	6	g
Electricity	0.623	kWh
Output		
Sawdust	360	g
Particulates <2.5 µm, air	0.90	g
Dyeing		
Input		
Paint	20	g
Varnish	240	g
Hardener Varnish	120	g
Thinner	80	g
Hardener	160	g
Primer	360	g
Process Water	70	g
Steam	5	g
Electricity	1.086	kWh
Output		
Spent Solvent	310	g
Waste Paint	2	g
Upholstering		
Input		
Loaf	26	g
Staples	54	g
Foam	288	g
Nail	2	g
Velcro Tape	34	g
Polyester (PES) Interlining	19	g
Woven Fabric	338	g
Padding	69	g
Liquid Hotmelt	90	g
Electricity	0.030	kWh
Output		
Waste Plastic	14	g

Table 4.1 (cont’d)

Material Flow	**Quantity**	**Unit**
Assembly		
Input		
Electricity	0.015	kWh
Packaging		
Input		
Screw	124	g
Allen Wrench	15	g
PE Film	498	g
Dowel	1	g
Corrugated Board Box	3,440	g
User Manual and Label	2	g
Cardboard Glue	25	g
Electricity	0.010	kWh
Output		
Waste Paperboard	55	g
Distribution		
Input		
Highway	6.12	t*km
Seaway	0.39	t*km
Use		
Output		
Waste PE	498	g
Waste Paperboard	3,440	g
EoL (Incineration)		
Output		
Waste Wood	7,756	g
Waste Textile	391	g
Waste Plastic	358	g
Scrap Steel	220	g

The inputs and outputs are based on the data provided by the company. When these data are not available, they are proportioned from similar processes of similar products in the literature. The only inputs missing from any database were the chemicals used in dyeing. These were created manually in SimaPro based on the chemical composition and concentration information given in the material safety data sheet (MSDS) documents provided by the company from its suppliers. Since the waste generated from the processes is known to be given to licensed companies, the common waste management practice in Türkiye was considered. The baseline assumes that all waste is incinerated to facilitate comparison between the impacts of waste management methods in the scenario analysis.

For the distribution of chairs to warehouses in different provinces after they leave the factory gate, 2023 data provided by the company's sales department was used. The eight provinces with the highest distribution in the domestic market, which covers 96% of the entire distribution, and the four countries with the highest number of product shipments in the foreign market are taken as basis. The weighted average of highway and seaway transportation is calculated to show the impact of one chair in t*km in the distribution phase. Detailed information on transportation data is given in Table A. 3.

4.4.2.1 Assumptions

In nearly all LCA studies, data gaps and limitations of software and databases are prevalent. Consequently, it becomes necessary to employ educated guesswork, drawing upon references such as industry norms, waste management regulations, or other credible figures sourced from online platforms. The assumptions and acceptances made within the scope of this study are summarized below.

- To include environmental impacts due to transportation, information on the supplier of each raw material was obtained from the facility. Subsequently, the distance between the supplier and the producer was calculated and t*km unit transportation data was entered into SimaPro. It is assumed that EURO4 type 7.5-16 metric tons lorry is used for all transport.

- While material types or quantities were changed within the scenarios, transportation inputs were left the same as in the base scenario.
- In calculations, wood densities are estimated as 800 kg/m^3 for hardwood, 730 kg/m^3 for MDF, 730 kg/m^3 for veneer, and 630 kg/m^3 for particleboard.
- It is assumed that the environmental impact of materials for which no concentration information for the composition is given in the MSDS documents of manually input chemicals can be ignored.
- The amount of waste paint in the dyeing is assumed 10% of the total paint input.
- Since some of the process-generated wastes were measured together with all other production processes in the facility, data specific to chair production could not be provided. For these, LCA studies of products with similar materials from the literature were utilized, and proportioning was made according to their weights. The details are given in Table A. 1, along with the relevant references.
- Distribution ratios to branches were calculated based on the total amount of chairs in single, double, and six-pack packages. Domestic and foreign branches, with less than 5% of the overall distribution, were not included in the calculation. First, the domestic and foreign figures were proportioned to calculate relative distance, and then the t*km value was calculated over the chair plus package weight based on the distribution ratios. The details are given in Table A. 3.
- Only packaging waste has been considered during the use phase, as its use usually does not require energy or resource consumption, and consumer habits can vary significantly regarding cleaning and maintenance.
- It is assumed that the Allen wrench provided in the packaging for customers to assemble the product is not disposed of during the use or EoL phases.
- EoL is assumed to involve the disposal and incineration of the whole product.
- When calculating the material weights for EoL, the amounts of all chemicals, such as adhesives, paints, varnishes, etc., used in chair production are included in the wood.

4.4.3 Impact Assessment

Impact assessment methods quantitatively evaluate various environmental impacts, identifying critical points in a product's life cycle and helping decision-makers to inform modifications that can be made. SimaPro software incorporates various assessment methodologies, each having different impact categories. This assessment ensures that the methodology is aligned with the study's objective and includes impact categories directly related to the nature of the product being studied.

A wide variety of impact assessment methods have been utilized in LCA studies for furniture or wood products. As seen in Table 3.1, EI99 and CML are widely used in furniture or wood-based product LCAs. EI99 assesses environmental damage using an endpoint approach, whereas CML employs a midpoint approach to assess the degree of environmental effects. On the other hand, the ReCiPe methodology can be utilized for both the midpoint approach, known as the ReCiPe midpoint, and the endpoint approach, known as the ReCiPe endpoint. EI99 and CML are seen as the predecessors of the ReCiPe model since the ReCiPe method incorporates the CML 2002 model and the EI99 methodology in an upgraded version (Verbitsky & Pushkar, 2018). Moreover, the ReCiPe 2016 offers characterization factors that are globally applicable rather than limited to the European level (Huijbregts et al., 2017). Hence, the ReCiPe 2016 impact assessment method was chosen for this study.

The three methodological approaches, individualist, hierarchist, and egalitarian, vary based on several criteria, such as the number of substances being analyzed, the data set used for normalization, and the data set used for weighting. In the egalitarian perspective, the preferred time frame is significantly long-term, whereas the individualist perspective favors a short-term duration. The hierarchist perspective represents a harmonious balance between the egalitarian and individualist approaches and is usually suggested to be used as the default.

Characterization factors at the midpoint level are commonly situated at a specific juncture along the cause-impact pathway, where the environmental system for every environmental flow associated with that impact category becomes the same. Endpoint-level characterization factors usually indicate damage in one of three protection areas: human health, ecosystem quality, and resource availability. The midpoint characterization has a deeper connection with the environmental flows. It occurs with less variable apprehension overall, but the endpoint characterization can be more straightforward to comprehend with respect to its relevance to the environmental flows. This is why the two methods are considered complementary to one another, as can be seen in Figure 4.4 (Huijbregts et al., 2017).

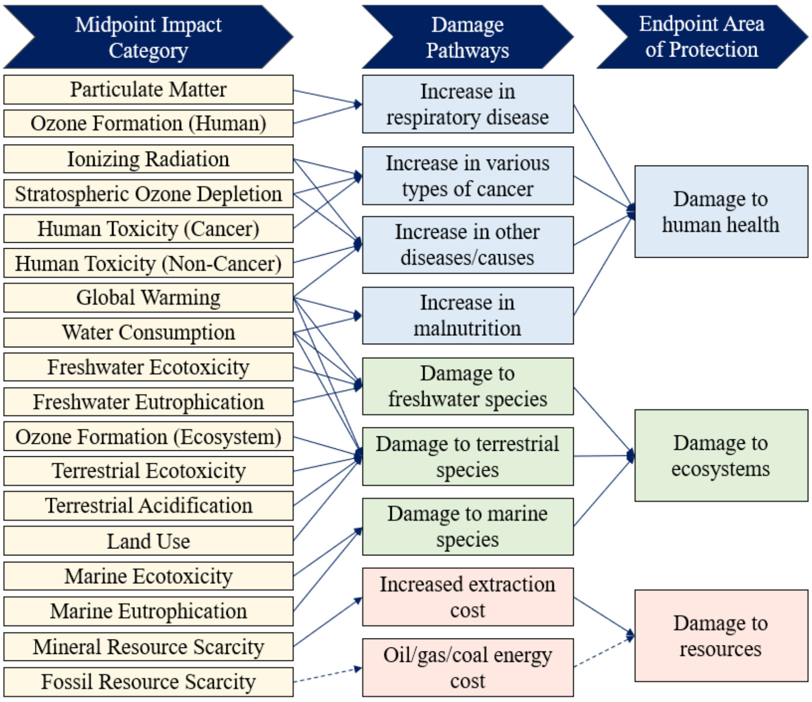


Figure 4.4. Impact Categories and Related Protection Areas of ReCiPe 2016

Thus, both midpoint and endpoint methods are evaluated in this study to present a complete impact assessment. All of the default impact categories in the ReCiPe 2016 (H) model are analyzed in the scope of the study. Midpoint impact categories and their indicators are given in Table 4.2, along with the characterization factors (Huijbregts et al., 2017).

Table 4.2. Midpoint Impact Categories and Related Indicators

Impact Category	**Indicator**	**Characterization Factor**	**Unit**
Global Warming (GW)	Increase in infrared radiative forcing	Global Warming Potential	kg CO_2-eq to air
Stratospheric Ozone Depletion (SOD)	Decrease in stratospheric ozone	Ozone Depletion Potential	kg CFC-11-eq to air
Ionizing Radiation (IR)	Increase in absorbed dose	Ionizing Radiation Potential	kBq Co-60-eq to air
Ozone Formation: Human Health (OFHH)	Increase in tropospheric ozone population intake	Photochemical Oxidant Formation Potential: Humans	kg NOx-eq to air
Fine Particulate Matter Formation (FPMF)	Increase in PM2.5 population intake	Particulate Matter Formation Potential	kg PM2.5-eq to air
Ozone Formation: Terrestrial Ecosystems (OFTE)	Increase in tropospheric ozone	Photochemical Oxidant Formation Potential: Ecosystems	kg NOx-eq to air
Terrestrial Acidification (TA)	Proton increase in natural soils	Terrestrial Acidification Potential	kg SO_2-eqtoair
Freshwater Eutrophication (FET)	Phosphorus increase in freshwater	Freshwater Eutrophication Potential	kg P-eq to freshwater
Marine Eutrophication (MET)	Nitrogen increase in marine water	Marine Eutrophication Potential	kg N-eq to marine water
Terrestrial Ecotoxicity (TE)	Hazard-weighted increase in natural soils	Terrestrial Ecotoxicity Potential	kg 1,4-DCB-eq to industrial soil
Freshwater Ecotoxicity (FE)	Hazard-weighted increase in freshwaters	Freshwater Ecotoxicity Potential	kg 1,4-DCB-eq to freshwater
Marine Ecotoxicity (ME)	Hazard-weighted increase in marine water	Marine Ecotoxicity Potential	kg 1,4-DCB-eq to marine water
Human Carcinogenic Toxicity (HCT)	Risk increase of cancer disease incidence	Human Toxicity Potential	kg 1,4-DCB-eq to urban air
Human Non-Carcinogenic Toxicity (HNCT)	Risk increase of non-cancer disease incidence	Human Toxicity Potential	kg 1,4-DCB-eq to urban air
Land Use (LU)	Occupation and time-integrated land transformation	Agricultural Land Occupation Potential	m^2 × yr annual cropland-eq
Mineral Resource Scarcity (MRS)	Increase in ore extracted	Surplus Ore Potential	kg Cu-eq

Table 4.2 (cont'd)

Impact Category	**Indicator**	**Characterization Factor**	**Unit**
Fossil Resource Scarcity (FRS)	Upper heating value	Fossil Fuel Potential	kg oil-eq
Water Consumption (WC)	Increase in water consumed	Water Consumption Potential	m^3 water-eq consumed

4.4.4 Interpretation

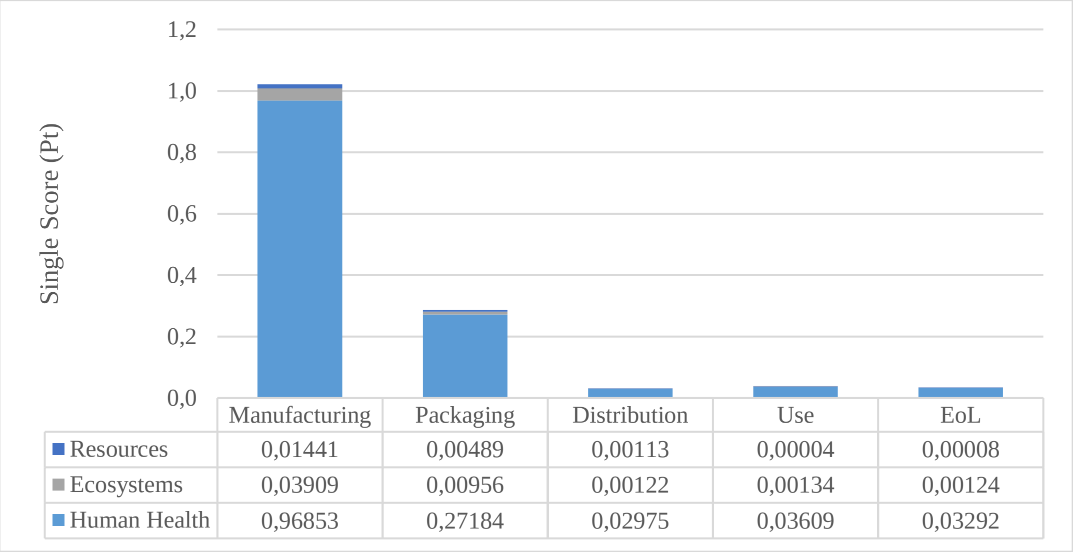
The final stage of the LCA included examining the results obtained from the inventory and the impact assessment. All inputs and outputs defined in the inventory phase were selected from the relevant database and entered into the software. Subsequently, baseline and alternative scenarios were analyzed using the predetermined impact assessment method. Environmental impacts were calculated and reported per functional unit of one piece of chair. In this way, findings were finalized in relation to the goal and scope of the study, and accordingly, multiple choices to enhance the associated study were presented.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results of the Base Scenario

The results are presented by considering the current manufacturing processes and the baseline assumptions for the chair's whole life cycle. Since the manufacturing phase is prominent in terms of environmental impacts in the furniture industry, the results are given by combining all manufacturing processes. Manufacturing here refers to the following processes: veneer joining, machining, dyeing, upholstering, and assembly. Figure 5.1 demonstrates the single score results of the baseline scenario in Pt. The single score aggregates several environmental impact categories into one common score, which is applied using weighting factors that reflect the relative importance of each impact category. The value in units of Pt indicates that the impact of the analyzed process is equivalent to the average annual environmental impact of that number of people in the world (PRé Sustainability, 2023).



	Manufacturing	Packaging	Distribution	Use	EoL
■ Resources	0,01441	0,00489	0,00113	0,00004	0,00008
■ Ecosystems	0,03909	0,00956	0,00122	0,00134	0,00124
■ Human Health	0,96853	0,27184	0,02975	0,03609	0,03292

Figure 5.1. Endpoint Single Score Results of the Baseline Scenario

As clearly seen in Figure 5.1, the manufacturing stage dominates among all life cycle stages of a chair in terms of environmental impacts, with an approximately 1.0 Pt indicating that the manufacturing process is equivalent to that of the impact caused by an average of 1.0 person in the world per year. Common to all stages is that human health is the impact category most significantly affected. When total impacts are considered, the manufacturing stage is followed by packaging, which is also a process before the product leaves the factory gate. Figure 5.2 shows the relative distribution of impacts of life cycle stages in endpoint impact categories.

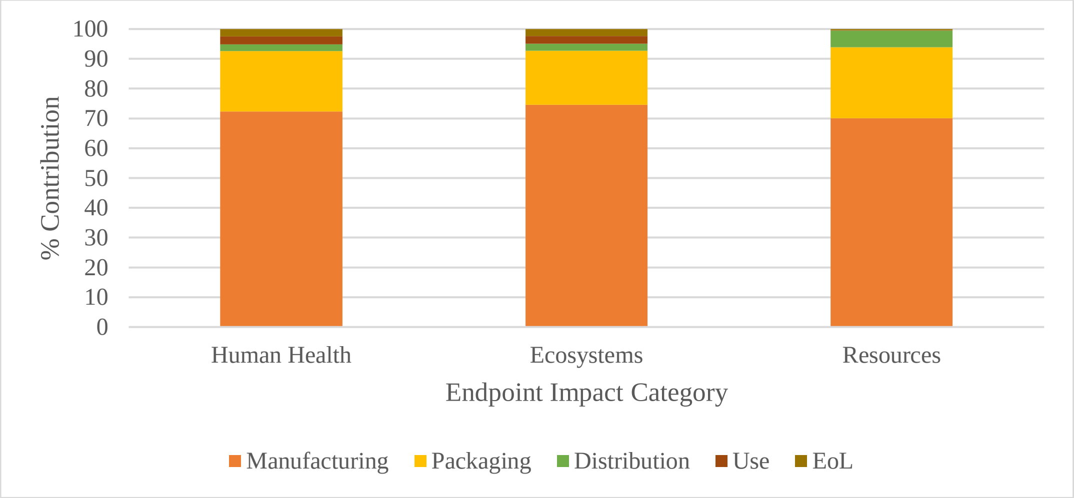


Figure 5.2. Endpoint Damage Assessment Results of the Baseline Scenario

As can be inferred from this figure, the manufacturing stage has the highest impact distribution in all categories, emphasizing the need for a detailed analysis and potential mitigation strategies. The packaging stage, which uses conventional materials, also has a considerable share, especially in the resources area of damage. As expected, the distribution, use, and EoL phases have very minimal impacts on endpoint impact categories compared to other life cycle stages. Figure 5.3 presents all midpoint impact categories affected by combined manufacturing and the rest of the stages.

Unlike the other graphs above, this graph, which gives the characterization results, displays the impact categories that are not dominated by manufacturing. The EoL phase has a significant impact in two impact categories: FE and ME. For both FE and ME, the high levels are attributed to emissions of nickel and manganese resulting from the disposal of coal and lignite mining waste related to incineration activities in the study of Mirabella et al. (2014). These increased impacts are linked to the incineration of scrap steel at the EoL of the product in this study. Since incineration is not the only post-use option for the chair product, it would be useful to test whether it is possible to reduce the relatively higher contribution of EoL in these impact categories through alternative scenarios.

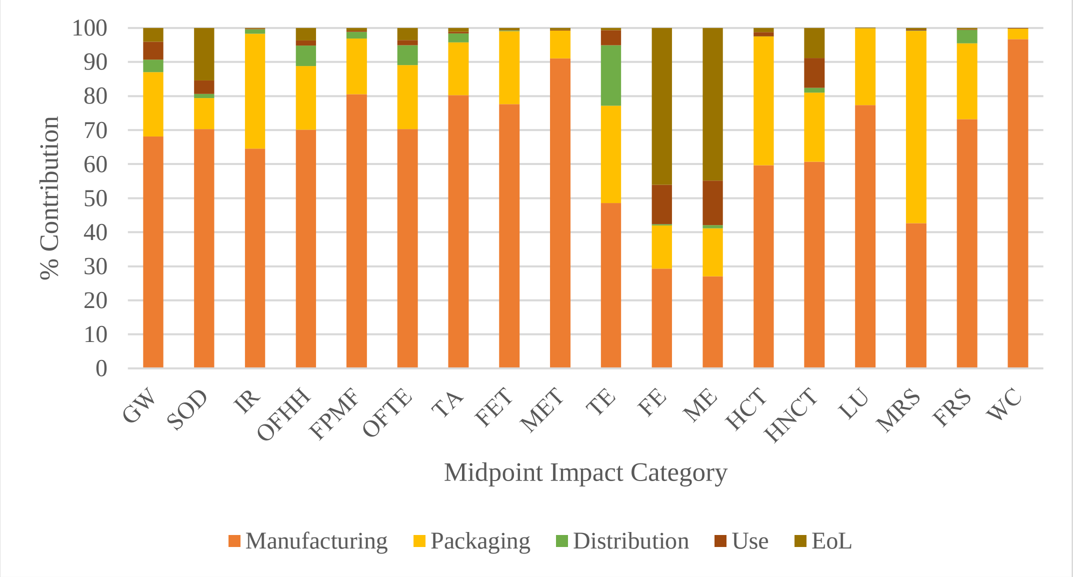


Figure 5.3. Midpoint Characterization Results of the Baseline Scenario

While there are no significant impacts from the packaging materials that are wasted in the use phase, it is noteworthy that the environmental impact of the distribution of the final product to the local and international branches in the TE impact category is more than 10%, which shows that the impact of fuel consumption on terrestrial ecosystems is quite apparent. Further, in line with the graphs above, packaging stands out after manufacturing in many impact categories, especially in MRS. This is due to the auxiliary metal parts placed inside the packaging rather than the packaging material itself. In Figure 5.4, which of all these impact categories is more affected by the life cycle stages of the chair is visualized through the normalization method.

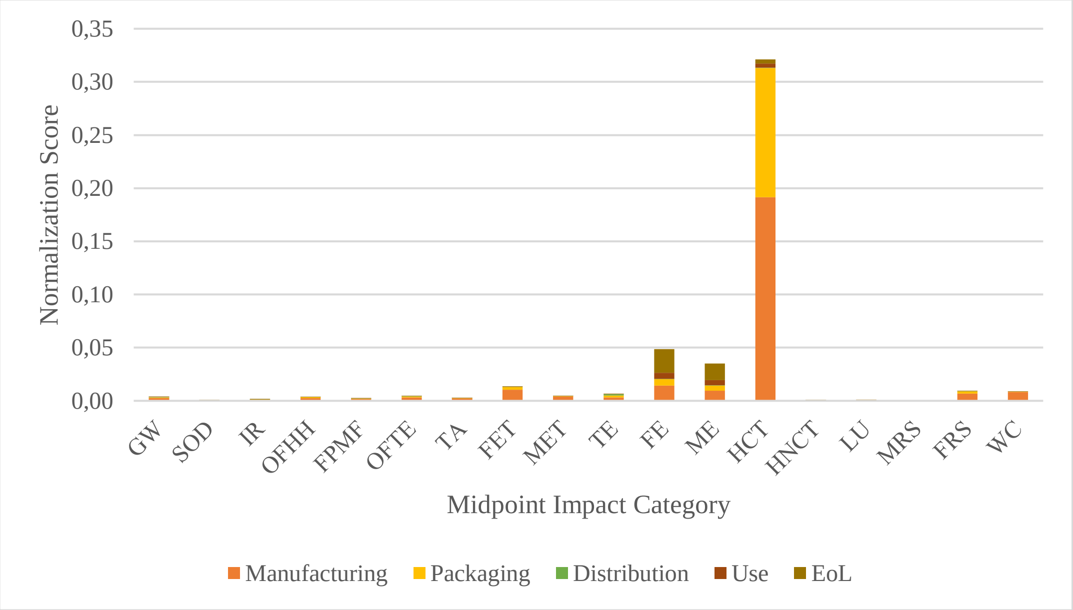
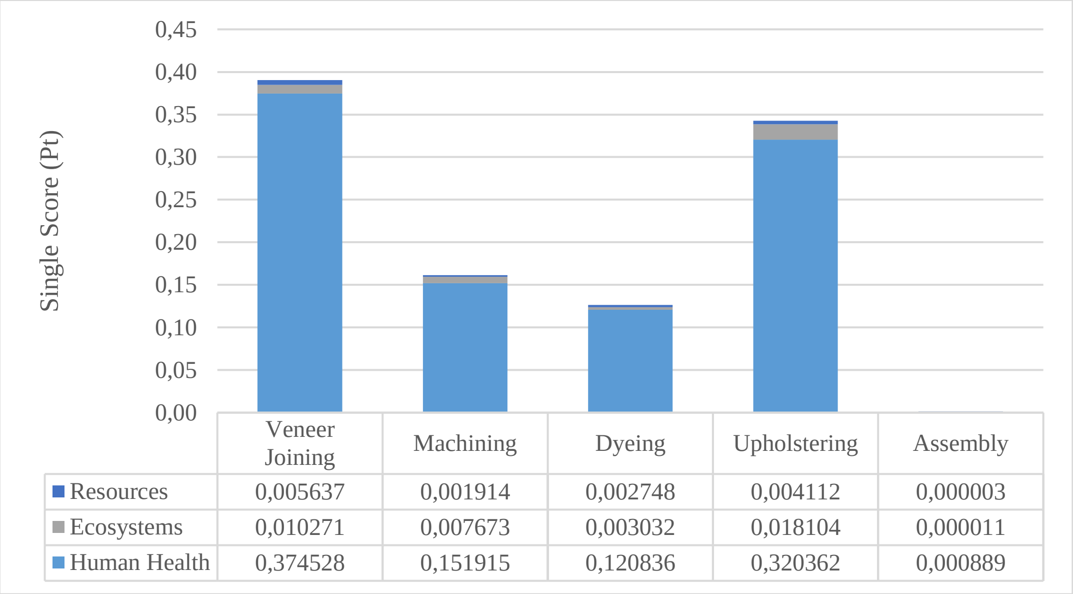


Figure 5.4. Midpoint Normalization Results of the Baseline Scenario

The HCT category has the highest normalized score and is strongly impacted by the manufacturing and packaging processes. This result supports the findings in Figure 5.1, which shows that the impacts of all stages on the human health impact category are the highest among the other indicators. Following HCT, the life cycle of the cradle-to-grave chair has a relatively great impact on the FE and ME impact categories. In these impact categories, the highest contributor is the EoL stage, where the chair is disposed of and incinerated. Figure 5.5 is a detailed LCA graph where the breakdown of the impacts of each manufacturing process across three impact categories can be seen and thus be used for alternative scenario building by clearly showing the stages that need to be focused on during production.



	Veneer Joining	Machining	Dyeing	Upholstering	Assembly
■ Resources	0,005637	0,001914	0,002748	0,004112	0,000003
■ Ecosystems	0,010271	0,007673	0,003032	0,018104	0,000011
■ Human Health	0,374528	0,151915	0,120836	0,320362	0,000889

Figure 5.5. Endpoint Single Score Results of Manufacturing Processes

In Figure 5.5, which shows the endpoint impact categories in terms of a single score, it is possible to state that the assembly stage has almost no environmental impact since it consists only of electrical input and does not involve any raw materials. Of all the manufacturing stages with significantly more impact on the human health category than on resources and ecosystems, the veneer joining process has the highest impact where wood sheets are glued to form plywood. The next stage with the highest impact is the preparation and assembly of upholstery materials onto the wooden parts of the chair. On the other hand, machining has much less impact compared to these two stages. The subsequent dyeing stage, although chemical-intensive, has minimal harmful effects compared to the other stages due to the use of chemicals in small quantities. Figure 5.6 shows the percentage of damage contributed by manufacturing processes to each endpoint category.

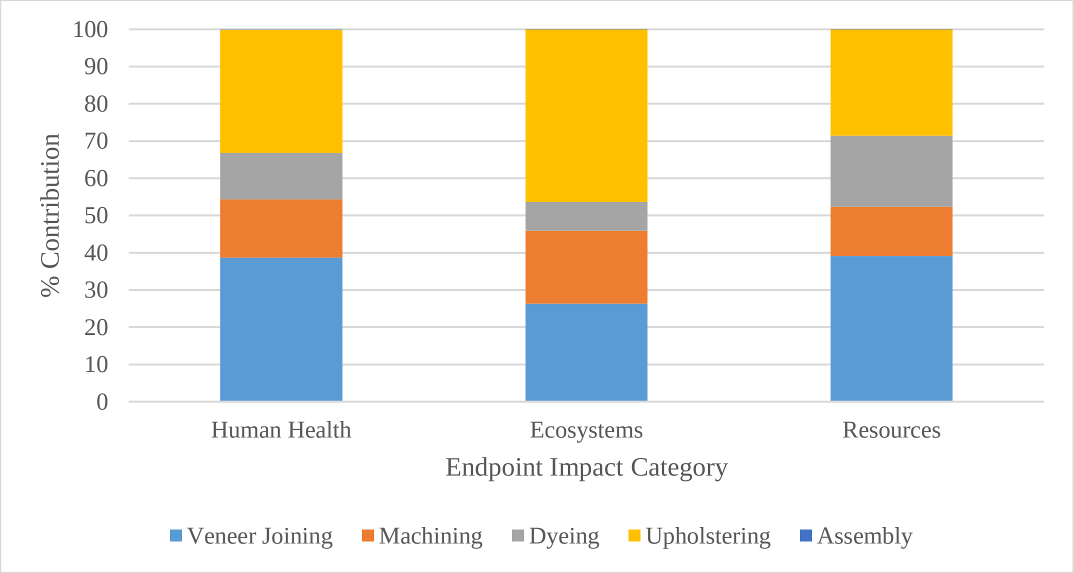


Figure 5.6. Endpoint Damage Assessment Results of Manufacturing Processes

While the phase that has the highest damage on human health and resource impact categories is veneer joining, it is seen that upholstering is the process most affecting the ecosystems. Also, machining has a higher impact percentage on ecosystems compared to its impact in other categories due to the use of variable wood products that potentially damage terrestrial species. Furthermore, the dyeing process is predicted to damage resources, as the mineral resources used to produce the chemicals may be depleted. Figure 5.7 plots the percentage distribution of the five manufacturing stages in each midpoint impact category.

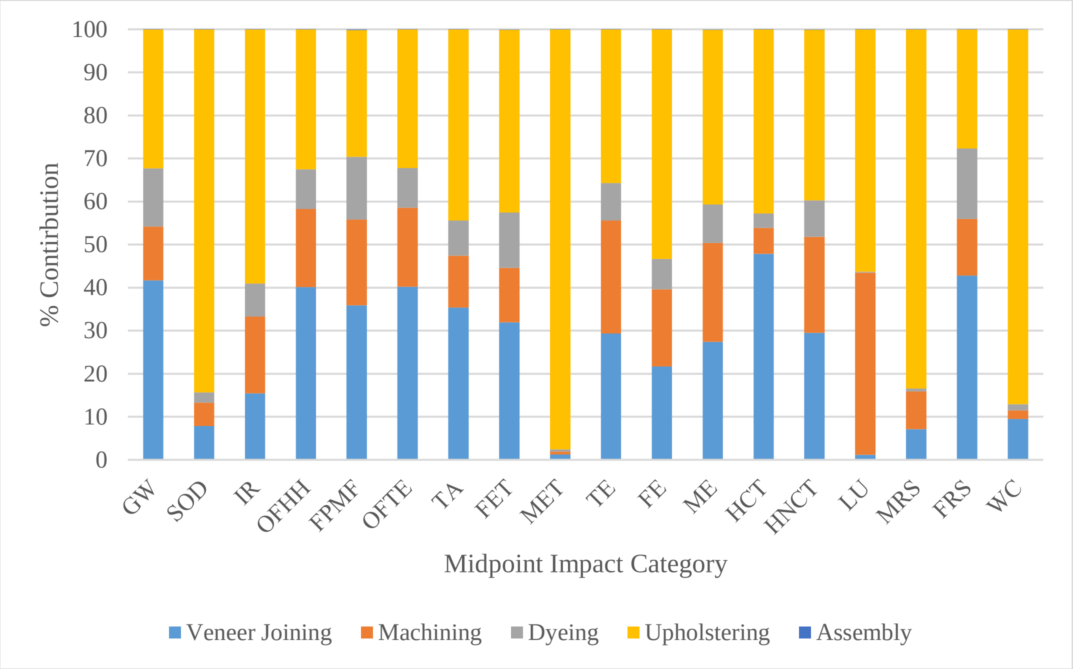


Figure 5.7. Midpoint Characterization Results of Manufacturing Processes

This graph clearly shows which impact categories of veneer joining and upholstering processes have a higher environmental impact than each other. For example, the upholstering process clearly has more impact on SOD, MET, MRS, and WC impact categories than other processes. Noting that this process involves fabrics and the metal parts used to assemble them into the chair's frame, it is interpreted that there is an impact from background data from the production of raw materials.

In a study conducted by Ali et al. (2024), textile production was identified as one of the leading causes of acidification and eutrophication in LCAs carried out in China and Türkiye. These findings align with the results presented here, where TA and especially MET are dominated by upholstering. Furthermore, the machining process, which involves the shaping and joining of three different types of wood, has a major impact on LU, as it directly contributes to the reduction of forest cover. It can be inferred from the graph that both the veneer joining and upholstering stages have an apparent high impact across most impact categories, prompting a detailed examination of these processes.

In Figure 5.8, the impacts of the inputs of the veneer joining process in the midpoint impact categories are given graphically.

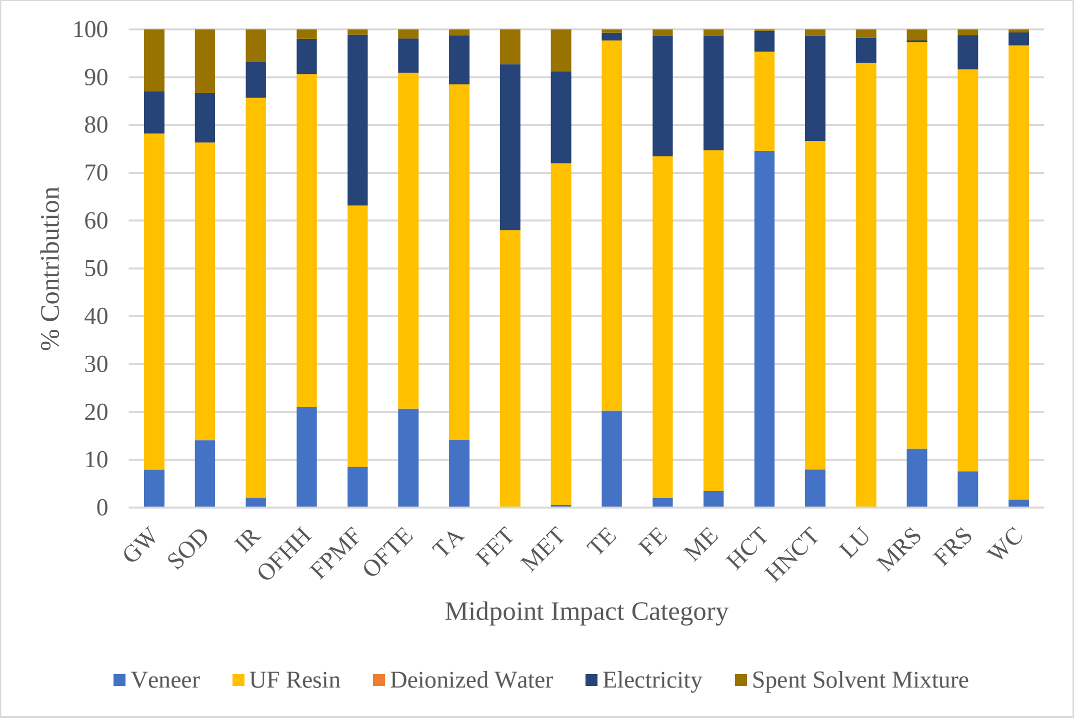


Figure 5.8. Midpoint Characterization Results of Veneer Joining

As seen in Figure 5.8, it is clear that the environmental hotspot of the veneer joining phase is UF resin used to join the veneers to form plywood in almost all impact categories because it is a synthetic material that is quintessentially toxic to the environment (please also see Table B. 9). As suggested by Hartini et al. (2019), the extensive use of paint and glue can cause tremendous environmental impacts in furniture manufacturing since these materials include VOCs and formaldehyde emissions. In the case of UF resin, the utilization of urea in glue production also significantly contributes to the environmental impacts (Yang & Rosentrater, 2020).

Only HCT is dominated by veneer due to the use of wood fuel and heat to dry veneers. The background processes for veneer production in the USLCI database involve utilizing wood waste generated during milling operations and a portion of purchased wood fuel in an industrial boiler for combustion, thereby producing heat. This heat is utilized to dry veneer hardwood. The combustion process emits various carcinogenic compounds, significantly contributing to health impacts, particularly in the HCT category.

Figure 5.9 gives the breakdown of inputs for upholstering, another stage that has a significant impact on manufacturing processes.

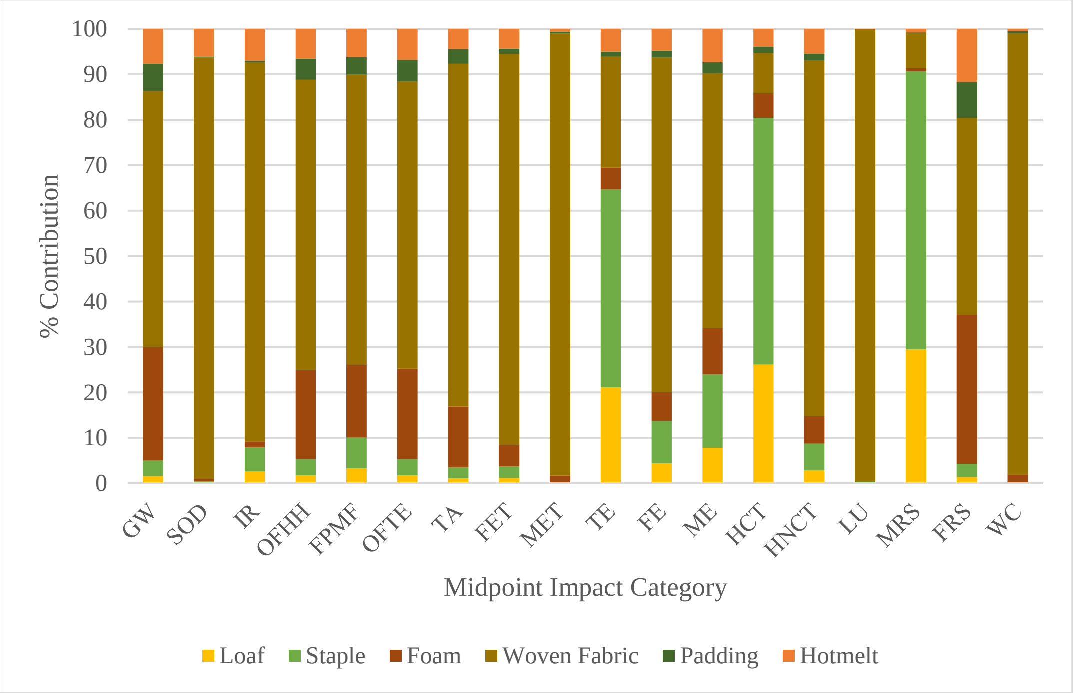


Figure 5.9. Midpoint Characterization Results of Upholstering

In the upholstering consisting of 11 inputs, materials with less than 1% total share of impact in all categories are not included in the graph to demonstrate the impact of dominant materials. It is seen that auxiliary joining parts welded from steel have a high environmental impact in the TE, HCT, and MRS categories. The raw materials needed for steel production are extracted from mineral deposits. These mining activities can increase soil pollution, alter habitats related to TE, and lead to the depletion of natural and mineral resources, which potentially causes a shortage of raw materials and MRS. Similarly, Mirabella et al. (2014) discovered that producing iron parts in a school desk was the primary cause of TE. This was mainly linked to the production of cast iron and the subsequent release of mercury and zinc. Furthermore, the increased impact on HCT is attributed to mercury and manganese release during cast iron production.

It is also observed that the foam roll and contour foam made of PUR contributes significantly to the FRS category since its production requires the use of polyol and toluene, which is included as background data. However, upon assessing the distribution as a whole, it is determined that the effects stemming from the upholstering phase predominantly result from the type of fabric employed, woven fabric (please also see Table B. 10).

Figure 5.10 shows the midpoint characterization results of packaging, which is another prominent stage apart from the manufacturing processes.

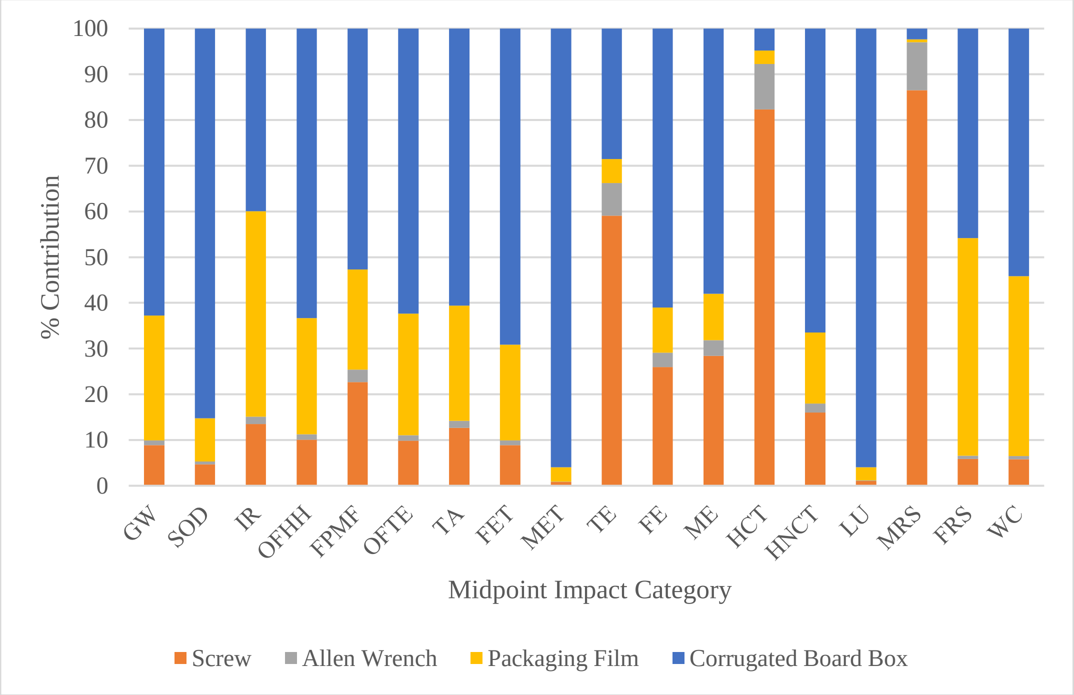


Figure 5.10. Midpoint Characterization Results of Packaging

In Figure 5.10, materials with a share of less than 2% of the total impact in each impact category at the packaging stage have been omitted. Thus, it is understood that the cardboard box and PE film, which are the main materials of packaging, and the screws and Allen wrench used to mount the disassembled chair are significant inputs in packaging. Similar to the upholstering results in Figure 5.9, screws, which are metal components, dominate in the same impact categories: TE, HCT, and MRS. Another conclusion to be drawn is that corrugated board boxes, which are used in high quantities, are the main contributor in almost all impact categories, and the material-induced impact of PE-based packaging film is high, though it is used in much lower quantities (please also see Table B. 11).

5.2 Scenario Development and LCA Results

Different scenarios were studied according to the results obtained in the base scenario to test the improvement potential of furniture production from the cradle to the grave in terms of environmental impacts. While creating the scenarios, attention was paid to ensuring they were realistic and feasible, and in this context, support was received from company employees who were familiar with the sector, and literature sources were referred to. Description of the scenarios and the life cycle stages that involve the modifications are given in Table 5.1.

Table 5.1. Summary of Scenario Development

Scenario No	Description	Affected Life Cycle Stage
Scenario 1	Replacement of the glue	Veneer Joining
Scenario 2	Replacement of the fabric	Upholstering
Scenario 3	Reduction in packaging	Packaging
Scenario 4	Recycling of process wastes	Upholstering + Packaging
Scenario 5	Recycling of the packaging and product	Use + EoL
Scenario 6	Switching the electricity source	Manufacturing + Packaging

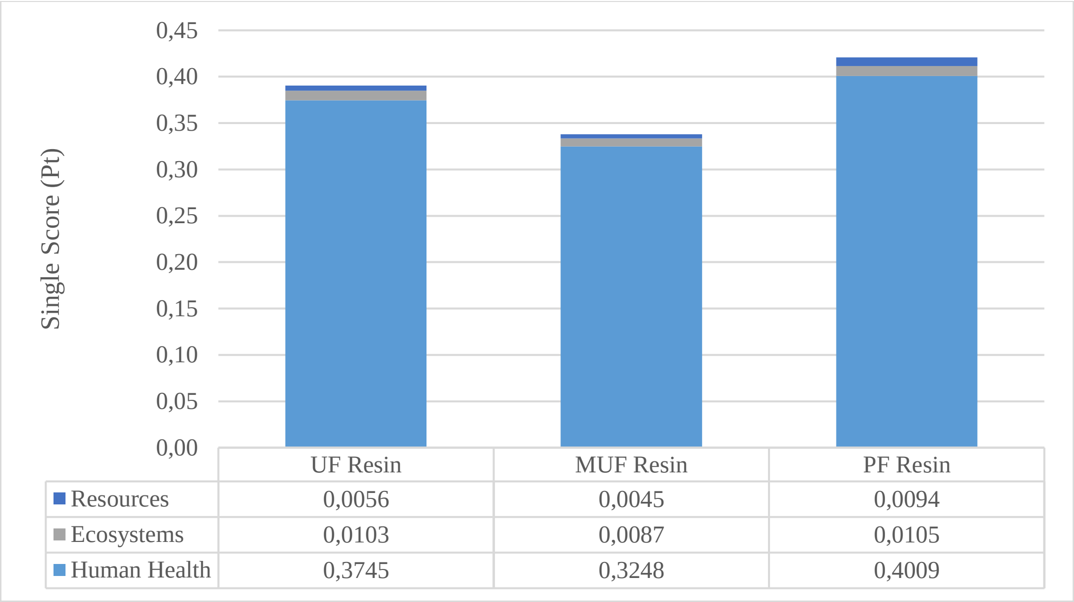
5.2.1 Scenario 1: Replacement of the Glue

The environmental characteristics of wooden products might be substantially influenced by the adverse effects on human health stemming from using UF resin in producing wood-based panels. Iritani et al. (2015) summarized both renewable compounds and synthetic adhesives that can be alternatives to UF resin. Among these alternatives, the two most commonly utilized alternatives were studied to minimize the environmental impacts by replacing UF resin in the veneer joining stage.

The first alternative is melamine urea-formaldehyde (MUF) resin. Silva et al. (2015) investigated whether MUF resin could replace UF resin through an LCA study on MUF resin production. In light of MUF resin's recurrent application as an adhesive in wood-based panel manufacturing, an inquiry was undertaken to evaluate its suitability as a substitute for UF resin with the aim of mitigating environmental impacts with more sustainable alternatives.

Another adhesive most commonly used in the wood industry is PF resin. The PF resin glue forms robust bonding that can withstand the effects of solvents and aging, making it an appealing option for large-scale projects (Pang et al., 2018). In order to see which of these adhesives, which have different properties, advantages, and disadvantages, stands out environmentally, the entire UF resin was replaced with MUF and PF resins.

Two distinct LCA studies were conducted for both MUF resin and PF resin. In evaluating these alternatives, it was assumed that the adhesives were sourced from the same supplier as UF resin, and transportation details remained unchanged. In addition, all adhesives were assumed to be mixed in powder form with equal weights and amounts of deionized water. Accordingly, the comparative results of the veneer joining process utilizing these three different adhesives are shown in Figure 5.11.



	UF Resin	MUF Resin	PF Resin
■ Resources	0,0056	0,0045	0,0094
■ Ecosystems	0,0103	0,0087	0,0105
■ Human Health	0,3745	0,3248	0,4009

Figure 5.11. Comparative Endpoint Single Score Results of Scenario 1

The common point in all three types of glue here is that the highest potential damage of all of them is to the human health impact category. Overall, the MUF resin alternative appears more environmentally preferable than UF and PF resin. It is also observed that the PF resin has a higher total impact than the adhesive used in the baseline scenario.

In an LCA study comparing formaldehyde-based adhesives, some parameters in TRACI were comparatively evaluated for UF and PF resin using GaBi by Yang & Rosentrater (2020). They found that the production process of UF resin generates fewer greenhouse gases in contrast to PF adhesive. It was highlighted that the UF resin recycles CO_2 due to its use as a raw material in urea production, resulting in reduced energy consumption and, consequently, lower greenhouse gas emissions. Furthermore, a reduced quantity of formaldehyde is employed in the production of UF resin, resulting in a lower emission of greenhouse gases during the UF resin process (Yang & Rosentrater, 2020).

In line with the conclusion drawn, the PF resin, which has the highest overall impact, is fixed at 100% in all impact categories, and the results of the relative damage assessment of the other two materials are in Figure 5.12.

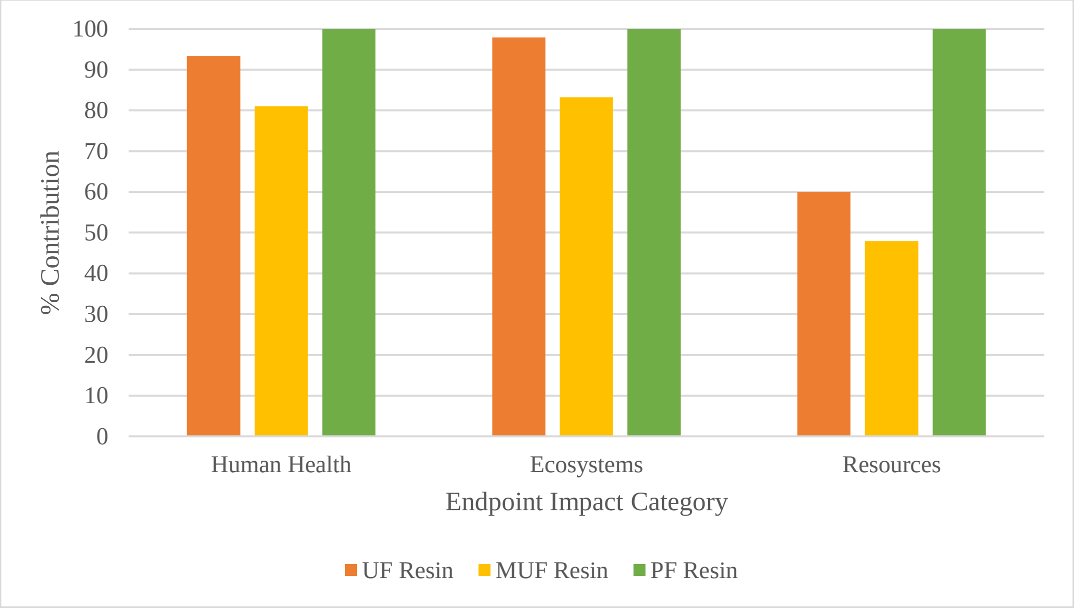


Figure 5.12. Comparative Endpoint Damage Assessment Results of Scenario 1

In the human health category, which is the most affected endpoint impact category by the veneer joining process, the environmental impact of MUF resin is 19% less than the PF resin. It is noteworthy that the impact on human health increased by 7% by the use of PF resin compared to the base scenario.

When the impact of adhesives on ecosystems is analyzed, MUF resin appears to be more environmentally friendly than the other two resins. The results show a negligible difference between UF and PF resin in terms of the impacts on ecosystems.

It is clearly seen here that PF resin differs from UF resin mostly in its negative effect on the resources, so it is not viable as a sustainable alternative. Its impact is about 40% higher than the base scenario. MUF resin, on the other hand, showed noticeable improvement in this impact category.

The results of the veneer joining scenarios in each midpoint impact category are shown in Figure 5.13.

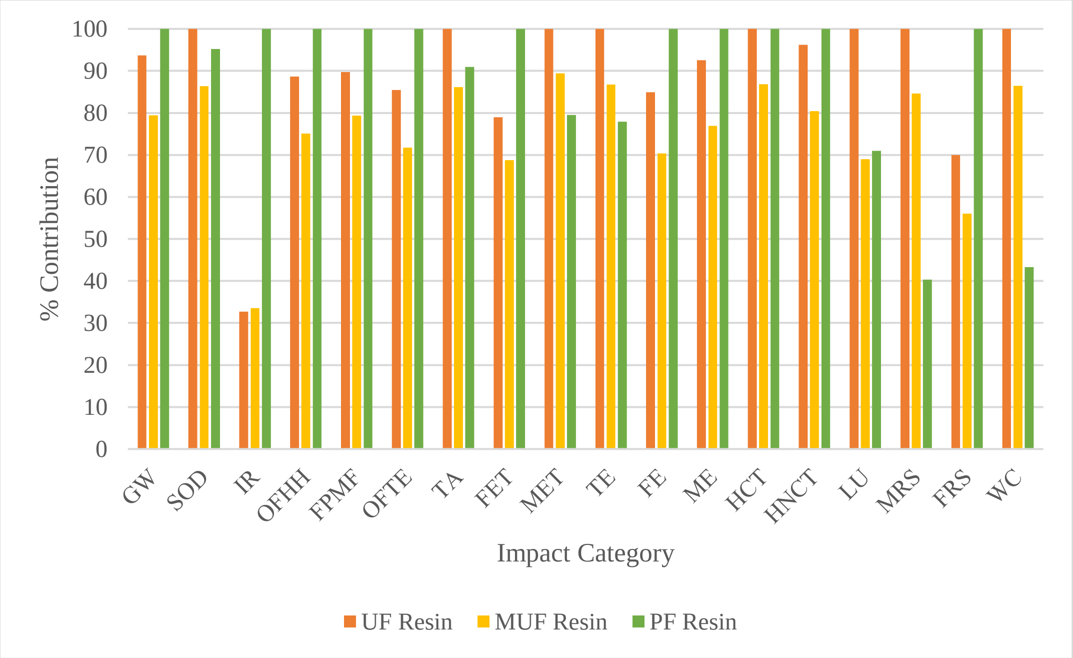


Figure 5.13. Comparative Midpoint Characterization Results of Scenario 1

In their study, Silva et al. (2015) evaluated the possible environmental impacts of MUF resin by examining seven impact categories using CML and USEtox methodologies, which differ from the ReCiPe impact categories. They compared the manufacturing of particleboards using MUF and UF resins. Although it is not possible to make a direct comparison due to variations in impact methods, characterization factors, and system models employed during material entering, the study suggested that MUF resin gives more favorable outcomes.

In a study assessing the environmental impacts of different resins, the utilization of UF resin in particleboard manufacturing showed greater impacts on photochemical oxidation, ecotoxicity, and human toxicity categories compared to the alternative option of employing MUF resin (Silva et al., 2015). This finding aligns with the results obtained in this study as revealed for TE, FE, ME, HCT, and HNCT categories.

The utilization of MUF resin resulted in significant effects on the abiotic depletion and eutrophication categories compared to the usage of UF resin, primarily caused by the production of melamine, as observed in Silva et al. (2015)'s study. In contrast, UF resin exhibited a higher impact by about 10% in the FET and MET categories, which individually indicate eutrophication.

The impact category where MUF resin performed exceptionally well and proved to be an alternative to UF resin was LU, with a difference of 30%. In the remaining impact categories, it seems to provide an improvement of between 5 and 10%, except for one. MUF resin has more impact than UF resin in only one impact category, IR, with a difference that does not even reach 1%.

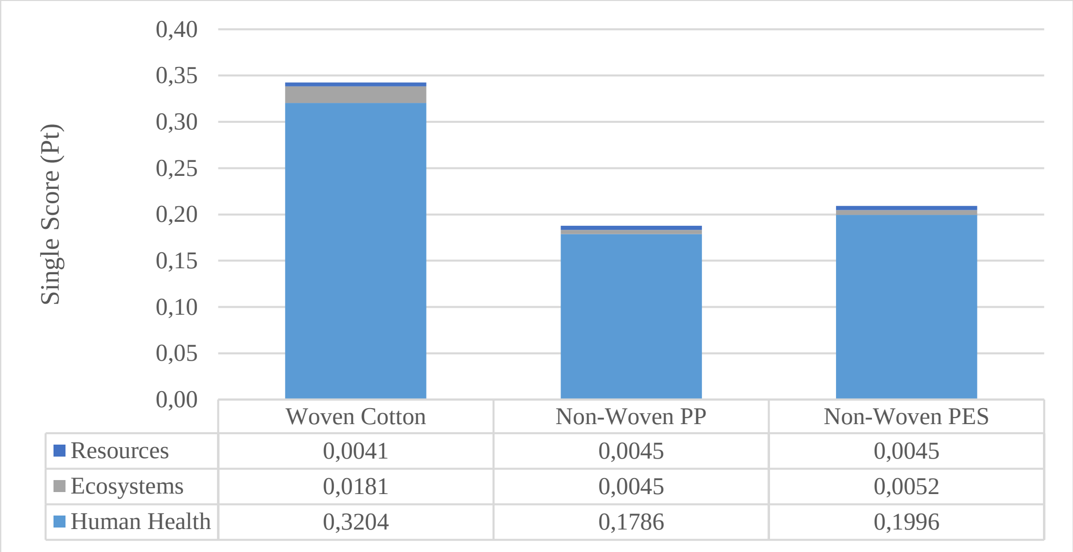
The study conducted by Yang & Rosentrater (2020) discovered that in specific environmental impact assessment categories like global warming potential, smog air, and ozone depletion, the PF resin demonstrates more significant impacts than the UF resin. The comparison of the veneer joining scenario for the GW impact category shows the same result, but a different environmental profile is observed for SOD. On the other hand, PF resin showed lower environmental impacts in the acidification potential and eutrophication potential categories. Similarly, this study revealed that PF resin is favorable in the TA and MET categories but not FET.

Other outcomes from the LCA suggest that PF resin has a relatively lower impact than UF resin in the TA, MET, TE, and LU categories. Moreover, in the MRS and WC impact categories, PF resin shows substantially lower environmental impact than the other alternatives, UF and MUF resin. However, PF resin yielded the highest contribution to environmental impact in all other impact categories, demonstrating its potential for greater degradation compared to its alternatives.

5.2.2 Scenario 2: Replacement of the Fabric

In the base scenario, upholstering was identified as one of the chair's environmental hotspots. As demonstrated in Figure 5.9, textiles were the main contributors to the upholstering process's impacts. The results are in line with the literature on furniture LCAs, where products with fabrics have been studied. Ali et al. (2024) conducted a cradle-to-gate LCA on a traditional wooden furniture set and reported that the fabric utilized in the sofa was the primary contributor to environmental impact across various categories. Furthermore, Mermertas et al. (2018) suggested directing additional efforts towards mitigating the environmental impacts of used textiles by either replacing them with new materials with lower life cycle environmental impacts or optimizing the textile manufacturing process.

In order to reduce the environmental impact of the upholstering process, alternative fabrics to woven cotton fabric were investigated. One of the main materials of the chair of the subject is fabric, a visible material from the exterior. For this reason, the fabric used is of great importance for both the manufacturer and the consumer. The fabrics of the seat and back support parts of a chair, which are in direct contact with users, must be resistant to wear and tear. Although there are different fabric types in the program, only functional and viable alternatives, non-woven polypropylene (PP) and non-woven PES fabrics, were studied within the scope of the scenario based on insights derived from the industry. Figure 5.14 illustrates how effective these alternatives are on the single score results.



	Woven Cotton	Non-Woven PP	Non-Woven PES
■ Resources	0,0041	0,0045	0,0045
■ Ecosystems	0,0181	0,0045	0,0052
■ Human Health	0,3204	0,1786	0,1996

Figure 5.14. Comparative Endpoint Single Score Results of Scenario 1

Upon comprehensive assessment of the three types of fabrics, it is evident that non-woven fabrics exhibit superior environmental friendliness and entail reduced implications for human health compared to woven cotton fabric. In fact, if non-woven PP (total Single Score of 0.1876 Pt) is used as an alternative to woven cotton fabric (total Single Score of 0.3426 Pt), a reduction of 45% in total impacts will be achieved. In comparison, the utilization of non-woven PES (total Single Score of 0.2093 Pt) will result in a reduction of 39%, which is a substantial improvement.

The most significant impact across all three fabrics is observed in the human health category (Figure 5.14). Furthermore, an examination of the impacts on the ecosystem reveals the dominance of non-woven fabrics over woven cotton. When the effect of the three fabrics on the resources is analyzed, PP and PES yielded identical single score results of 0.0045 Pt. The resources category is the only impact category where woven cotton gave lower impact results with a score of 0.0041 Pt.

In a study where cotton fabric and PP-based non-woven fabric were compared, the ReCiPe 2016 method showed more emphasis on the human health category, which is in line with the findings of the present study. Moreover, it is pointed out that non-woven material accounts for a relatively minor portion of the overall impact throughout the manufacturing phase. At this particular stage of production, cotton knit fabric exhibited the highest environmental effect, presumably attributable to its origin (Maceno et al., 2023). Figure 5.15 clearly depicts how the environmental impact of different fabrics in endpoint impact categories varies.

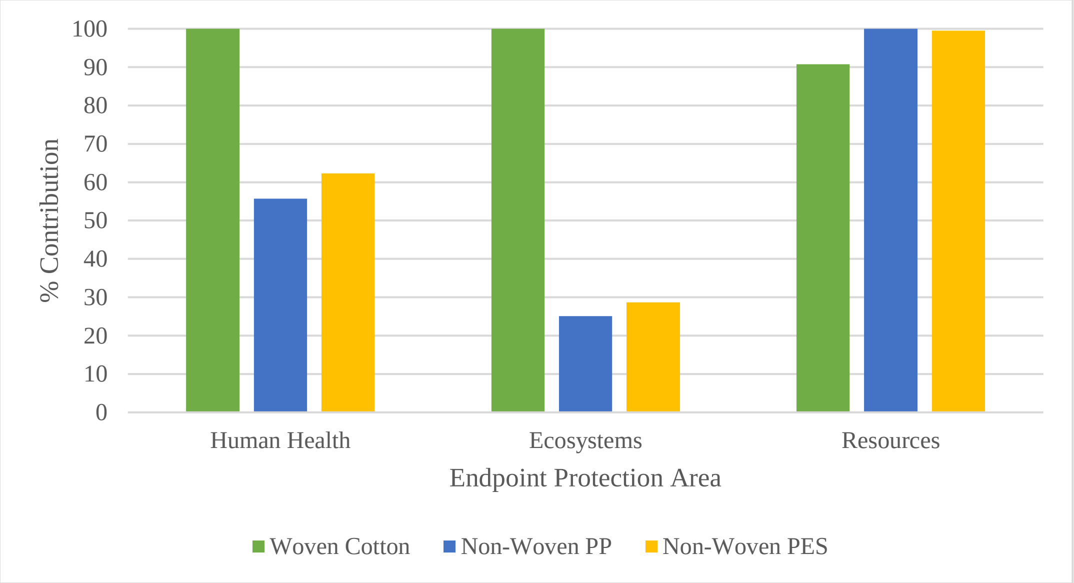


Figure 5.15. Comparative Endpoint Damage Assessment Results Scenario 2

As can be deduced from this graph, the most significant improvement when the woven fabric is replaced with non-woven fabrics is obtained in the ecosystems impact category. Although the slight differences between PP and PES relative to the woven fabric in the resources category point to PES, this can be considered negligible. In the human health impact category, where the most improvement was seen after ecosystems, the use of PP and PES reduced impacts by 44% and 38%, respectively.

Demirdelen et al. (2023) investigated the environmental impacts of these two products using LCA. Their analytical results revealed that the carbon footprint of PES is greater than that of PP. Furthermore, a comparison of the energy consumption and raw material acquisition of the materials reveals that PP yarn has a reduced carbon footprint, making it safer for the environment. Apart from the quantitative findings, the study suggested opting for PP yarn instead of other synthetic yarn due to its superior recycling benefits and mechanical resistance to the effects of relative humidity. Figure 5.16 comparatively presents the impacts of the three fabrics in midpoint impact categories, where the results are quantified by multiplying by the characterization factor.

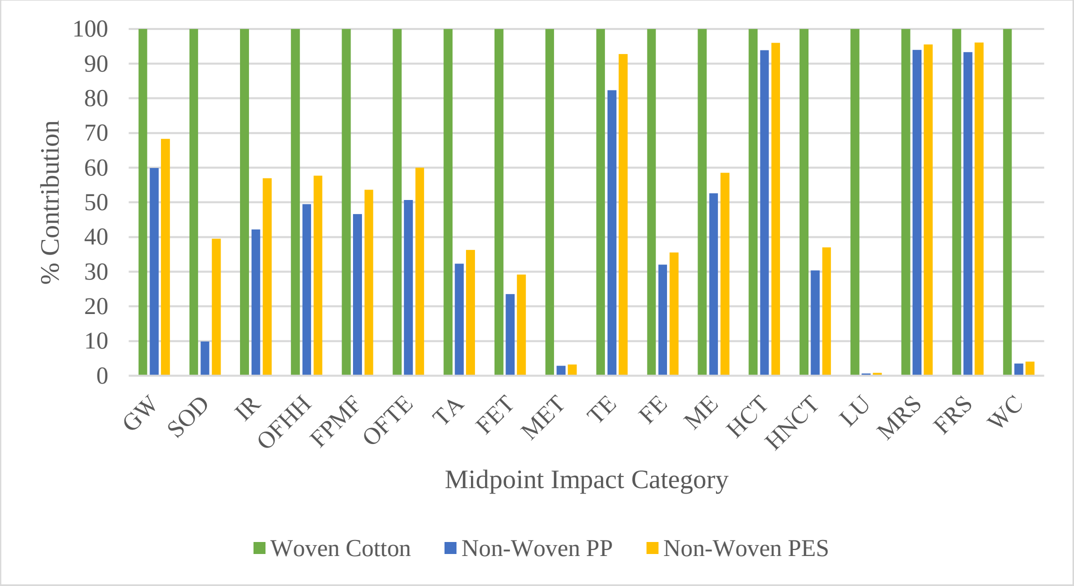


Figure 5.16. Comparative Midpoint Characterization Results Scenario 2

Textile fabric is manufactured using one of three fundamental methods: non-woven, knit, and weave. Weaving, in particular, is known for high energy demand, relying on both energy and compressed air. The energy consumption can vary depending on the type of technology employed. In contrast, non-woven materials typically require lower energy input (Peters et al., 2015). Therefore, non-wovens appear to be more advantageous than woven in all impact categories. The fibers consist of synthetic materials such as PES, polyamide, and elastane, as well as natural materials such as cotton. Since cotton is a raw material from a natural plant harvested from the field, woven cotton fabric is most prominent in the LU impact category.

A study evaluating the life cycle of fabrics discovered that the fabric production stage makes a relatively large contribution to the carbon footprint. This explains the significant environmental difference between woven and non-woven fabrics. Non-woven textiles can be manufactured using staple (spun bond) and filament fibers. The staple fiber non-woven is a completely dry method that does not involve any release of air pollutants, water consumption, or emissions (Roos et al., 2015). The non-woven PP fabric in the Ecoinvent database is constructed using the spun bond method. This explains why non-woven textiles showed little impact compared to woven cotton in the MET and WC categories.

To improve the durability of fabrics, they can be reinforced through the process of resin bonding or needle-punching (Roos et al., 2015) which was the production background of non-woven PES in the database. This additional procedure might be the reason behind the higher impact of PES compared to PP. Overall, it is possible to assert that both non-woven fabrics are much more eco-friendly than woven fabrics. In addition, PP-based material is a better alternative to cotton than PES.

5.2.3 Scenario 3: Reduction in Packaging

In this scenario, the environmental impact of reducing the weight of the packaging materials by 10% was analyzed. First, the material of the corrugated board box was reduced, followed by the PE packaging film, and finally, both the board box and PE film were reduced to present the differences in impact results. In packaging, there is a substantial amount of raw material input considering the product's weight, and minimizing the material used is a standard method used in LCA studies. Figure 5.17 displays the endpoint single score results comparing these three scenarios with the baseline.

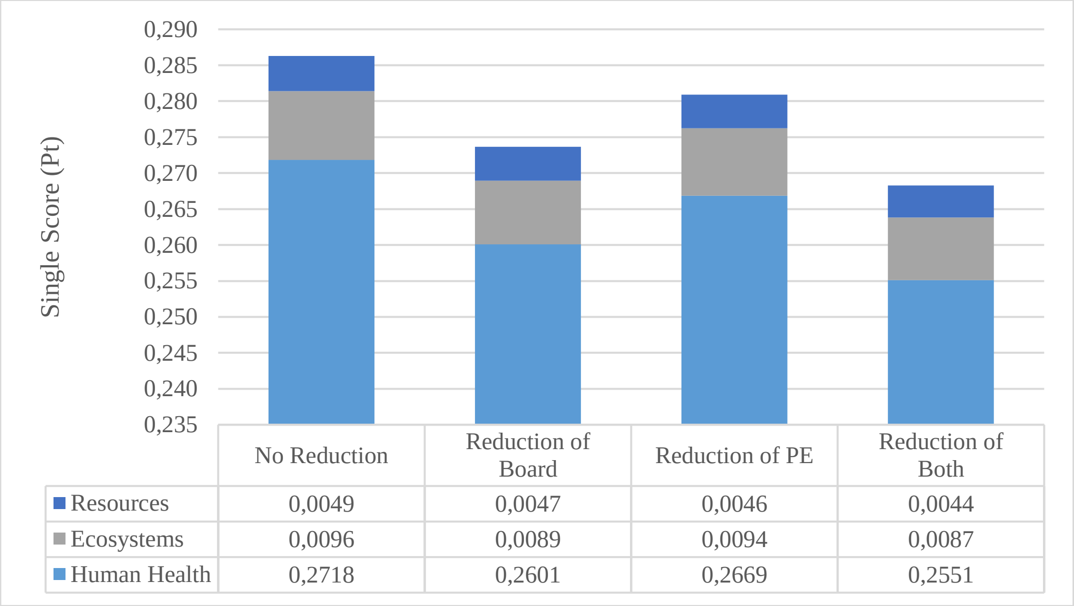


Figure 5.17. Comparative Endpoint Single Score Results of Scenario 3

When the total impact is evaluated, it becomes clear that reducing the board is more effective than reducing the PE. The total single score results were analyzed numerically to reveal the percentage changes in each endpoint impact category. The total single score decrease is close to 4.5% for the board alternative (total Single Score of 0.2737 Pt), while the difference is slightly less than 2% with the change in PE (total Single Score of 0.2809 Pt) when compared to “no reduction” case (total Single Score of 0.2863 Pt). When these two alternatives are combined, and both materials are reduced equally (total Single Score of 0.2682 Pt), the total single score is observed to decrease by more than 6%. To support the single score results presented with numerical differences, Figure 5.18, the damage assessment graph, clearly shows which alternative achieved the most improvement in which impact category.

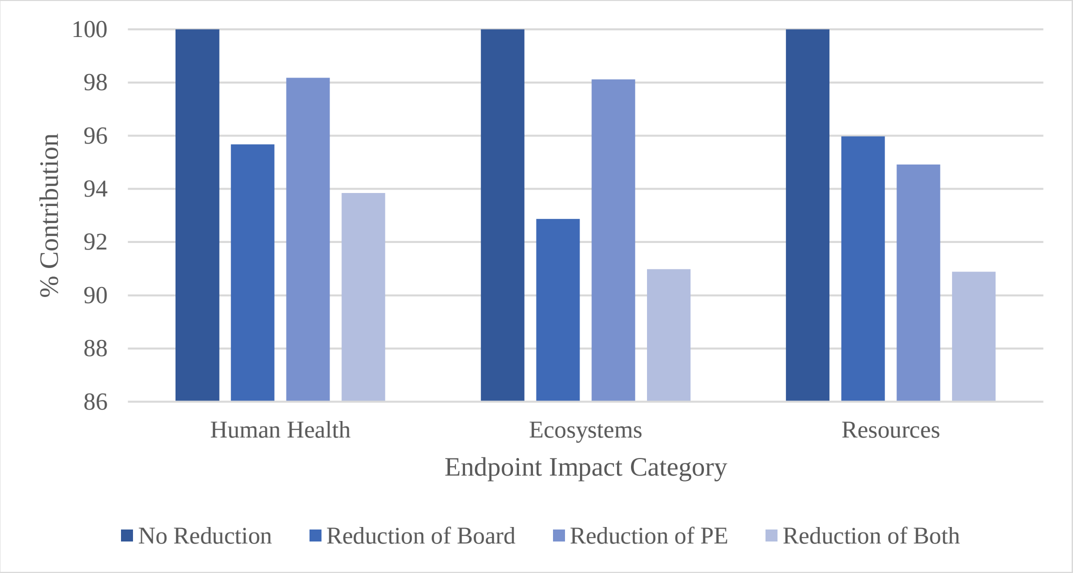


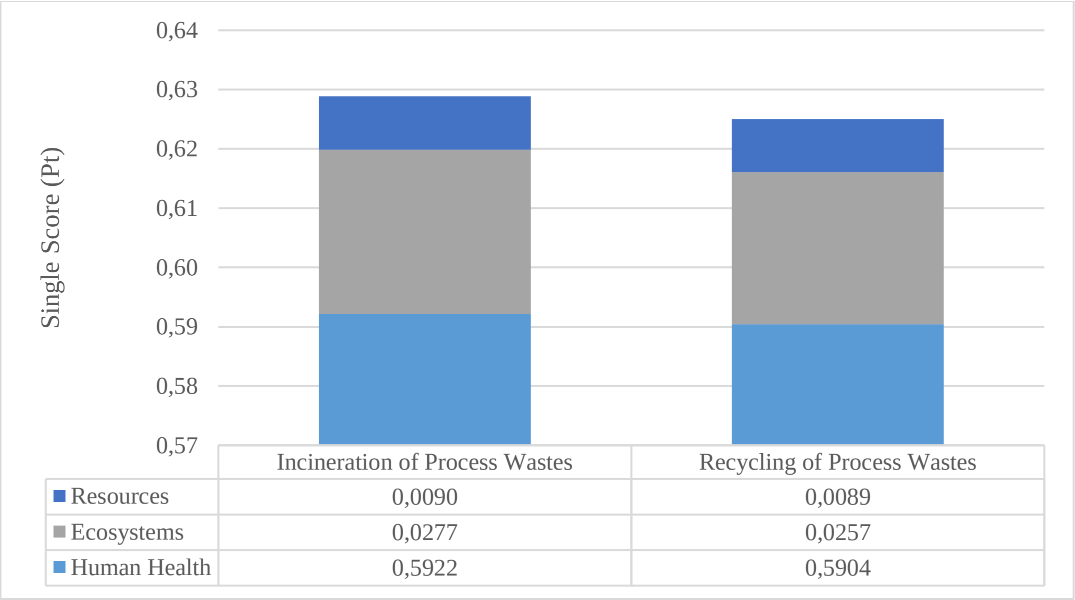
Figure 5.18. Comparative Endpoint Damage Assessment Results of Scenario 3

Although human health is the most impacted category in the packaging process, it is not an impact category where the change is most prominent, with reductions of 4% and 2% in the board and PE scenarios, respectively. More effective on ecosystems is the reduction of board scenario with a 7% change, which corresponds to a rather significant difference compared to a 2% PE reduction. Looking at the resources impact category, compared to the baseline scenario, the reduction in board material made a difference of about 4%. In comparison, the savings in PE packaging led to an improvement of about 5%. To summarize, board reduction mitigates mostly the impacts on ecosystems, while PE reduction contributes more to resource conservation. The cardboard boxes are produced from pulpwood in the Ecoinvent database. Thus, the production process is indirectly related to habitat loss and reduced biodiversity, which explains why reducing cardboard is slightly more impactful on ecosystems. Also, less energy and fossil fuel requirements are required in the production process of PE packaging film, resulting in more emphasis on resources (González-García et al., 2011).

5.2.4 Scenario 4: Recycling of Process Wastes

There are six stages of production processes in total, from the raw materials entering the factory until the final product leaves the factory, and waste is generated in all of them except assembly. These generated wastes will be referred to as process waste. All process waste is assumed to be sent to incineration in the base scenario. The incineration with energy recovery method is selected for chemical wastes, but no option with energy recovery was available for the other wastes in the Ecoinvent. In this scenario, it was investigated whether the environmental impacts would be reduced on a process basis if the process wastes generated were sent for recycling. The waste that can be recycled, i.e., plastic and paper, is generated in the upholstering and packaging processes, and in this scenario, it was tested that all of the waste is handled by recycling.

Upholstering is a process that uses plastic protection parts such as interlining, foam rolls, contour foams, and PUR foam padding material. Packaging predominantly employs corrugated cardboard boxes, and a discernible quantity of waste is generated when customizing these packages to accommodate the product, as estimated by literature sources. Recycling plastic and paper is a common practice in Türkiye. For that reason, in the scenario thought to be quite realistic, all 67 g of waste plastics and 55 g of waste paper were recycled instead of incineration to observe the impacts of different waste management approaches. This recycling scenario yielded the following results, as given in Figure 5.19.



	Incineration of Process Wastes	Recycling of Process Wastes
Resources	0,0090	0,0089
Ecosystems	0,0277	0,0257
Human Health	0,5922	0,5904

Figure 5.19. Comparative Endpoint Single Score Results of Scenario 4

As Figure 5.19 shows, process waste management does not have a considerable share in the environmental impact of upholstering and packaging processes. This can be explained by the fact that process waste is generated in minimal quantities compared to inputs. The furniture industry is typically not associated with significant waste generation, whereas in this case, the production of chairs involves highly optimized processes. For instance, fabrics are cut to the appropriate size and stapled to the chair frame, resulting in minimal waste. Similarly, in the case of plastic upholstering and protection materials, waste from one product can be used in another. Overall, it is clear that recycling is a more environmentally friendly practice than incineration, although the difference between these two waste management practices is relatively minor. Figure 5.20 clearly shows which impact category is affected more when recycling is employed.

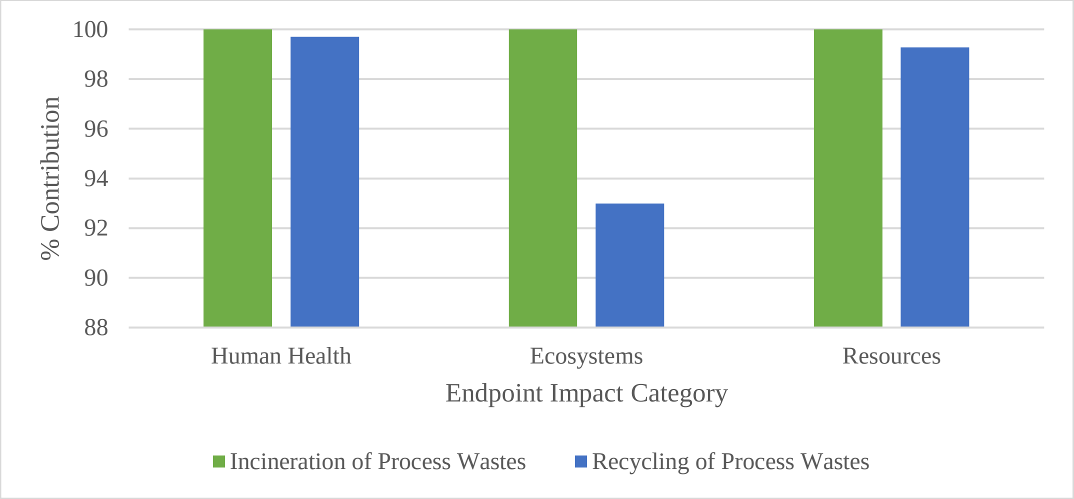


Figure 5.20. Comparative Endpoint Damage Assessment Results of Scenario 4

No noteworthy change is observed between the two practices in terms of resources and human health. The impact on human health decreases by less than 1%, while a slightly better improvement is observed in the resources impact category. Recycling resulted in a 7% decrease in the impact of incineration on the ecosystem, which is where the most noticeable change occurred. Comparative midpoint characterization results of the mentioned processes where two different waste management practices are applied are given in Figure 5.21.

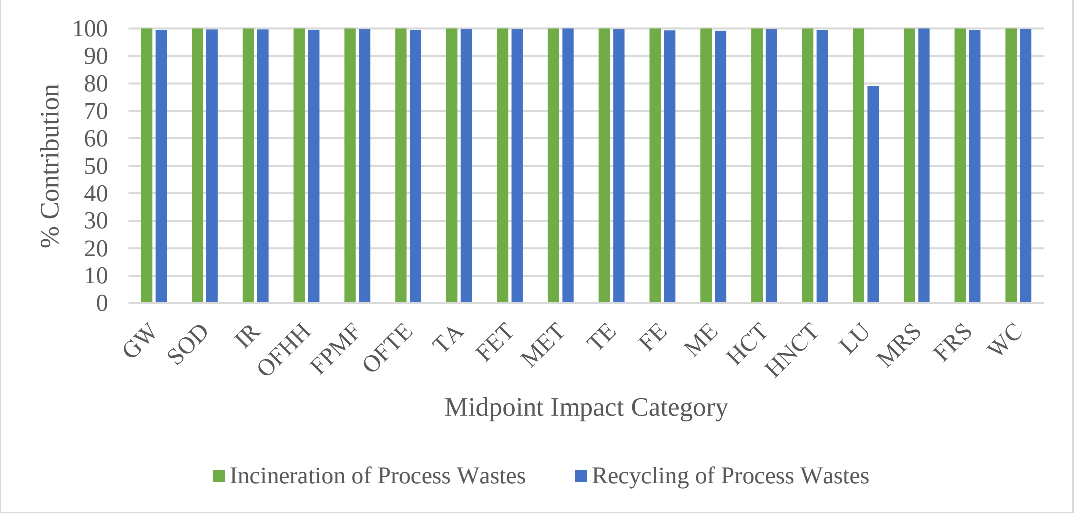
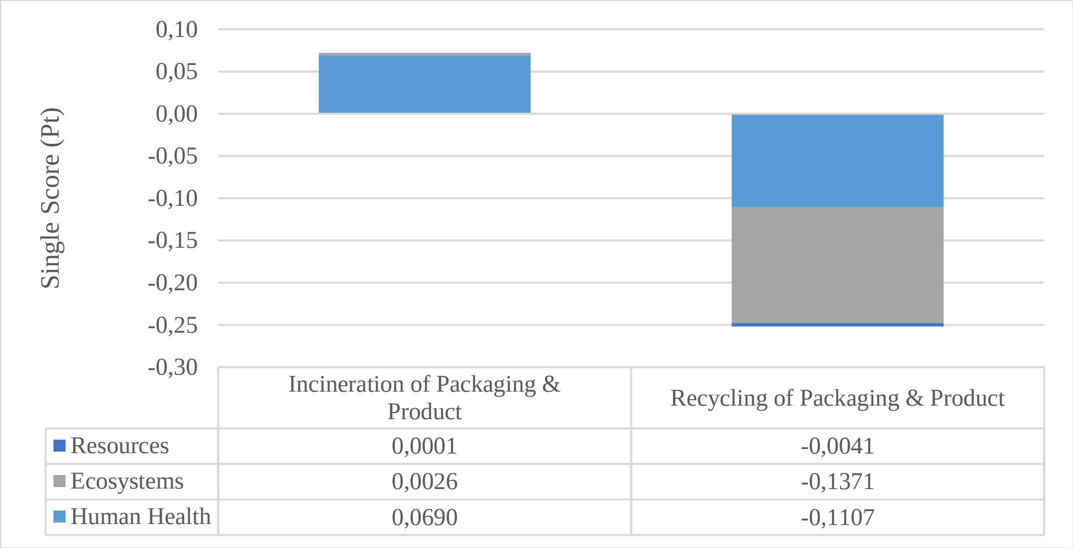


Figure 5.21. Comparative Midpoint Characterization Results of Scenario 4

Since the packaging process generates much more waste than upholstering and the share of waste within all inputs and outputs is high, recycling paper-based packaging waste has made a notable difference in the LU impact category with a reduction of 21%. It is possible to attribute the 7% improvement observed in the ecosystems in Figure 5.20 primarily to recycling waste paperboard, with a further breakdown indicating the decreased impacts in the LU category. Recycling of process waste might not make a substantial difference on a single chair, but it is a slightly better performing method and should be preferred to incineration when considering the waste of the entire factory.

5.2.5 Scenario 5: Recycling of the Packaging and Product

This scenario consists of alternative strategies for handling waste generated during the use and EoL phases. In the baseline scenario, it was assumed that the packaging and wrapping materials in the use phase and the final product in the EoL phase would be disposed of by incineration, like any other waste generated during manufacturing processes. For EoL, the four main materials that make up the final product, i.e., wood, fabric, plastics, and metals, are recycled at the very end of their lifecycle in this scenario, with the quantities remaining the same. The recycling transformation for metals and plastics was retrieved directly from the Ecoinvent database, while open sources were used, and new processes were created as a proxy for wood and textiles due to the absence of these processes in the database. Wood recycling includes the production of particleboard from waste wood with the avoidance of plywood production. It was assumed that the production of cotton fiber and plastics would be avoided for textiles, along with heat and energy recovery (see Table A. 5 for details). The single score results of the use and EoL alternatives are given in Figure 5.22.



	Incineration of Packaging & Product	Recycling of Packaging & Product
■ Resources	0,0001	-0,0041
■ Ecosystems	0,0026	-0,1371
■ Human Health	0,0690	-0,1107

Figure 5.22. Comparative Endpoint Single Score Results of Scenario 5

When the total impacts in Pt are compared in this graph, a more than 450% decrease is observed from recycling (total Single Score of -0.2519 Pt) to incineration (total Single Score of 0.0717 Pt). This significant change provides strong evidence for the superiority of recycling. Although this graph provides two distinct waste management strategies for a range of materials, from metal to plastic, it is evident that the impacts are correlated closely with wood due to its predominance among the other materials in quantity, followed by the cardboard box.

In Figure 5.22, the negative score for the recycling alternative is attributed to the new product produced through material recovery, which in this system refers to particleboard since it has much less impact than the avoided product, plywood. In other words, recycling gives a negative score as the use of waste wood replaces the production of a new wooden product from virgin timber. One of the striking points in the graph is that incineration significantly affects human health damage impact, whereas recycling markedly mitigates these impacts. It is also worth noting that recycling drastically reduces the potential impact on ecosystems. Figure 5.23 illustrates the normalization comparison of the use and EoL scenarios.

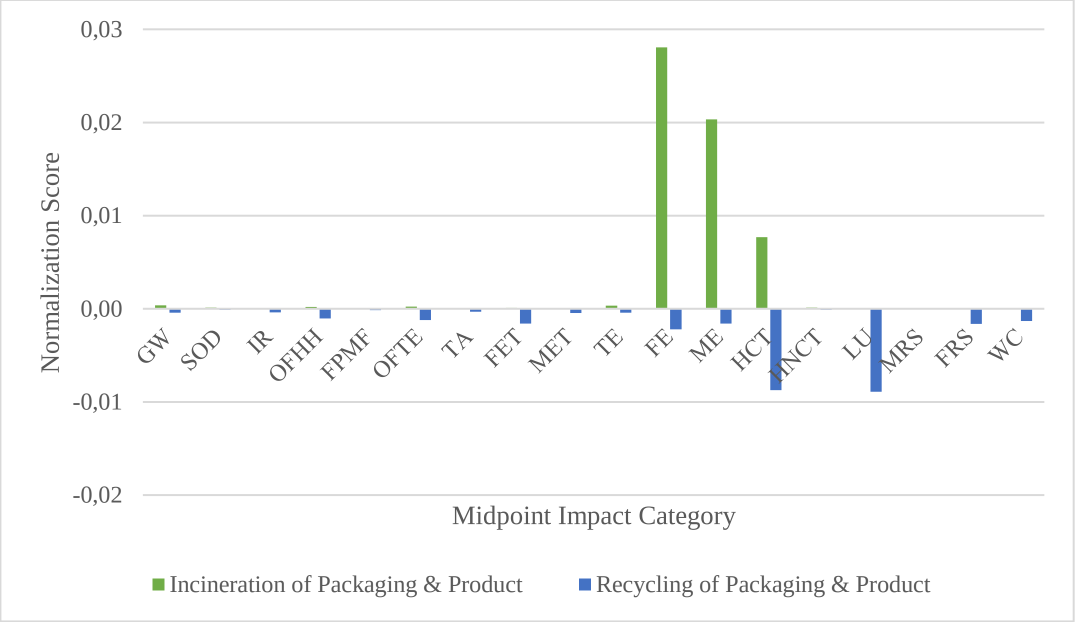


Figure 5.23. Comparative Midpoint Normalization Results of Scenario 5

This graph implies that the environmental impact of incineration of packaging and final products is equivalent to the FE impact caused by 0.028 persons per year, or 2.8% of the FE impact caused by an average person in a year on a world level. The midpoint impact categories where incineration had the greatest impact were FE, followed by ME and HCT. Potential impacts in the HCT and LU categories are notably avoided when recycling is employed.

These results are in line with the study of Farjana et al. (2023) comparing EoL scenarios for engineered wood products, MDF, and particleboard since material recovery turned out to be the most favorable method among energy recovery and landfill for most of the impact categories in ReCiPe. Toxicity results were highest in energy recovery for MDF, as obtained in Figure 5.23, while a different profile was obtained in particleboard, so it would not be accurate to compare different engineered woods directly. In addition, this study does not include energy recovery in the database for all incineration processes. However, it is possible to argue that recycling stands out overall.

Furthermore, in textile mechanical recycling, environmental benefits outweigh impacts in most impact categories in the study of Duhoux et al. (2021). In particular, avoided cotton fibers and avoided non-woven materials dominate the recycling process, replacing potential environmental impacts, resulting in a total profile below 0, which is in line with Figure 5.22 and Figure 5.23.

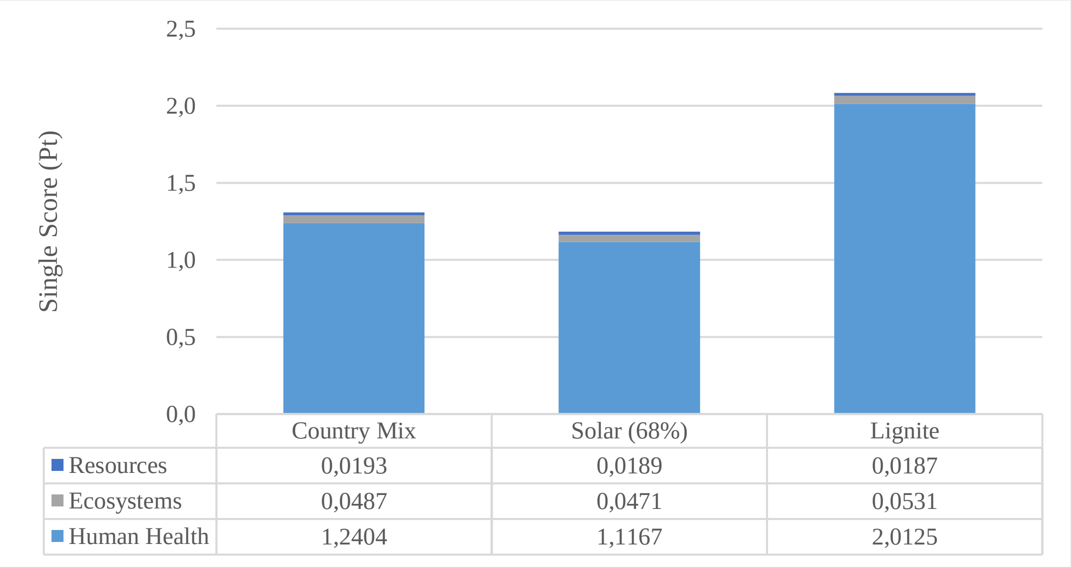
5.2.6 Scenario 6: Switching the Electricity Source

Manufacturing and packaging processes all have electrical input, which is assumed to be high-voltage electricity in the Turkish country mix. Türkiye-specific electricity country mix in the Ecoinvent dataset was created using information from 2017. In 2017, the breakdown of Türkiye's electricity generation by source shows that natural gas ranked first with a share of 37%. Following this, the other energy sources with the largest share in generation are imported coal, hydroelectric power plants with dams, and lignite (TEİAŞ, 2017). Although the share of renewable resources in production is much higher today, the country mix in Ecoinvent was preferred, despite being outdated, as it is the most comprehensive data set and in line with other inputs and outputs of the study.

In 2023, the transition period of the Carbon Border Adjustment Mechanism, which aims to reduce carbon emissions from EU imports, started, and electricity was classified as a high carbon emitting sector. Consequently, many large companies with high electricity consumption have begun to cover their self-consumption with unlicensed SPPs in order to avoid being subject to carbon tax (PwC, 2024).

In addition to becoming increasingly necessary, renewable energy investments have also been highly supported by the government in Türkiye recently. For instance, unlicensed rooftop SPPs have been included in regional incentives under the Decree on State Aids in Investments issued by the Ministry of Industry and Technology. These and similar developments push factories to invest in rooftop SPPs.

It was already mentioned that the company had a rooftop SPP investment. In line with the information received recently, the rooftop SPP installation was completed, and according to the data for 2024, it was producing enough to meet 68% of the total electricity required by the facility. For this reason, the first alternative of Scenario 6 is designed to substitute 68% of the electricity taken from the national grid with solar energy. As mentioned before, since the country mix includes many different energy sources, a second alternative is also included in which electricity from lignite, which is the most widely used fossil fuel type in Türkiye today, meets the entire need in order to see how much benefit the base and solar scenarios provide compared to electricity generated entirely from fossil fuels. These three scenarios of electricity source are compared in terms of endpoint single score in Figure 5.24.



	Country Mix	Solar (68%)	Lignite
■ Resources	0,0193	0,0189	0,0187
■ Ecosystems	0,0487	0,0471	0,0531
■ Human Health	1,2404	1,1167	2,0125

Figure 5.24. Comparative Endpoint Single Score Results of Scenario 6

The alternatives of electricity consumption by source vary in all endpoint impact categories. What they all have in common is that the highest impact is on the human health category. Compared to lignite, the baseline scenario reveals that the current situation is not pessimistic regarding energy sources and has even improved with the increasing installed capacity of renewable energy since 2017. Keeping the energy utilization from solar energy at 68% has undoubtedly limited the reduction of environmental impacts in the base-case. Nevertheless, compared to the baseline scenario (total Single Score of 1.3084 Pt), the total reduction in environmental impacts in the solar scenario (total Single Score of 1.1827 Pt) is not ignorable, around 7%. Compared to the alternative where all electricity is provided from fossil fuels, lignite (total Single Score of 2.0843 Pt), a decrease of 37% in the country mix and 42% in the solar scenario is observed. It can be seen in Figure 5.25 which categories achieved the most decrease in environmental impacts.

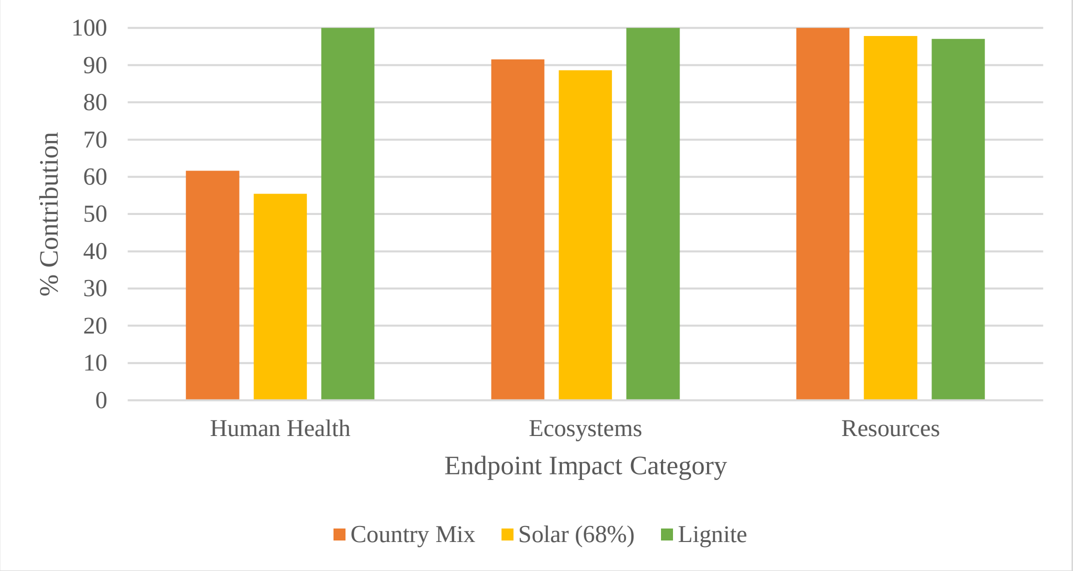


Figure 5.25. Comparative Endpoint Damage Assessment Results of Scenario 6

In this chart, the impact of the processes in which lignite is used in the human health category is fixed at 100%, while the relative rates of the reduced impact in the other two alternatives are given. When evaluating the percentage difference, it is compatible with the decrease rates in total impact interpreted from Figure 5.24. Although its overall impact is low, there is a considerable improvement in ecosystems compared to lignite. Here, both country mix and solar scenarios emerge as better alternatives with a difference of about 10%. It should be noted that the highest impact in the resources endpoint impact category is in the country mix scenario, even though there is no significant difference. This can be attributed to the fact that the same amount of electricity is sourced from diverse sources rather than a single source. The country mix consists of various energy production sources, ranging from imported coal to liquid fuels, from wind to geothermal energy. Understandably, this variety would have a greater impact on resources than a single type of lignite coal. In Figure 5.26, the midpoint impact categories are evaluated comparatively.

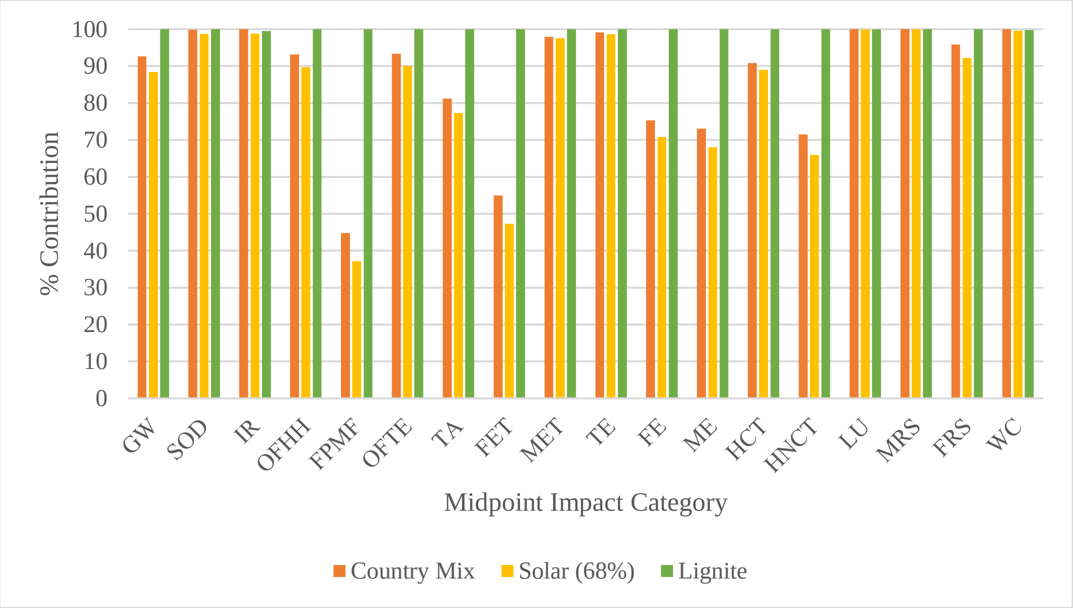


Figure 5.26. Comparative Midpoint Characterization Results of Scenario 6

It is seen that country mix and solar alternatives stand out at different levels in different impact categories. In the LCA and DfE study of the wooden childhood furniture set, González-García et al. (2012) found that two processes have an important role in manufacturing: the production of wooden panels and electricity consumption. One suggested strategy is to use 50% renewable energy, namely solar. The most significant decreases were seen in air pollutants like sulfur dioxide, nitrogen oxides, beryllium, and vanadium, resulting in notable reductions in acidification, freshwater aquatic ecotoxicity, and marine aquatic ecotoxicity.

Similarly, this study shows that solar energy has a lower impact than country mix and 100% fossil fuel in the TA, FE, and ME impact categories. In the ReCiPe method, substantial differences are observed mainly in the FPMF, FET, and HNCT categories. One significant cause of FPMF during energy production from lignite is the combustion of coal, which releases various pollutants, including particulate matter, into the atmosphere. Harmful substances released into the atmosphere during lignite burning can further cause air pollution and respiratory diseases, which explains why renewable energy plays a critical role in the HNCT category.

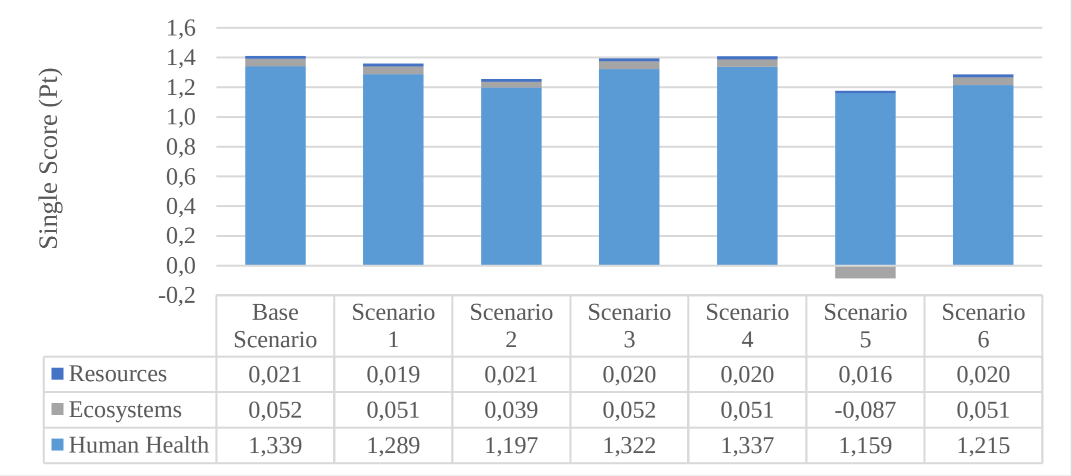
5.3 Comparison of Scenarios

In this LCA study of a chair product, six scenarios were built to maximize the reduction of environmental impacts associated with chair production while considering realistic alternatives. A comparative analysis was conducted among these scenarios to understand their effectiveness. In this context, the alternative that gives the best result in the scenarios was inputted to represent the relevant scenario. At the same time, to accurately compare the scenarios, the proposed alternatives were integrated across the entire life cycle, not just the processes they affect. Table 5.2 shows the preferred alternative in each scenario.

Table 5.2. Selected Alternatives in Each Scenario for Comparison

Scenario	**Selected Alternative**
Scenario 1	MUF resin
Scenario 2	Non-woven PP
Scenario 3	Reduction of both board box & PE film
Scenario 4	Recycling of process wastes
Scenario 5	Recycling of the packaging & product
Scenario 6	68% solar

Accordingly, the chair's whole life cycle is compared using six different scenarios, and the results of the following endpoint single score are presented in Figure 5.27.



	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
■ Resources	0,021	0,019	0,021	0,020	0,020	0,016	0,020
■ Ecosystems	0,052	0,051	0,039	0,052	0,051	-0,087	0,051
■ Human Health	1,339	1,289	1,197	1,322	1,337	1,159	1,215

Figure 5.27. Comparative Endpoint Single Score Results of All Scenarios

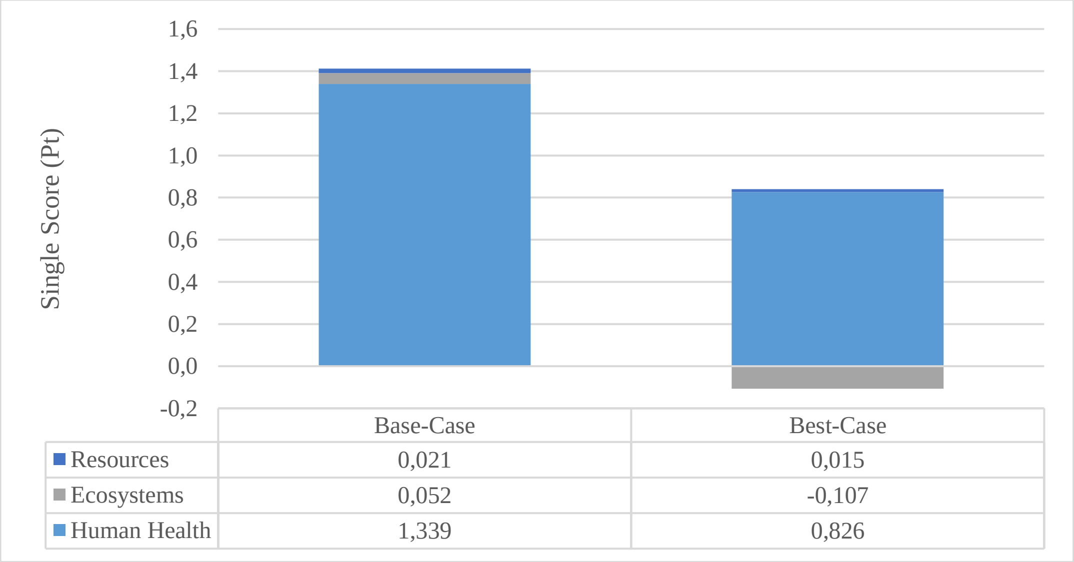
The alternatives to the use and EoL processes, which had a very low impact compared to the entire manufacturing process in the baseline scenario, minimized the life cycle impacts in Scenario 5 most with a Pt of 1.088 among the other scenarios. The life cycle essentially consists of nine stages and Scenario 5 includes 2 of these stages where all outputs are handled by recycling. This means that all the wood, metal, plastic, and fabric materials that made up the chair parts in the preceding processes were transformed into different products and substituted for new products to be produced. This substantially reduces environmental impact, making the recycling of packaging and final product waste the most promising potential improvement.

Following this, Scenario 2 stands out as the one where the most reduction is achieved in areas of damage, both in terms of human health and total impact. This is a significant and reassuring result, given the large difference between woven and non-woven fabrics in terms of process and resource consumption. Scenario 6, which yields results very close to Scenario 2, underscores the importance of the energy source. While it's true that not all electricity is currently provided by solar, and some portion is still taken from the grid, this also means there's still significant potential for improvement in this scenario.

A highly expected result is that Scenario 4 showed the highest impact scores. The low quantities of process wastes resulted in a change in waste management strategy, yielding an insignificant difference when the whole life cycle is analyzed.

5.4 Comparison of Base and Best-Case Scenarios

To determine the extent to which the environmental impacts of the baseline scenario can be reduced through realistic applications, a best-case scenario was created by integrating all alternatives that provided better results throughout the life cycle. The single score results of this scenario, together with the base-case, are shown in Figure 5.28.



	Base-Case	Best-Case
■ Resources	0,021	0,015
■ Ecosystems	0,052	-0,107
■ Human Health	1,339	0,826

Figure 5.28. Comparative Endpoint Single Score Results of the Best-Case

It has already been mentioned that the life cycle of the chair has the most damaging impact on human health. There is a 38% improvement in impacts in this impact category. The impact on ecosystems drops below zero due to avoided products with the adoption of recycling and is lower by more than 300% compared to the baseline scenario. In terms of resources, a 29% reduction is achieved. Based on the total impact, the best-case scenario (total Single Score of 0.734 Pt) turns out to be 48% greener than the baseline (total Single Score of 1.412 Pt). It can be interpreted from the single score results that, in the base-case, the production and use impact of a chair is comparable to the annual impact of 1.41 average persons worldwide, while in the best-case, this equivalent impact reduces to 0.73 persons. Figure 5.29 displays the percentage impact of the related scenario compared to the dominating scenario in the midpoint impact categories.

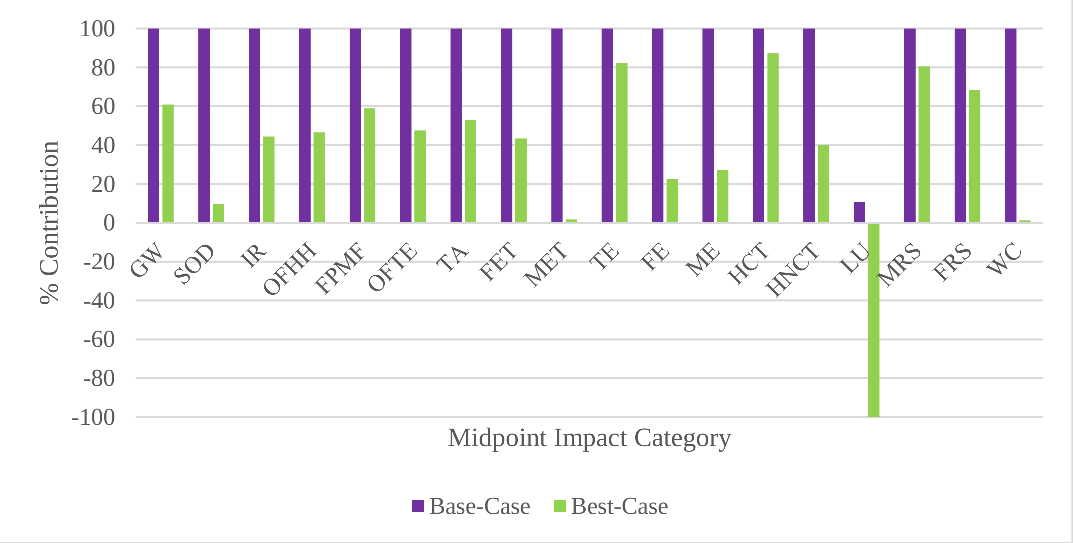


Figure 5.29. Comparative Midpoint Characterization Results of the Best-Case

For all categories except LU, a comparison of the best-case scenario with respect to the baseline scenario is given. In the LU impact category, the use of wood in the best-case is optimized in such a way that the contribution of the base-case is calculated based on the best-case result fixed at -100%. Subsequently, serious reductions are also achieved in the SOD, MET, and WC categories. The change in fabric seems to be particularly effective here. The categories that did not exhibit much decrease in impact were TE, HCT, and MRS. This is an anticipated result, considering no alternative scenario studies were conducted for metal and plastics.

CHAPTER 6

CONCLUSIONS

This thesis investigated the environmental impacts of a dining chair through an LCA methodology. The LCIA was conducted using SimaPro 9.2.0.2 software, employing the ReCiPe 2016 methodology at both midpoint and endpoint levels from a Hierarchist perspective. To explore potential improvements and reduce life cycle impacts, six scenarios were developed based on key parameters such as material selection, material quantity, waste management, and electricity source. These scenarios were then compared to identify the most effective alternative.

Results showed that most of the cumulative environmental impacts of the chair throughout its life cycle derive from the manufacturing phase. This is followed by the packaging of the disassembled final product. Additionally, the human health impact category was found to be the most affected endpoint impact category for all stages throughout the life cycle. When the breakdown of manufacturing processes was evaluated, it was discovered that veneer joining and upholstering stages were the main contributors to the impacts on manufacturing. These stages were further examined to pinpoint the hotspots of each process so that alternatives could be suggested.

The midpoint characterization results of the veneer joining process revealed that the UF resin is the primary environmental hotspot. When alternatives to UF resin were investigated, MUF resin proved more environmentally preferable than both UF and PF resins. Furthermore, PF resin had a higher overall environmental impact than UF resin. In the midpoint impact category of LU, MUF resin showed a 30% reduction in impact compared to UF resin.

For the upholstering process, the environmental hotspot was identified as the woven fabric. A comprehensive assessment of the three fabrics revealed that non-woven fabrics are more environmentally friendly and have fewer adverse effects on human health than woven cotton fabric. Specifically, using non-woven PP as a substitute for woven cotton fabric results in a substantial 45% reduction in total single score of upholstering process. Similarly, the adoption of non-woven PES leads to a significant 39% reduction in total impacts. These findings highlight the great environmental benefits of non-woven fabrics.

Also, further analysis of the packaging revealed that most of the environmental impacts stem from using corrugated board boxes. The environmental impact of reducing the weight of packaging materials (PE and board) by 10% was analyzed. Reducing the board proved more effective than reducing the weight of the PE. In the human health category, which is the most affected endpoint impact category in the packaging process, 4% and 2% improvements were achieved in the board and PE scenarios, respectively.

When the disposal alternatives of incineration and recycling were compared, sending process wastes for recycling, as opposed to incineration, resulted in minimal environmental impact on the upholstering and packaging processes due to the small quantities of waste generated. Recycling led to a 7% reduction in the impact of incineration on the ecosystem, marking the most significant change observed. Conversely, the comparative results of shifting from incineration to recycling for packaging and final product waste were quite substantial, indicating a more than 450% decrease in environmental impacts. This significant change arose as all materials used in manufacturing and packaging were disposed of differently than in the baseline case, and these materials were present in vast quantities. The impacts were closely correlated with the disposal of wood, the predominant material in quantity, followed by the cardboard box.

A comparison among different electricity generation sources used during manufacturing and packaging revealed that the current country mix, which includes a significant share of renewables, is considerably more environmentally friendly than the lignite alternative, as expected. Compared to the current country electricity mix, the use of solar energy was found to provide a notable 7% reduction in total environmental impacts. Additionally, when all electricity is sourced from fossil fuels, a reduction of 37% is observed in the country mix and 42% in solar energy, demonstrating the great environmental advantage of these alternatives.

A comparison of the scenarios revealed that the use & EoL alternative achieved the greatest reduction in life cycle impacts, making the recycling of packaging and final product waste the most promising improvement. Following this, the replacement of the fabric showed significant reductions in both human health and total impact due to the substantial difference in process and resource consumption between woven and non-woven fabrics.

Finally, the highest achievable reduction in environmental impacts was analyzed by integrating all alternatives that provided better results throughout the life cycle. Modifications to current practices can reduce the environmental impacts of a chair product by up to 48%. This proves the prominent improvement potential of the furniture industry.

CHAPTER 7

RECOMMENDATIONS

The following recommendations are presented according to the results of this thesis for the players of the furniture industry that want to improve their production with an environmental perspective, future literature studies, and all kinds of research to be conducted on this subject:

- Instead of utilizing UF resin, which is now considered outdated technology, manufacturers are advised to adopt MUF resin, a more environmentally friendly alternative. To facilitate the widespread use of bio-based adhesives, which are still under research and development, it is recommended that the volume of literature studies on this topic be enhanced. Also, fabric selection should be made by prioritizing environmental impacts as well as the comfort of use, durability, and aesthetics. The use of non-woven fabrics in different products should be diversified. Another proposal is to minimize the use of materials in packaging as much as possible and, if feasible, to replace the PE materials used for protective wrap inside cardboard boxes with recycled paper, which can achieve the same function in packaging. Furthermore, it is essential that all materials used in furniture production, especially wood, are sourced from those with sustainable certificates.
- It is recommended that factories with available space and high electricity generation potential include rooftop SPP installation in their prioritized investment plans.
- Although logistics appear to have minimal environmental impact on the results, the transportation of all products leaving the factory is estimated to have a significant effect. A separate study could be conducted to explore this further. At this stage, it is essential to advocate for governmental policies that reduce freight shipping activities and promote rail transportation, especially within the country.

- To design products in accordance with DfE principles, existing LCA studies should be utilized and, where possible, new studies should be conducted with real data for key product groups within the company. However, open-source databases like Ecoinvent may not include data specific to the country where the study is conducted. Furthermore, not all data in the database are regularly updated. Hence, a comprehensive study of LCA databases is needed to provide country-specific, up-to-date data.
- This study demonstrated that a well-known and internationally recognized company can provide comprehensive, high-quality data. However, small-scale companies often lack well-documented information on their production models and processes. This issue can be addressed through government regulations mandating companies' detailed data storage and encouraging customers to prefer companies that offer transparent product information. Such measures will enhance the quality of future LCA studies.

REFERENCES

Aho, J., Järvinen, K., Saari, P., Horváth, M., Leino, K., Kontiokari, V., Joelsson, A., Asker, A., Eklöv, I., Lindqvist, K., Collin, C., Hald, J., & Sjöstrand, C. K. (2022). LCA for treatment of wood waste in the Nordics. https://doi.org/10.6027/temanord2022-539

Ali, F., Rehman, F., Hadi, R., Raza, G., Khan, N., Ibrahim, F., Aziz, F., Amin, M., Khalil, B., Mahwish, M., Bashir, S., Ali, A., & Hussain, M. (2024). Environmental sustainability assessment of wooden furniture produced in Pakistan. Brazilian Journal of Biology, 84. https://doi.org/10.1590/1519-6984.253107

Azapagic, A. (1999). Life cycle assessment and its application to process selection, design and optimisation. Chemical Engineering Journal 73, 1–21.

Bauer, B., Watson, D., Gylling, A., Remmen, A., Lysemose, M. H., Hohenthal, C., & Jönbrink, A.-K. (2018). Potential Ecodesign Requirements for Textiles and Furniture (TemaNord). Nordic Council of Ministers. https://doi.org/10.6027/TN2018-535

Bianco, I., Thiébat, F., Carbonaro, C., Pagliolico, S., Blengini, G. A., & Comino, E. (2021). Life Cycle Assessment (LCA)-based tools for the eco-design of wooden furniture. Journal of Cleaner Production, 324. https://doi.org/10.1016/j.jclepro.2021.129249

Bovea, M. D., & Vidal, R. (2004). Materials selection for sustainable product design: A case study of wood based furniture eco-design. Materials and Design, 25(2), 111–116. https://doi.org/10.1016/j.matdes.2003.09.018

Brusseau, M. L. (2019). Sustainable Development and Other Solutions to Pollution and Global Change. In Environmental and Pollution Science (pp. 585–603). Elsevier. https://doi.org/10.1016/b978-0-12-814719-1.00032-x

Carollo, F. (2022). Banca Dati Italiana LCA. Process Data Set: Wood, Recycling. https://bancadatiitalianalca.enea.it/Node/datasetdetail/process.xhtml?lang=en&uuid=771817eb-e58d-453e-9f4b-2da07e5ca071&version=01.00.000

Çınar, H. (2005). Eco-design and furniture: Environmental impacts of wood-based panels, surface and edge finishes. Forest Products Journal, 55(11), 27–33. https://www.researchgate.net/publication/286615732

Csanády, E., Kovács, Z., Magoss, E., & Ratnasingam, J. (2019). Furniture Production Processes: Theory to Practice. In Optimum Design and Manufacture of Wood Products (pp. 367–421). Springer International Publishing. https://doi.org/10.1007/978-3-030-16688-5_5

Curran, M. A. (2016). Life Cycle Assessment. In Kirk-Othmer Encyclopedia of Chemical Technology (pp. 1–28). Wiley. https://doi.org/10.1002/0471238961.lifeguin.a01.pub2

Demirdelen, T., Aksu, İ. Ö., Yilmaz, K., Koç, D. D., Arikan, M., & Şener, A. (2023). Investigation of the Carbon Footprint of the Textile Industry: PES- and PP-Based Products with Monte Carlo Uncertainty Analysis. Sustainability (Switzerland), 15(19). https://doi.org/10.3390/su151914237

Dimoula, V., Kehagia, F., & Tsakalidis, A. (2016). A holistic approach for estimating carbon emissions of road and rail transport systems. Aerosol and Air Quality Research, 16(1), 61–68. https://doi.org/10.4209/aaqr.2015.05.0313

Donatello, S., Moons, H., & Wolf, O. (2017). Revision of EU Ecolabel criteria for furniture products. Final Technical Report. In Final Technical Report. https://doi.org/10.2760/59027

Duhoux, T., Maes, E., Hirschnitz-Garbers, M., Peeters, K., Asscherickx, L., Christis, M., Stubbe, B., Colignon, P., Hinzmann, M., & Sachdeva, A. (2021). Study on the technical, regulatory, economic and environmental effectiveness of textile fibres recycling. Final Report.

European Commission. (n.d.). About the EU Ecolabel. Retrieved June 30, 2024, from https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel/about-eu-ecolabel_en

European Commission. (2024). Ecodesign for Sustainable Products Regulation. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en

Farjana, S. H., Tokede, O., Tao, Z., & Ashraf, M. (2023). Life cycle assessment of end-of-life engineered wood. Science of the Total Environment, 887. https://doi.org/10.1016/j.scitotenv.2023.164018

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. Journal of Environmental Management, 91(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Finnveden, G., & Potting, J. (2014). Life Cycle Assessment. In Encyclopedia of Toxicology: Third Edition (pp. 74–77). Elsevier. https://doi.org/10.1016/B978-0-12-386454-3.00627-8

Forest Stewardship Council. (2023). FSC Principles and Criteria for Forest Stewardship.

Gamage, G. B., & Boyle, C. (2006). Developing the Use of Environmental Impact Assessment in Commercial Organisations: A Case Study of Formway

Furniture. 13th CIRP International Conference on Life Cycle Engineering, 119–124.

González-García, S., Gasol, C. M., Lozano, R. G., Moreira, M. T., Gabarrell, X., Rieradevall i Pons, J., & Feijoo, G. (2011). Assessing the global warming potential of wooden products from the furniture sector to improve their ecodesign. Science of the Total Environment, 410–411, 16–25. https://doi.org/10.1016/j.scitotenv.2011.09.059

González-García, S., Lozanol, R. G., Estévez, J. C., Pascual, R. C., Moreira, M. T., Gabarrell, X., Pons, J. R., & Feijoo, G. (2012). Environmental assessment and improvement alternatives of a ventilated wooden wall from LCA and DfE perspective. In International Journal of Life Cycle Assessment (Vol. 17, Issue 4, pp. 432–443). https://doi.org/10.1007/s11367-012-0384-0

Grand View Research. (2022). Eco-friendly Furniture Market Size, Share & Trends Analysis Report By Application (Residential, Commercial), By Distribution Channel (Offline, Online), By Region, And Segment Forecasts, 2023 - 2030. https://www.grandviewresearch.com/industry-analysis/eco-friendly-furniture-market#

Gültekin, A. B., & Çelebi, G. (2016). Yaşam Döngüsü Değerlendirme Yöntemi Kapsamında Yapı Ürünlerinin Çevresel Etkilerinin Değerlendirilmesine Yönelik Bir Model Önerisi. Düzce Üniversitesi Bilim ve Teknoloji Dergisi, 3, 1–36.

Güneş, S., & Demirarslan, D. (2020). Sürdürülebilirlik ve Mobilya Tasarımında Çevreci Yaklaşımlar. Uluslararası İnsan ve Sanat Araştırmaları Dergisi, 5(6), 81–99.

Hartini, S., Wicaksono, P. A., Prastawa, H., Hadyan, A. F., & Sriyanto. (2019). The Environmental Impact Assessment of Furniture Production Process Using the Life Cycle Assessment. IOP Conference Series: Materials Science and Engineering, 598(1). https://doi.org/10.1088/1757-899X/598/1/012078

Hauschild, M., Jeswiet, J., & Alting, L. (2005). From Life Cycle Assessment to Sustainable Production: Status and Perspectives. CIRP Annals, 54(2), 1–21. https://doi.org/10.1016/S0007-8506(07)60017-1

Hellweg, S., & Milà Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. Science, 344(6188), 1109–1113. https://doi.org/10.1126/science.1248361

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Hollander, A., Zijp, M., & van Zelm, R. (2017). ReCiPe 2016 v1.1. A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. www.rivm.nl/en

Iritani, D. R., Silva, D. A. L., Saavedra, Y. M. B., Grael, P. F. F., & Ometto, A. R. (2015). Sustainable strategies analysis through Life Cycle Assessment: A case study in a furniture industry. Journal of Cleaner Production, 96, 308–318. https://doi.org/10.1016/j.jclepro.2014.05.029

ISO. (2006). Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006).

Jolliet, O., Saadé-Sbeih, M., Shaked, S., Jolliet, A., & Crettaz, P. (2016). Environmental Life Cycle Assessment. CRC Press.

Keoleian, G. A., & Spitzley, D. V. (2006). Life Cycle Based Sustainability Metrics. In M. A. Abraham (Ed.), Sustainability Science and Engineering: Defining principles (pp. 127–159). Elsevier B.V. https://doi.org/10.1016/S1871-2711(05)01007-X

Koridze, N. (2022). World Furniture Industry. Journal of Social Research and Behavioral Sciences, 8(15), 198–207. https://doi.org/10.52096/jsrbs.8.15.14

Lee, K.-M., & Inaba, A. (2004). Life Cycle Assessment. Best Practices of ISO 14040 Series.

Linkosalmi, L., Husgafvel, R., Fomkin, A., Junnikkala, H., Witikkala, T., Kairi, M., & Dahl, O. (2016). Main factors influencing greenhouse gas emissions of wood-based furniture industry in Finland. Journal of Cleaner Production, 113, 596–605. https://doi.org/10.1016/j.jclepro.2015.11.091

Llorach-Massana, P., Farreny, R., & Oliver-Solà, J. (2015). Are Cradle to Cradle certified products environmentally preferable? Analysis from an LCA approach. Journal of Cleaner Production, 93, 243–250. https://doi.org/10.1016/j.jclepro.2015.01.032

Maceno, M. M. C., João, S., Voltolini, D. R., & Zattar, I. C. (2023). Life cycle assessment and circularity evaluation of the non-medical masks in the Covid-19 pandemic: a Brazilian case. Environment, Development and Sustainability, 25(8), 8055–8082. https://doi.org/10.1007/s10668-022-02388-2

Martínez-Rocamora, A., Solís-Guzmán, J., & Marrero, M. (2016). LCA databases focused on construction materials: A review. In Renewable and Sustainable Energy Reviews (Vol. 58, pp. 565–573). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.12.243

Medeiros, D. L., Tavares, A. O. do C., Rapôso, Á. L. Q. R. e. S., & Kiperstok, A. (2017). Life cycle assessment in the furniture industry: the case study of an office cabinet. International Journal of Life Cycle Assessment, 22(11), 1823–1836. https://doi.org/10.1007/s11367-017-1370-3

Mermertas, M., Ozsoy, K., Gloria, T. P., & Germirli Babuna, F. (2018). Environmental Sustainability of a Sofa. Eurasia 2018 Waste Management Symposium, 654–660. https://www.researchgate.net/publication/325403020

Ministry of Economy. (2018). Wood and Forestry Products Industry in Turkey.

Mirabella, N., Castellani, V., & Sala, S. (2014). LCA for assessing environmental benefit of eco-design strategies and forest wood short supply chain: A furniture case study. International Journal of Life Cycle Assessment, 19(8), 1536–1550. https://doi.org/10.1007/s11367-014-0757-7

Morris, M., & Dunne, N. (2004). Driving environmental certification: Its impact on the furniture and timber products value chain in South Africa. Geoforum, 35(2), 251–266. https://doi.org/10.1016/j.geoforum.2003.09.006

Navajas, A., Uriarte, L., & Gandía, L. M. (2017). Application of eco-design and life cycle assessment standards for environmental impact reduction of an industrial product. Sustainability (Switzerland), 9(10). https://doi.org/10.3390/su9101724

Pang, B., Li, M. K., Yang, S., Yuan, T. Q., Du, G. Ben, & Sun, R. C. (2018). Eco-Friendly Phenol-Urea-Formaldehyde Co-condensed Resin Adhesives Accelerated by Resorcinol for Plywood Manufacturing. ACS Omega, 3(8), 8521–8528. https://doi.org/10.1021/acsomega.8b01286

Peters, G., Svanström, M., Roos, S., Sandin, G., & Zamani, B. (2015). Carbon footprints in the textile industry. In Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing (pp. 3–30). Elsevier Inc. https://doi.org/10.1016/B978-0-08-100169-1.00001-0

Prak, A. L., & Myers, T. W. (1981). Furniture Manufacturing Processes (Third). North Carolina State University.

Pražanová, A., Knap, V., & Stroe, D. I. (2022). Literature Review, Recycling of Lithium-Ion Batteries from Electric Vehicles, Part II: Environmental and Economic Perspective. In Energies (Vol. 15, Issue 19). MDPI. https://doi.org/10.3390/en15197356

PRé Sustainability. (2023). SimaPro Tutorial.

Purwaningsih, R., Susanto, N., Adiaksa, D. A., & Putri, A. A. A. (2021). Analysis of the eco-efficiency level in the dining table production process using life cycle assessment method to increase industry sustainability. IOP Conference Series: Materials Science and Engineering, 1072(1), 012014. https://doi.org/10.1088/1757-899x/1072/1/012014

PwC. (2024). Dünyada ve Türkiye’de Güneş Enerjisi Sektörü.

Ram, A., & Sharma, P. (2017). A study on Life Cycle Assessment. International Journal of Engineering and Advanced Technology, 6(NASET17), 197–201. https://www.researchgate.net/publication/330760490

Rinawati, D. I., Sriyanto, Sari, D. P., & Prayodha, A. C. (2018). Eco-efficiency Analysis of Furniture Product Using Life Cycle Assessment. E3S Web of Conferences 31, 08005, 31. https://doi.org/10.1051/e3sconf/20183108005

Roos, S., Sandin, G., Zamani, B., & Peters, G. (2015). Environmental assessment of Swedish fashion consumption. Five garments - sustainable futures.

Sakib, M. N., Kabir, G., & Ali, S. M. (2024). A life cycle analysis approach to evaluate sustainable strategies in the furniture manufacturing industry. Science of the Total Environment, 907. https://doi.org/10.1016/j.scitotenv.2023.167611

Sanayi Genel Müdürlüğü. (2020). Mobilya Sektörü Raporu.

Sanayi Genel Müdürlüğü. (2021). Mobilya Sektör Raporu.

Septiani, M., Putri, N. C., Verma, G., & Sasongko, N. A. (2022). Eco-design practice towards sustainable furniture: A Review. IOP Conference Series: Earth and Environmental Science, 1108(1). https://doi.org/10.1088/1755-1315/1108/1/012059

Silva, D. A. L., Lahr, F. A. R., Varanda, L. D., Christoforo, A. L., & Ometto, A. R. (2015). Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: A case study in Brazil. Journal of Cleaner Production, 96, 299–307. https://doi.org/10.1016/j.jclepro.2014.03.007

Silva, D. A. L., Nunes, A. O., Moris, V. A. da S., Piekarski, C. M., & Rodrigues, T. O. (2017). How important is the LCA software tool you choose Comparative results from GaBi, openLCA, SimaPro and Umberto. CILCA 2017, 1–6. https://www.researchgate.net/publication/318217178

Stringer, C. (2006). Forest certification and changing global commodity chains. Journal of Economic Geography, 6(5), 701–722. https://doi.org/10.1093/jeg/lbl001

TEİAŞ. (2017). Türkiye Elektrik Üretim-İletim 2017 Yılı İstatistikleri. https://www.teias.gov.tr/turkiye-elektrik-uretim-iletim-istatistikleri

Terece, Z., Edirne Erdinç, J., & Kariptaş, F. S. (2020). Türkiye’de Mobilya Sektörünün Durumu ve 2000’li Yıllardan Sonra Küreselleşme Etkisi ile Değişimi. Haliç Üniversitesi Fen Bilimleri Dergisi, 3(1), 159–180. https://doi.org/10.46373/hafebid.682892

Ticaret Bakanlığı. (2021). Mobilya Sektör Raporu.

TOBB. (2017). Türkiye Mobilya Ürünleri Meclisi Sektör Raporu. www.tobb.org.tr

Trzepacz, S., Lingås, D. B., Asscherickx, L., Peeters, K., van Duijn, H., & Akerboom, M. (2023). LCA-based assessment of the management of European used textiles.

Uddin, M. M., & Wright, M. M. (2022). Life cycle analysis of biochar use in water treatment plants. In Sustainable Biochar for Water and Wastewater Treatment (pp. 705–735). Elsevier. https://doi.org/10.1016/B978-0-12-822225-6.00012-9

Üst, S. (2015). Konutlarda İç Mekan İle Mobilya Etkileşimi Bağlamında Mobilyaya Dair Özelliklerin İncelenmesi. Sanat ve Tasarım Dergisi, 15, 103–118. https://doi.org/10.18603/std.73583

Verbitsky, O., & Pushkar, S. (2018). Eco-Indicator 99, ReCiPe and ANOVA for Evaluating Building Technologies Under LCA Uncertainties. Environmental Engineering and Management Journal, 17(11), 2549–2559. http://www.eemj.icpm.tuiasi.ro/;http://www.eemj.eu

Wang, S., Su, D., & Zhu, S. (2016). A Comparative Study on Life Cycle Assessment of Typical Wood base Furniture. 5th International Conference on Sustainable Energy and Environment Engineering, 634–640.

Wenker, J. L., Richter, K., & Rüter, S. (2018). A Methodical Approach for Systematic Life Cycle Assessment of Wood-Based Furniture. Journal of Industrial Ecology, 22(4), 671–685. https://doi.org/10.1111/jiec.12581

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. International Journal of Life Cycle Assessment, 21(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Widheden, J., & Ringström, E. (2007). Life Cycle Assessment. In I. Johansson & P. Somasundaran (Eds.), Handbook for Cleaning/Decontamination of Surfaces (pp. 695–720). Elsevier B.V.

Xiong, X., Ma, Q., YingyingYuan, Wu, Z., & Zhang, M. (2020). Current situation and key manufacturing considerations of green furniture in China: A review. Journal of Cleaner Production, 267. https://doi.org/10.1016/j.jclepro.2020.121957

Yang, M., & Rosentrater, K. A. (2020). Life Cycle Assessment of Urea-Formaldehyde Adhesive and Phenol-Formaldehyde Adhesives. Environmental Processes, 7(2), 553–561. https://doi.org/10.1007/s40710-020-00432-9

Yazıcı, H., & Karayılmazlar, S. (2001). Türkiye Ahşap Mobilya Sektörü ve Ekonomik Gelişimi. ZKÜ Bartın Orman Fakültesi Dergisi, 3(3), 3–17.

Zimmerman, G. (2005). Certified Green? Building Operating Management. http://www.facilitiesnet.com/bom/default.asp?id=bo0705

APPENDICES

A. Inventory Data

Table A. 1. Inventory Data of Life Cycle Stages in the Baseline Scenario

	Data	**Quantity**	**Unit**	**Transport (t*km)**	**Source**
	Veneer Joining				
Inputs	Veneer, hardwood, dry, at veneer mill, E/kg/RNA	1,314	g	0.736	Company Data
	Urea formaldehyde resin {RoW}| market for urea formaldehyde resin | Cut-off, U	1,814	g	7.256	Company Data
	water, deionised {RoW}| market for water, deionised | Cut-off, U	200	g	-	Company Data
	Electricity, high voltage {TR}| market for | Cut-off, U	1.307	kWh	-	Company Data
Outputs	spent solvent mixture {RoW}| treatment of spent solvent mixture, hazardous waste incineration, with energy recovery | Cut-off, U	573	g	-	Company Data
	Machining				
Inputs	Sawnwood, hardwood, dried (u=20%), planed {RoW}| market for | Cut-off, U	0.000790	m^3	0.002	Company Data
	medium density fibreboard {RoW}| market for medium density fibreboard | Cut-off, U	0.000195	m^3	0.101	Company Data
	particleboard, uncoated {RoW}| market for particleboard, uncoated | Cut-off, U	0.003974	m^3	1.803	Company Data
	Zinc {GLO}| market for | Cut-off, U	14	g	0.012	Company Data
	Vinyl acetate {GLO}| market for | Cut-off, U	4	g	0.003	Company Data
	polyurethane adhesive {GLO}| market for polyurethane adhesive | Cut-off, U	6	g	0.0001	Company Data
	Electricity, high voltage {TR}| market for | Cut-off, U	0.623	kWh	-	Company Data
Outputs	Particulates, < 2.5 µm	0.90	g	-	Estimated (Medeiros et al., 2017)

Table A. 1 (cont’d)

	Data	**Quantity**	**Unit**	**Transport (t*km)**	**Source**
	sawdust, loose, wet, measured as dry mass {GLO}| market for sawdust, loose, wet, measured as dry mass | Cut-off, U	360	g	-	Estimated (González-García et al., 2012)
	Dyeing				
Inputs	Paint[*]	20	g	0.017	MSDS
	Varnish[*]	240	g	0.204	MSDS
	Hardener Varnish[*]	120	g	0.102	MSDS
	Thinner[*]	80	g	0.068	MSDS
	Hardener[*]	160	g	0.136	MSDS
	Primer[*]	360	g	0.306	MSDS
	water, deionised {RoW}| market for water, deionised | Cut-off, U	70	g	-	Company Data
	Electricity, high voltage {TR}| market for | Cut-off, U	1.086	kWh	-	Company Data
	steam, in chemical industry {RoW}| market for steam, in chemical industry | Cut-off, U	5	g	-	Company Data
Outputs	spent solvent mixture {RoW}| treatment of spent solvent mixture, hazardous waste incineration, with energy recovery | Cut-off, U	310	g	-	Company Data
	waste paint {RoW}| treatment of waste paint, hazardous waste incineration, with energy recovery | Cut-off, U	2	g	-	Estimated
	Upholstering				
Inputs	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U (loaf)	26	g	0.009	Company Data
	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U (staples)	54	g	0.00005	Company Data
	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U (roll and contour foam)	288	g	0.0009	Company Data
	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U (nails)	2	g	0.00001	Company Data

---

[*] Material processes were created manually using Ecoinvent. Please see Table A. 2 for details.

Table A. 1 (cont’d)

	Data	**Quantity**	**Unit**	**Transport (t*km)**	**Source**
	textile, non-woven polypropylene {GLO}| market for textile, non woven polypropylene | Cut-off, U	34	g	0.021	Company Data
	textile, non-woven polyester {GLO}| market for textile, non woven polyester | Cut-off, U	19	g	0.0006	Company Data
	Textile, woven cotton {GLO}| market for | Cut-off, U	338	g	0.001	Company Data
	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U (padding)	69	g	0.0002	Company Data
	polyurethane adhesive {GLO}| market for polyurethane adhesive | Cut-off, U	90	g	0.065	Company Data
	Electricity, high voltage {TR}| market for | Cut-off, U	0.03	kWh	-	Company Data
Outputs	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	14	g	-	Company Data
	Assembly				
Inputs	Electricity, high voltage {TR}| market for | Cut-off, U	0.015	kWh	-	Company Data
	Packaging				
Inputs	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U (screw)	124	g	0.0004	Company Data
	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U (Allen wrench)	15	g	0.00005	Company Data
	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U	498	g	0.0015	Company Data
	Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U	1	g	0.0009	Company Data
	Corrugated board box {RoW}| market for corrugated board box | Cut-off, U	3,440	g	0.01	Company Data
	Printed paper {GLO}| market for | Cut-off, U	2	g	0.00001	Company Data

Table A. 1 (cont’d)

	Data	**Quantity**	**Unit**	**Transport (t*km)**	**Source**
	polyurethane adhesive {GLO}| market for polyurethane adhesive | Cut-off, U	25	g	0.0195	Company Data
	Electricity, high voltage {TR}| market for | Cut-off, U	0.01	kWh	-	Company Data
Outputs	Waste paperboard {RoW}| treatment of, municipal incineration | Cut-off, U	55	g	-	Estimated (González-García et al., 2012)
	Distribution				
Inputs	transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U	0.39	t*km	Calculated	-
	Transport, freight, lorry 7.5-16 metric ton, euro4 {RoW}| market for transport, freight, lorry 7.5-16 metric ton, EURO4 | Cut-off, U	6.12	t*km	Calculated	-
	Use				
Outputs	Waste polyethylene {RoW}| treatment of waste polyethylene, municipal incineration | Cut-off, U	498	g	-	Estimated
	Waste paperboard {RoW}| treatment of, municipal incineration | Cut-off, U	3,440	g	-	Estimated
	EoL				
Outputs	Scrap steel {RoW}| treatment of scrap steel, municipal incineration | Cut-off, U	220	g	-	Estimated
	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	358	g	-	Estimated
	Waste wood, untreated {RoW}| treatment of waste wood, untreated, municipal incineration | Cut-off, U	7,756	g	-	Estimated
	Waste textile, soiled {RoW}| treatment of, municipal incineration | Cut-off, U	391	g	-	Estimated

Table A. 2. Inventory Data of Material Processes Created for Dyeing

1 g of Material	**Data**	**Quantity**	**Unit**
Paint	Naphtha {RoW}| market for | Cut-off, U	0.20	g
	Xylene {RoW}| market for xylene | Cut-off, U	0.14	g
	White spirit {GLO}| market for | Cut-off, U	0.11	g
	Toluene, liquid {RoW}| market for toluene, liquid | Cut-off, U	0.03	g
Varnish	Butyl acetate {RoW}| market for butyl acetate | Cut-off, U	0.01	g
	Xylene {RoW}| market for xylene | Cut-off, U	0.49	g
	Dipropylene glycol monomethyl ether {RoW}| market for dipropylene glycol monomethyl ether | Cut-off, U	0.08	g
Hardener Varnish	Toluene, liquid {RoW}| market for toluene, liquid | Cut-off, U	0.09	g
	Butyl acetate {RoW}| market for butyl acetate | Cut-off, U	0.05	g
	Xylene {RoW}| market for xylene | Cut-off, U	0.35	g
	Dipropylene glycol monomethyl ether {RoW}| market for dipropylene glycol monomethyl ether | Cut-off, U	0.04	g
Thinner	Butyl acetate {RoW}| market for butyl acetate | Cut-off, U	0.35	g
	Methyl ethyl ketone {RoW}| market for methyl ethyl ketone | Cut-off, U	0.10	g
	Xylene {RoW}| market for xylene | Cut-off, U	0.40	g
	Dipropylene glycol monomethyl ether {RoW}| market for dipropylene glycol monomethyl ether | Cut-off, U	0.10	g
Hardener	Butyl acetate {RoW}| market for butyl acetate | Cut-off, U	0.30	g
	Xylene {RoW}| market for xylene | Cut-off, U	0.285	g
	Toluene diisocyanate {RoW}| market for toluene diisocyanate | Cut-off, U	0.195	g
	Dipropylene glycol monomethyl ether {RoW}| market for dipropylene glycol monomethyl ether | Cut-off, U	0.045	g
Primer	Toluene, liquid {RoW}| market for toluene, liquid | Cut-off, U	0.03	g
	Xylene {RoW}| market for xylene | Cut-off, U	0.33	g

Table A. 3. Input Data for the Calculation of Distribution Inventory

Market	Market Distribution Ratio	Branch Location	Highway Distance (km)	Seaway Distance (km)	Branch Distribution Ratio
Domestic	96%	Ankara, Yenimahalle	360	-	23.51%
		Samsun, Çarşamba	480	-	20.17%
		Konya, Büyük Kayacık	280	-	11.83%
		İstanbul, Avrupa	780	-	12.97%
		İstanbul, Tuzla	730	-	8.56%
		Kahramanmaraş, Onikişubat	240	-	8.42%
		Adana, Yüreğir	310	-	7.64%
		Bursa, Yenice	610	-	6.89%
Foreign	4%	Lebanon, Beirut	800	-	40.14%
		Azerbaijan, Baku	1640	-	33.54%
		Morocco, Casablanca	300	4,300	16.41%
		Iraq, Duhok	930	-	9.90%

Table A. 4. Inventory Data of Scenarios

No	Life Cycle Stage	Input / Output	Data	Scenario Development
1	Veneer Joining	Glue	melamine urea formaldehyde adhesive {GLO}| market for melamine urea formaldehyde adhesive | Cut-off, U	Material Replacement
			Phenolic resin {RoW}| market for phenolic resin | Cut-off, U	Material Replacement
2	Upholstering	Fabric	textile, non-woven polyester {GLO}| market for textile, non woven polyester | Cut-off, U	Material Replacement
			textile, non-woven polypropylene {GLO}| market for textile, non woven polypropylene | Cut-off, U	Material Replacement
3	Packaging	Packaging Material	Corrugated board box {RoW}| market for corrugated board box | Cut-off, U	Material Reduction
			Packaging film, low density polyethylene {GLO}| market for | Cut-off, U	Material Reduction

Table A. 4 (cont'd)

No	**Life Cycle Stage**	**Input / Output**	**Data**	**Scenario Development**
4	Upholstering	Waste Plastic	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | APOS, U	Change of waste treatment
	Packaging	Waste Paper	Paper (waste treatment) {GLO}| recycling of paper | APOS, U	Change of waste treatment
5	Use	Waste PE	PE (waste treatment) {GLO}| recycling of PE | APOS, U	Change of waste treatment
		Waste Paper	Paper (waste treatment) {GLO}| recycling of paper | APOS, U	Change of waste treatment
	EoL	Waste Metal	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | APOS, U	Change of waste treatment
		Waste Plastic	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | APOS, U	Change of waste treatment
		Waste Wood*	-	Change of waste treatment
		Waste Fabric*	-	Change of waste treatment
6	Manufacturing + Packaging	Electricity	Electricity, low voltage {TR}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, U	Switching the electricity source
			Electricity, high voltage {TR}| electricity production, lignite | Cut-off, U	Switching the electricity source

---

* Recycling processes were created manually using Ecoinvent. Please see Table A. 5 for details.

Table A. 5. Inventory Data of Recycling Processes Created for Scenario 5

		Data	Quantity	Unit	Notes
Recycling 1 ton of Wood	*Avoided Product*	plywood {RoW}| market for plywood | Cut-off, U	0.82	m^3	Plywood is assumed to be avoided with a substitution ratio of 1:0.6 (Carollo, 2022).
	Inputs	particleboard, uncoated {RoW}| market for particleboard, uncoated | Cut-off, U	1.4846	m^3	The product provided in the Ecoinvent database is modified by excluding the bark chips, pulpwood, sawdust, etc. (Carollo, 2022). It is assumed that making 1 kg of particleboard requires 1.07 kg of wood waste according to Ecoinvent (Aho et al., 2022).
Recycling 1 ton of Textile	*Avoided Products*	fibre, cotton {GLO}| market for fibre, cotton | Cut-off, U	0.125	ton	According to Duhoux et al. (2021), the mechanical recycling for cotton can replace 5% of spinnable fibers in the worst-case scenario, whereas in the best-case scenario, it can replace up to 20% of spinnable fibers. This study uses the average of 12.5% as of the study in Trzepacz et al. (2023).
		Polyethylene terephthalate, granulate, bottle grade {RoW}| production | Cut-off, U	0.1825	ton	Unknown part of total fluff and filling materials is assumed to be half (Duhoux et al., 2021).
		Polypropylene, granulate {RoW}| production | Cut-off, U	0.1825	ton	Unknown part of total fluff and filling materials is assumed to be half (Duhoux et al., 2021).
		Electricity, medium voltage {TR}| market for | Cut-off, U	42	MJ	Electricity recovery from cotton incineration is calculated (Trzepacz et al., 2023).
		Heat, district or industrial, other than natural gas {GLO}| market group for | Cut-off, U	90	MJ	Heat recovery from cotton incineration is calculated (Trzepacz et al., 2023).

Table A. 5 (cont'd)

		Data	**Quantity**	**Unit**	**Notes**
	Inputs	Tap water {GLO}| market group for | Cut-off, U	20	kg	(Duhoux et al., 2021)
		Electricity, low voltage {TR}| market for | Cut-off, U	500	kWh	(Duhoux et al., 2021)
	Outputs	Waste textile, soiled {RoW}| treatment of, municipal incineration | Cut-off, U	0.03	ton	(Duhoux et al., 2021)

B. Results

Table B. 1. Endpoint Single Score Results of the Baseline Scenario

Impact Category	Unit	Total	Manufacturing	Packaging	Distribution	Use	EoL
Total	Pt	1.41E+00	1.02E+00	2.86E-01	3.21E-02	3.75E-02	3.42E-02
Human Health	Pt	1.34E+00	9.69E-01	2.72E-01	2.97E-02	3.61E-02	3.29E-02
Ecosystems	Pt	5.25E-02	3.91E-02	9.56E-03	1.22E-03	1.34E-03	1.24E-03
Resources	Pt	2.06E-02	1.44E-02	4.89E-03	1.13E-03	3.82E-05	7.72E-05

Table B. 2. Endpoint Damage Assessment Results of the Baseline Scenario

Impact Category	Unit	Total	Manu-facturing	Packaging	Distri-bution	Use	EoL
Human Health	DALY	8.03E-05	5.81E-05	1.63E-05	1.78E-06	2.16E-06	1.97E-06
Ecosystems	species.yr	1.94E-07	1.45E-07	3.54E-08	4.51E-09	4.96E-09	4.59E-09
Resources	USD2013	2.88E+00	2.02E+00	6.85E-01	1.59E-01	5.35E-03	1.08E-02

Table B. 3. Midpoint Characterization Results of the Baseline Scenario

Impact Category	Unit	Total	Manu-facturing	Packaging	Distri-bution	Use	EoL
GW	kg CO_2-eq	3.04E+01	2.07E+01	5.75E+00	1.09E+00	1.60E+00	1.24E+00
SOD	kg CFC-11-eq	4.01E-05	2.82E-05	3.66E-06	4.94E-07	1.59E-06	6.20E-06
IR	kBq Co-60-eq	6.36E-01	4.10E-01	2.15E-01	8.58E-03	1.18E-03	1.08E-03
OFHH	kg NOx-eq	7.76E-02	5.44E-02	1.45E-02	4.66E-03	1.18E-03	2.86E-03
FPMF	kg PM2.5-eq	5.55E-02	4.47E-02	9.09E-03	1.10E-03	2.01E-04	4.24E-04
OFTE	kg NOx-eq	8.01E-02	5.63E-02	1.50E-02	4.70E-03	1.18E-03	2.87E-03
TA	kg SO_2-eq	1.11E-01	8.94E-02	1.73E-02	2.88E-03	5.76E-04	1.24E-03
FET	kg P-eq	8.68E-03	6.74E-03	1.86E-03	2.08E-05	9.91E-06	5.26E-05
MET	kg N-eq	2.08E-02	1.90E-02	1.69E-03	1.74E-06	3.31E-05	1.24E-04
TE	kg 1,4-DCB-eq	1.01E+02	4.91E+01	2.89E+01	1.80E+01	4.54E+00	6.22E-01
FE	kg 1,4-DCB-eq	1.23E+00	3.59E-01	1.56E-01	3.73E-03	1.42E-01	5.65E-01
ME	kg 1,4-DCB-eq	1.53E+00	4.12E-01	2.16E-01	1.42E-02	1.99E-01	6.85E-01
HCT	kg 1,4-DCB-eq	3.31E+00	1.97E+00	1.25E+00	2.53E-03	3.90E-02	4.03E-02
HNCT	kg 1,4-DCB-eq	2.09E+01	1.27E+01	4.25E+00	2.96E-01	1.82E+00	1.85E+00
LU	m^2a crop-eq	5.62E+00	4.35E+00	1.27E+00	5.86E-04	7.01E-04	8.96E-04
MRS	kg Cu-eq	1.18E-01	5.06E-02	6.69E-02	1.43E-04	2.92E-04	5.76E-04
FRS	kg oil-eq	9.03E+00	6.62E+00	2.01E+00	3.56E-01	1.63E-02	3.25E-02
WC	m^3	2.28E+00	2.20E+00	7.09E-02	3.58E-04	4.21E-03	-3.10E-04

Table B. 4. Midpoint Normalization Results of the Baseline Scenario

Impact Category	Total	Manufacturing	Packaging	Distribution	Use	EoL
GW	3.81E-03	2.60E-03	7.20E-04	1.37E-04	2.01E-04	1.55E-04
SOD	6.70E-04	4.71E-04	6.11E-05	8.25E-06	2.65E-05	1.03E-04
IR	1.32E-03	8.53E-04	4.46E-04	1.78E-05	2.45E-06	2.24E-06
OFHH	3.77E-03	2.65E-03	7.04E-04	2.27E-04	5.73E-05	1.39E-04
FPMF	2.17E-03	1.75E-03	3.56E-04	4.29E-05	7.85E-06	1.66E-05
OFTE	4.51E-03	3.17E-03	8.46E-04	2.65E-04	6.66E-05	1.61E-04
TA	2.72E-03	2.18E-03	4.22E-04	7.03E-05	1.40E-05	3.02E-05
FET	1.34E-02	1.04E-02	2.87E-03	3.20E-05	1.53E-05	8.10E-05
MET	4.52E-03	4.12E-03	3.67E-04	3.78E-07	7.19E-06	2.70E-05
TE	6.65E-03	3.23E-03	1.90E-03	1.18E-03	2.99E-04	4.09E-05
FE	4.87E-02	1.42E-02	6.20E-03	1.48E-04	5.62E-03	2.24E-02
ME	3.51E-02	9.47E-03	4.97E-03	3.26E-04	4.58E-03	1.57E-02
HCT	3.21E-01	1.91E-01	1.22E-01	2.45E-04	3.78E-03	3.91E-03
HNCT	6.69E-04	4.07E-04	1.36E-04	9.46E-06	5.84E-05	5.91E-05
LU	9.10E-04	7.04E-04	2.05E-04	9.49E-08	1.14E-07	1.45E-07
MRS	9.87E-07	4.21E-07	5.57E-07	1.19E-09	2.43E-09	4.80E-09
FRS	9.21E-03	6.75E-03	2.05E-03	3.64E-04	1.66E-05	3.31E-05
WC	8.55E-03	8.27E-03	2.66E-04	1.34E-06	1.58E-05	-1.15E-06

Table B. 5. Endpoint Single Score Results of Manufacturing Processes

Impact Category	Unit	Total	Veneer Joining	Machining	Dyeing	Upholstering	Assembly
Total	Pt	1.02E+00	3.90E-01	1.62E-01	1.27E-01	3.43E-01	9.03E-04
Human Health	Pt	9.69E-01	3.75E-01	1.52E-01	1.21E-01	3.20E-01	8.89E-04
Ecosystems	Pt	3.91E-02	1.03E-02	7.67E-03	3.03E-03	1.81E-02	1.13E-05
Resources	Pt	1.44E-02	5.64E-03	1.91E-03	2.75E-03	4.11E-03	2.98E-06

Table B. 6. Endpoint Damage Assessment Results of Manufacturing Processes

Impact Category	Unit	Total	Veneer Joining	Machining	Dyeing	Upholstering	Assembly
Human Health	DALY	5.81E-05	2.25E-05	9.11E-06	7.24E-06	1.92E-05	5.33E-08
Ecosystems	species.yr	1.45E-07	3.80E-08	2.84E-08	1.12E-08	6.70E-08	4.17E-11
Resources	USD2013	2.02E+00	7.90E-01	2.68E-01	3.85E-01	5.76E-01	4.18E-04

Table B. 7. Midpoint Characterization Results of Manufacturing Processes

Impact Category	Unit	Total	Veneer Joining	Machi-ning	Dyeing	Uphols-tering	Assem-bly
GW	kg CO$_2$-eq	2.07E+01	8.65E+00	2.58E+00	2.81E+00	6.69E+00	8.76E-03
SOD	kg CFC-11-eq	2.82E-05	2.22E-06	1.53E-06	6.62E-07	2.38E-05	2.64E-09
IR	kBq Co-60-eq	4.10E-01	6.34E-02	7.31E-02	3.14E-02	2.42E-01	5.50E-05
OFHH	kg NOx-eq	5.44E-02	2.18E-02	9.90E-03	5.00E-03	1.77E-02	1.84E-05
FPMF	kg PM2.5-eq	4.47E-02	1.60E-02	8.90E-03	6.53E-03	1.32E-02	6.58E-05
OFTE	kg NOx-eq	5.63E-02	2.27E-02	1.03E-02	5.20E-03	1.81E-02	1.85E-05
TA	kg SO$_2$-eq	8.94E-02	3.16E-02	1.08E-02	7.27E-03	3.97E-02	3.71E-05
FET	kg P-eq	6.74E-03	2.15E-03	8.51E-04	8.67E-04	2.86E-03	8.58E-06
MET	kg N-eq	1.90E-02	2.42E-04	1.21E-04	1.01E-04	1.85E-02	5.34E-07
TE	kg 1,4-DCB-eq	4.91E+01	1.44E+01	1.29E+01	4.25E+00	1.75E+01	2.66E-03
FE	kg 1,4-DCB-eq	3.59E-01	7.78E-02	6.45E-02	2.53E-02	1.91E-01	2.25E-04
ME	kg 1,4-DCB-eq	4.12E-01	1.13E-01	9.44E-02	3.68E-02	1.67E-01	3.10E-04
HCT	kg 1,4-DCB-eq	1.97E+00	9.44E-01	1.18E-01	6.61E-02	8.43E-01	4.67E-04
HNCT	kg 1,4-DCB-eq	1.27E+01	3.75E+00	2.83E+00	1.08E+00	5.04E+00	9.45E-03
LU	m^{2}a crop-eq	4.35E+00	4.95E-02	1.84E+00	9.00E-03	2.45E+00	2.96E-05
MRS	kg Cu-eq	5.06E-02	3.59E-03	4.45E-03	3.54E-04	4.22E-02	1.29E-07
FRS	kg oil-eq	6.62E+00	2.83E+00	8.74E-01	1.08E+00	1.83E+00	2.31E-03
WC	m^3	2.20E+00	2.10E-01	4.36E-02	3.09E-02	1.92E+00	6.51E-05

Table B. 8. Midpoint Normalization Results of Manufacturing Processes

Impact Category	Total	Veneer Joining	Machining	Dyeing	Upholstering	Assembly
GW	2.60E-03	1.08E-03	3.23E-04	3.52E-04	8.37E-04	1.10E-06
SOD	4.71E-04	3.71E-05	2.56E-05	1.10E-05	3.97E-04	4.40E-08
IR	8.53E-04	1.32E-04	1.52E-04	6.53E-05	5.04E-04	1.14E-07
OFHH	2.65E-03	1.06E-03	4.81E-04	2.43E-04	8.60E-04	8.92E-07
FPMF	1.75E-03	6.27E-04	3.48E-04	2.55E-04	5.15E-04	2.57E-06
OFTE	3.17E-03	1.28E-03	5.82E-04	2.93E-04	1.02E-03	1.04E-06
TA	2.18E-03	7.70E-04	2.64E-04	1.77E-04	9.68E-04	9.06E-07
FET	1.04E-02	3.31E-03	1.31E-03	1.34E-03	4.40E-03	1.32E-05
MET	4.12E-03	5.25E-05	2.63E-05	2.20E-05	4.02E-03	1.16E-07
TE	3.23E-03	9.47E-04	8.49E-04	2.79E-04	1.15E-03	1.75E-07
FE	1.42E-02	3.09E-03	2.56E-03	1.01E-03	7.59E-03	8.92E-06
ME	9.47E-03	2.60E-03	2.17E-03	8.47E-04	3.85E-03	7.13E-06
HCT	1.91E-01	9.17E-02	1.15E-02	6.42E-03	8.18E-02	4.54E-05
HNCT	4.07E-04	1.20E-04	9.06E-05	3.44E-05	1.61E-04	3.02E-07
LU	7.04E-04	8.01E-06	2.98E-04	1.46E-06	3.97E-04	4.79E-09
MRS	4.21E-07	2.99E-08	3.70E-08	2.95E-09	3.51E-07	1.07E-12
FRS	6.75E-03	2.89E-03	8.91E-04	1.10E-03	1.87E-03	2.36E-06
WC	8.27E-03	7.87E-04	1.63E-04	1.16E-04	7.20E-03	2.44E-07

Table B. 9. Endpoint Single Score Results of Veneer Joining

Impact Category	Unit	Total	Veneer	UF Resin	Deionized Water	Electricity	Spent Solvent Mixture
Total	Pt	3.90E-01	6.67E-02	2.24E-01	1.29E-05	7.87E-02	2.07E-02
Human Health	Pt	3.75E-01	6.53E-02	2.12E-01	1.20E-05	7.74E-02	1.97E-02
Ecosystems	Pt	1.03E-02	9.62E-04	7.40E-03	8.70E-07	9.82E-04	9.23E-04
Resources	Pt	5.64E-03	4.39E-04	4.85E-03	4.30E-08	2.60E-04	8.93E-05

Table B. 10. Endpoint Single Score Results of Upholstering

Impact Category	Unit	Total	Loaf	Staple	Foam	Woven Fabric	Padding	Hotmelt
Total	Pt	3.43E-01	1.87E-02	3.87E-02	5.45E-02	1.87E-01	1.31E-02	2.03E-02
Human Health	Pt	3.20E-01	1.85E-02	3.83E-02	5.12E-02	1.71E-01	1.23E-02	1.92E-02
Ecosystems	Pt	1.81E-02	1.44E-04	2.96E-04	1.80E-03	1.46E-02	4.31E-04	5.84E-04
Resources	Pt	4.11E-03	5.82E-05	1.17E-04	1.52E-03	1.29E-03	3.64E-04	4.86E-04

Table B. 11. Endpoint Single Score Results of Packaging

Impact Category	Unit	Total	Screw	Allen Wrench	Packaging Film	Corrugated Board Box
Total	Pt	2.86E-01	8.88E-02	1.07E-02	5.37E-02	1.26E-01
Human Health	Pt	2.72E-01	8.79E-02	1.06E-02	4.94E-02	1.18E-01
Ecosystems	Pt	9.56E-03	6.79E-04	8.22E-05	1.79E-03	6.82E-03
Resources	Pt	4.89E-03	2.70E-04	3.26E-05	2.48E-03	1.97E-03

Table B. 12. Endpoint Single Score Results of Scenario 1

Impact Category	Unit	UF Resin	MUF Resin	PF Resin
Total	Pt	3.90E-01	3.38E-01	4.21E-01
Human Health	Pt	3.75E-01	3.25E-01	4.01E-01
Ecosystems	Pt	1.03E-02	8.73E-03	1.05E-02
Resources	Pt	5.64E-03	4.50E-03	9.39E-03

Table B. 13. Endpoint Damage Assessment Results of Scenario 1

Impact Category	Unit	UF Resin	MUF Resin	PF Resin
Human Health	DALY	2.25E-05	1.95E-05	2.40E-05
Ecosystems	species.yr	3.80E-08	3.23E-08	3.88E-08
Resources	USD2013	7.90E-01	6.30E-01	1.32E+00

Table B. 14. Midpoint Characterization Results of Scenario 1

Impact Category	Unit	UF Resin	MUF Resin	PF Resin
GW	kg CO_2-eq	8.65E+00	7.33E+00	9.23E+00
SOD	kg CFC-11-eq	2.22E-06	1.92E-06	2.11E-06
IR	kBq Co-60-eq	6.34E-02	6.50E-02	1.94E-01
OFHH	kg NOx-eq	2.18E-02	1.85E-02	2.46E-02
FPMF	kg PM2.5-eq	1.60E-02	1.42E-02	1.79E-02
OFTE	kg NOx-eq	2.27E-02	1.90E-02	2.65E-02
TA	kg SO_2-eq	3.16E-02	2.72E-02	2.87E-02
FET	kg P-eq	2.15E-03	1.87E-03	2.73E-03
MET	kg N-eq	2.42E-04	2.17E-04	1.93E-04
TE	kg 1,4-DCB-eq	1.44E+01	1.25E+01	1.12E+01
FE	kg 1,4-DCB-eq	7.78E-02	6.44E-02	9.16E-02
ME	kg 1,4-DCB-eq	1.13E-01	9.39E-02	1.22E-01
HCT	kg 1,4-DCB-eq	9.44E-01	8.20E-01	9.44E-01
HNCT	kg 1,4-DCB-eq	3.75E+00	3.13E+00	3.89E+00
LU	m^2a crop-eq	4.95E-02	3.41E-02	3.51E-02
MRS	kg Cu-eq	3.59E-03	3.04E-03	1.45E-03
FRS	kg oil-eq	2.83E+00	2.27E+00	4.04E+00
WC	m^3	2.10E-01	1.82E-01	9.10E-02

Table B. 15. Midpoint Normalization Results of Scenario 1

Impact Category	UF Resin	MUF Resin	PF Resin
GW	1.08E-03	9.18E-04	1.16E-03
SOD	3.71E-05	3.20E-05	3.53E-05
IR	1.32E-04	1.35E-04	4.03E-04
OFHH	1.06E-03	8.99E-04	1.20E-03
FPMF	6.27E-04	5.55E-04	6.99E-04
OFTE	1.28E-03	1.07E-03	1.49E-03
TA	7.70E-04	6.63E-04	7.01E-04
FET	3.31E-03	2.89E-03	4.20E-03
MET	5.25E-05	4.70E-05	4.18E-05
TE	9.47E-04	8.22E-04	7.38E-04
FE	3.09E-03	2.56E-03	3.64E-03
ME	2.60E-03	2.16E-03	2.81E-03
HCT	9.17E-02	7.96E-02	9.17E-02
HNCT	1.20E-04	1.00E-04	1.25E-04
LU	8.01E-06	5.53E-06	5.69E-06
MRS	2.99E-08	2.53E-08	1.20E-08
FRS	2.89E-03	2.31E-03	4.13E-03
WC	7.87E-04	6.81E-04	3.41E-04

Table B. 16. Endpoint Single Score Results of Scenario 2

Impact Category	Unit	Woven Cotton	Non-Woven PP	Non-Woven PES
Total	Pt	3.43E-01	2.09E-01	1.88E-01
Human Health	Pt	3.20E-01	2.00E-01	1.79E-01
Ecosystems	Pt	1.81E-02	5.20E-03	4.54E-03
Resources	Pt	4.11E-03	4.51E-03	4.53E-03

Table B. 17. Endpoint Damage Assessment Results of Scenario 2

Impact Category	Unit	Woven Cotton	Non-Woven PP	Non-Woven PES
Human Health	DALY	1.92E-05	1.20E-05	1.07E-05
Ecosystems	species.yr	6.70E-08	1.92E-08	1.68E-08
Resources	USD2013	5.76E-01	6.32E-01	6.35E-01

Table B. 18. Midpoint Characterization Results of Scenario 2

Impact Category	Unit	Woven Cotton	Non-Woven PP	Non-Woven PES
GW	kg CO_2-eq	6.69E+00	4.57E+00	4.01E+00
SOD	kg CFC-11-eq	2.38E-05	9.39E-06	2.35E-06
IR	kBq Co-60-eq	2.42E-01	1.38E-01	1.02E-01
OFHH	kg NOx-eq	1.77E-02	1.02E-02	8.76E-03
FPMF	kg PM2.5-eq	1.32E-02	7.07E-03	6.15E-03
OFTE	kg NOx-eq	1.81E-02	1.09E-02	9.18E-03
TA	kg SO_2-eq	3.97E-02	1.44E-02	1.28E-02
FET	kg P-eq	2.86E-03	8.34E-04	6.73E-04
MET	kg N-eq	1.85E-02	5.98E-04	5.26E-04
TE	kg 1,4-DCB-eq	1.75E+01	1.63E+01	1.44E+01
FE	kg 1,4-DCB-eq	1.91E-01	6.79E-02	6.13E-02
ME	kg 1,4-DCB-eq	1.67E-01	9.80E-02	8.81E-02
HCT	kg 1,4-DCB-eq	8.43E-01	8.09E-01	7.91E-01
HNCT	kg 1,4-DCB-eq	5.04E+00	1.87E+00	1.53E+00
LU	m^2a crop-eq	2.45E+00	2.17E-02	1.64E-02
MRS	kg Cu-eq	4.22E-02	4.03E-02	3.97E-02
FRS	kg oil-eq	1.83E+00	1.76E+00	1.71E+00
WC	m^3	1.92E+00	7.75E-02	6.72E-02

Table B. 19. Midpoint Normalization Results of Scenario 2

Impact Category	Woven Cotton	Non-Woven PP	Non-Woven PES
GW	8.37E-04	5.72E-04	5.01E-04
SOD	3.97E-04	1.57E-04	3.92E-05
IR	5.04E-04	2.87E-04	2.12E-04
OFHH	8.60E-04	4.96E-04	4.26E-04
FPMF	5.15E-04	2.76E-04	2.40E-04
OFTE	1.02E-03	6.12E-04	5.17E-04
TA	9.68E-04	3.52E-04	3.13E-04
FET	4.40E-03	1.29E-03	1.04E-03
MET	4.02E-03	1.30E-04	1.14E-04
TE	1.15E-03	1.07E-03	9.49E-04
FE	7.59E-03	2.70E-03	2.43E-03
ME	3.85E-03	2.25E-03	2.03E-03
HCT	8.18E-02	7.86E-02	7.68E-02
HNCT	1.61E-04	5.97E-05	4.91E-05
LU	3.97E-04	3.51E-06	2.66E-06
MRS	3.51E-07	3.36E-07	3.30E-07
FRS	1.87E-03	1.79E-03	1.74E-03
WC	7.20E-03	2.90E-04	2.52E-04

Table B. 20. Endpoint Single Score Results of Scenario 3

Impact Category	Unit	No Reduction	Reduction of Board	Reduction of PE	Reduction of Both
Total	Pt	2.86E-01	2.74E-01	2.81E-01	2.68E-01
Human Health	Pt	2.72E-01	2.60E-01	2.67E-01	2.55E-01
Ecosystems	Pt	9.56E-03	8.88E-03	9.38E-03	8.70E-03
Resources	Pt	4.89E-03	4.70E-03	4.64E-03	4.45E-03

Table B. 21. Endpoint Damage Assessment Results of Scenario 3

Impact Category	Unit	No Reduction	Reduction of Board	Reduction of PE	Reduction of Both
Human Health	DALY	1.63E-05	1.56E-05	1.60E-05	1.53E-05
Ecosystems	species.yr	3.54E-08	3.28E-08	3.47E-08	3.22E-08
Resources	USD2013	6.85E-01	6.58E-01	6.50E-01	6.23E-01

Table B. 22. Midpoint Characterization Results of Scenario 3

Impact Category	Unit	No Reduction	Reduction of Board	Reduction of PE	Reduction of Both
GW	kg CO_2-eq	5.75E+00	5.40E+00	5.60E+00	5.24E+00
SOD	kg CFC-11-eq	3.66E-06	3.38E-06	3.63E-06	3.35E-06
IR	kBq Co-60-eq	2.15E-01	2.06E-01	2.05E-01	1.97E-01
OFHH	kg NOx-eq	1.45E-02	1.36E-02	1.41E-02	1.32E-02
FPMF	kg PM2.5-eq	9.09E-03	8.63E-03	8.90E-03	8.44E-03
OFTE	kg NOx-eq	1.50E-02	1.41E-02	1.46E-02	1.37E-02
TA	kg SO_2-eq	1.73E-02	1.63E-02	1.69E-02	1.59E-02
FET	kg P-eq	1.86E-03	1.74E-03	1.82E-03	1.70E-03
MET	kg N-eq	1.69E-03	1.53E-03	1.69E-03	1.53E-03
TE	kg 1,4-DCB-eq	2.89E+01	2.81E+01	2.87E+01	2.79E+01
FE	kg 1,4-DCB-eq	1.56E-01	1.47E-01	1.55E-01	1.45E-01
ME	kg 1,4-DCB-eq	2.16E-01	2.04E-01	2.14E-01	2.02E-01
HCT	kg 1,4-DCB-eq	1.25E+00	1.25E+00	1.25E+00	1.24E+00
HNCT	kg 1,4-DCB-eq	4.25E+00	3.97E+00	4.18E+00	3.91E+00
LU	m^2a crop-eq	1.27E+00	1.15E+00	1.26E+00	1.14E+00
MRS	kg Cu-eq	6.69E-02	6.67E-02	6.69E-02	6.67E-02
FRS	kg oil-eq	2.01E+00	1.92E+00	1.92E+00	1.83E+00
WC	m^3	7.09E-02	6.72E-02	6.82E-02	6.46E-02

Table B. 23. Midpoint Normalization Results of Scenario 3

Impact Category	No Reduction	Reduction of Board	Reduction of PE	Reduction of Both
GW	7.20E-04	6.76E-04	7.01E-04	6.57E-04
SOD	6.11E-05	5.65E-05	6.06E-05	5.60E-05
IR	4.46E-04	4.29E-04	4.27E-04	4.09E-04
OFHH	7.04E-04	6.61E-04	6.87E-04	6.43E-04
FPMF	3.56E-04	3.37E-04	3.48E-04	3.30E-04
OFTE	8.46E-04	7.94E-04	8.24E-04	7.72E-04
TA	4.22E-04	3.97E-04	4.12E-04	3.87E-04
FET	2.87E-03	2.67E-03	2.81E-03	2.61E-03
MET	3.67E-04	3.33E-04	3.66E-04	3.32E-04
TE	1.90E-03	1.85E-03	1.89E-03	1.84E-03
FE	6.20E-03	5.83E-03	6.14E-03	5.77E-03
ME	4.97E-03	4.68E-03	4.92E-03	4.64E-03
HCT	1.22E-01	1.21E-01	1.21E-01	1.21E-01
HNCT	1.36E-04	1.27E-04	1.34E-04	1.25E-04
LU	2.05E-04	1.86E-04	2.05E-04	1.85E-04
MRS	5.57E-07	5.56E-07	5.57E-07	5.56E-07
FRS	2.05E-03	1.96E-03	1.96E-03	1.87E-03
WC	2.66E-04	2.52E-04	2.56E-04	2.42E-04

Table B. 24. Endpoint Single Score Results of Scenario 4

Impact Category	Unit	Incineration of Process Waste	Recycling of Process Waste
Total	Pt	6.29E-01	6.25E-01
Human Health	Pt	5.92E-01	5.90E-01
Ecosystems	Pt	2.77E-02	2.57E-02
Resources	Pt	9.00E-03	8.94E-03

Table B. 25. Endpoint Damage Assessment Results of Scenario 4

Impact Category	Unit	Incineration of Process Waste	Recycling of Process Waste
Human Health	DALY	3.55E-05	3.54E-05
Ecosystems	species.yr	1.02E-07	9.51E-08
Resources	USD2013	1.26E+00	1.25E+00

Table B. 26. Midpoint Characterization Results of Scenario 4

Impact Category	Unit	Incineration of Process Waste	Recycling of Process Waste
GW	kg CO_2-eq	1.24E+01	1.24E+01
SOD	kg CFC-11-eq	2.74E-05	2.73E-05
IR	kBq Co-60-eq	4.57E-01	4.55E-01
OFHH	kg NOx-eq	3.22E-02	3.20E-02
FPMF	kg PM2.5-eq	2.23E-02	2.22E-02
OFTE	kg NOx-eq	3.31E-02	3.30E-02
TA	kg SO_2-eq	5.70E-02	5.69E-02
FET	kg P-eq	4.72E-03	4.72E-03
MET	kg N-eq	2.02E-02	2.02E-02
TE	kg 1,4-DCB-eq	4.64E+01	4.63E+01
FE	kg 1,4-DCB-eq	3.47E-01	3.45E-01
ME	kg 1,4-DCB-eq	3.83E-01	3.80E-01
HCT	kg 1,4-DCB-eq	2.10E+00	2.09E+00
HNCT	kg 1,4-DCB-eq	9.29E+00	9.24E+00
LU	m^2a crop-eq	3.72E+00	2.94E+00
MRS	kg Cu-eq	1.09E-01	1.09E-01
FRS	kg oil-eq	3.84E+00	3.82E+00
WC	m^3	1.99E+00	1.99E+00

Table B. 27. Midpoint Normalization Results of Scenario 4

Impact Category	Incineration of Process Waste	Recycling of Process Waste
GW	1.56E-03	1.55E-03
SOD	4.58E-04	4.57E-04
IR	9.50E-04	9.47E-04
OFHH	1.56E-03	1.56E-03
FPMF	8.71E-04	8.69E-04
OFTE	1.87E-03	1.86E-03
TA	1.39E-03	1.39E-03
FET	7.27E-03	7.26E-03
MET	4.39E-03	4.39E-03
TE	3.05E-03	3.05E-03
FE	1.38E-02	1.37E-02
ME	8.82E-03	8.74E-03
HCT	2.03E-01	2.03E-01
HNCT	2.97E-04	2.96E-04
LU	6.02E-04	4.76E-04
MRS	9.09E-07	9.08E-07
FRS	3.92E-03	3.90E-03
WC	7.47E-03	7.46E-03

Table B. 28. Endpoint Single Score Results of Scenario 5

Impact Category	Unit	Incineration of Packaging & Product	Recycling of Packaging & Product
Total	Pt	7.17E-02	-2.52E-01
Human Health	Pt	6.90E-02	-1.11E-01
Ecosystems	Pt	2.58E-03	-1.37E-01
Resources	Pt	1.15E-04	-4.11E-03

Table B. 29. Endpoint Damage Assessment Results of Scenario 5

Impact Category	Unit	Incineration of Packaging & Product	Recycling of Packaging & Product
Human Health	DALY	4.14E-06	-6.64E-06
Ecosystems	species.yr	9.55E-09	-5.07E-07
Resources	USD2013	1.62E-02	-5.75E-01

Table B. 30. Midpoint Characterization Results of Scenario 5

Impact Category	Unit	Incineration of Packaging & Product	Recycling of Packaging & Product
GW	kg CO_2-eq	2.84E+00	-3.27E+00
SOD	kg CFC-11-eq	7.79E-06	-6.01E-06
IR	kBq Co-60-eq	2.26E-03	-1.86E-01
OFHH	kg NOx-eq	4.04E-03	-2.13E-02
FPMF	kg PM2.5-eq	6.24E-04	-3.48E-03
OFTE	kg NOx-eq	4.05E-03	-2.13E-02
TA	kg SO_2-eq	1.81E-03	-1.28E-02
FET	kg P-eq	6.25E-05	-1.02E-03
MET	kg N-eq	1.57E-04	-2.07E-03
TE	kg 1,4-DCB-eq	5.16E+00	-6.56E+00
FE	kg 1,4-DCB-eq	7.07E-01	-5.54E-02
ME	kg 1,4-DCB-eq	8.83E-01	-6.86E-02
HCT	kg 1,4-DCB-eq	7.92E-02	-9.00E-02
HNCT	kg 1,4-DCB-eq	3.67E+00	-3.07E+00
LU	m^2a crop-eq	1.60E-03	-5.50E+01
MRS	kg Cu-eq	8.69E-04	-1.89E-02
FRS	kg oil-eq	4.88E-02	-1.58E+00
WC	m^3	3.90E-03	-3.51E-01

Table B. 31. Midpoint Normalization Results of Scenario 5

Impact Category	Incineration of Packaging & Product	Recycling of Packaging & Product
GW	3.56E-04	-4.10E-04
SOD	1.30E-04	-1.00E-04
IR	4.69E-06	-3.90E-04
OFHH	1.96E-04	-1.03E-03
FPMF	2.44E-05	-1.40E-04
OFTE	2.28E-04	-1.20E-03
TA	4.42E-05	-3.10E-04
FET	9.63E-05	-1.57E-03
MET	3.42E-05	-4.50E-04
TE	3.40E-04	-4.30E-04
FE	2.81E-02	-2.20E-03
ME	2.03E-02	-1.58E-03
HCT	7.69E-03	-8.73E-03
HNCT	1.17E-04	-9.81E-05
LU	2.59E-07	-8.91E-03
MRS	7.23E-09	-1.57E-07
FRS	4.97E-05	-1.62E-03
WC	1.46E-05	-1.32E-03

Table B. 32. Endpoint Single Score Results of Scenario 6

Impact Category	Unit	Country Mix	Solar (68%)	Lignite
Total	Pt	1.31E+00	1.18E+00	2.08E+00
Human Health	Pt	1.24E+00	1.12E+00	2.01E+00
Ecosystems	Pt	4.87E-02	4.71E-02	5.31E-02
Resources	Pt	1.93E-02	1.89E-02	1.87E-02

Table B. 33. Endpoint Damage Assessment Results of Scenario 6

Impact Category	Unit	Country Mix	Solar (68%)	Lignite
Human Health	DALY	7.44E-05	6.69E-05	1.21E-04
Ecosystems	species.yr	1.80E-07	1.74E-07	1.96E-07
Resources	USD2013	2.70E+00	2.65E+00	2.62E+00

Table B. 34. Midpoint Characterization Results of Scenario 6

Impact Category	Unit	Country Mix	Solar (68%)	Lignite
GW	kg CO_2-eq	2.65E+01	2.53E+01	2.86E+01
SOD	kg CFC-11-eq	3.19E-05	3.15E-05	3.19E-05
IR	kBq Co-60-eq	6.25E-01	6.17E-01	6.22E-01
OFHH	kg NOx-eq	6.89E-02	6.64E-02	7.40E-02
FPMF	kg PM2.5-eq	5.38E-02	4.47E-02	1.20E-01
OFTE	kg NOx-eq	7.14E-02	6.88E-02	7.64E-02
TA	kg SO_2-eq	1.07E-01	1.01E-01	1.31E-01
FET	kg P-eq	8.60E-03	7.40E-03	1.57E-02
MET	kg N-eq	2.07E-02	2.06E-02	2.11E-02
TE	kg 1,4-DCB-eq	7.80E+01	7.76E+01	7.86E+01
FE	kg 1,4-DCB-eq	5.15E-01	4.84E-01	6.84E-01
ME	kg 1,4-DCB-eq	6.28E-01	5.85E-01	8.60E-01
HCT	kg 1,4-DCB-eq	3.22E+00	3.16E+00	3.55E+00
HNCT	kg 1,4-DCB-eq	1.70E+01	1.56E+01	2.37E+01
LU	m^2a crop-eq	5.62E+00	5.61E+00	5.62E+00
MRS	kg Cu-eq	1.17E-01	1.17E-01	1.17E-01
FRS	kg oil-eq	8.63E+00	8.31E+00	9.00E+00
WC	m^3	2.28E+00	2.27E+00	2.27E+00

Table B. 35. Midpoint Normalization Results of Scenario 6

Impact Category	Country Mix	Solar (68%)	Lignite
GW	3.32E-03	3.16E-03	3.58E-03
SOD	5.32E-04	5.26E-04	5.33E-04
IR	1.30E-03	1.28E-03	1.29E-03
OFHH	3.35E-03	3.23E-03	3.60E-03
FPMF	2.10E-03	1.75E-03	4.70E-03
OFTE	4.02E-03	3.87E-03	4.30E-03
TA	2.60E-03	2.48E-03	3.20E-03
FET	1.32E-02	1.14E-02	2.41E-02
MET	4.49E-03	4.47E-03	4.58E-03
TE	5.13E-03	5.11E-03	5.17E-03
FE	2.05E-02	1.92E-02	2.71E-02
ME	1.44E-02	1.34E-02	1.98E-02
HCT	3.13E-01	3.07E-01	3.45E-01
HNCT	5.42E-04	5.00E-04	7.59E-04
LU	9.10E-04	9.09E-04	9.10E-04
MRS	9.79E-07	9.79E-07	9.79E-07
FRS	8.80E-03	8.47E-03	9.19E-03
WC	8.53E-03	8.50E-03	8.51E-03