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Department's title

COMPARATIVE LIFE CYCLE ASSESSMENT: CASE STUDY OF INTERIOR WOODEN DOORS MANUFACTURING INDUSTRY IN EUROPE

VÕRDLEV OLELUSRINGI HINDAMINE: PUITSISUSEUKSE TOOTMISTÖÖSTUSE JUHTUMIUURING EUROOPAS

MASTER THESIS

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Tallinn 2024

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THESIS TASK

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Study programme, EABM03/18 – Environmental Engineering and Management

main speciality: Environmental Engineering and Management

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Thesis topic:

(in English) Comparative life cycle assessment: case study of interior wooden doors manufacturing industry in Europe

(in Estonian) Võrdlev olelusringi hindamine: puitsisuseukse tootmistööstuse juhtumiuuring Euroopas

Thesis main objectives:

1. To conduct LCA of 4 interior wooden doors with different designs and materials used according to EN 15804+A2 considering 3 end-of-life scenarios for each door.
2. To compare results of the assessment considering end-of-life scenarios.
3. Analyse circularity perspectives resulting from comparative assessment.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Data collection	21.04.2024
2.	Calculations, methodology	28.04.2024
3.	Theoretical overview	12.05.2024
4.	Results and conclusion	20.05.2024

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PREFACE

This thesis explores the environmental impacts of four different interior wooden door designs in Europe using a comparative life cycle assessment (LCA). The analysis follows the EN 15804+A2 standards, with a functional unit defined as 1 m^2 of a door and considers the entire life cycle from raw material extraction to disposal, commonly referred to as the "cradle-to-grave" system boundary. Three disposal methods were evaluated in the disposal stage to understand their environmental impacts comprehensively. The findings indicate that the raw material extraction stage (A1) plays a pivotal role in contributing to the Global Warming Potential (GWP) category, regardless of the disposal method employed. The contribution ratio of this stage ranges significantly, underscoring its critical environmental impact.

Interestingly, Scenarios 1 and 3 exhibited very similar environmental impacts. This similarity is attributed to the recycling benefits accounted for outside the system boundary in module D, highlighting the positive effects of recycling on environmental performance. The reuse scenario demonstrated clear advantages across all impact categories. This is primarily due to the minimal impacts associated with End-of-Life (EoL) treatment, emphasizing the environmental benefits of reusing materials. Wood and wood-based materials used in the construction sector, particularly those with long service lifespans, contribute significantly to low carbon storage, resource and waste efficiency, and support the principles of the Circular Economy (CE). This case study specifically revealed that materials such as MDF, HDF, chipboard, and flaxboard, commonly used in door production, have a higher contribution to the GWP category during the raw material extraction stage. In contrast, designs utilizing solid wood showed a much lower contribution to GWP, underscoring the environmental benefits of using solid wood in door manufacturing. By examining these different designs and disposal methods, this research provides valuable insights into how interior wooden doors' environmental impacts can contribute to Circular Economy. It emphasizes the importance of material selection and waste management strategies in reducing the overall environmental footprint of construction products.

The input data for this research was obtained through constant monitoring of production processes and in-depth research conducted in collaboration with the leading wooden door manufacturing company in Europe. This close partnership ensured the accuracy and reliability of the data, providing a solid foundation for the LCA.

Keywords: life cycle assessment, circularity, end-of-life, wooden interior doors

List of abbreviations

LCA	Life Cycle Assessment
R&D	Research and Development department
CE	Circular Economy
EU	European Union
CPR	Construction Product Regulation
ESPR	Ecodesign for Sustainable Products Regulation
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SVHC	Substances of Very High Concern
SDS	Safety Data Sheet
FSC	Forest Stewardship Council
EoL	End-of-Life
LCIA	Life Cycle Impact Assessment
EPD	Environmental Product Declaration
EAM	European Attribute Mix
BIM	Building Information Modelling
EHS	Environment, Health, and Safety
LCI	Life Cycle Inventory
GWP	Global Warming Potential
GHG	Greenhouse Gas
VOCs	Volatile Organic Compounds

1. INTRODUCTION

Building and construction activities account for 39% of global carbon emissions, with 28% coming from operational emissions and 11% from the production of materials and construction processes throughout a building's lifecycle (World Green Building Council Report, 2019). In the future, materials will be the main source of CO2 emissions from buildings. To reduce the environmental impact of construction, it is crucial to shift towards more sustainable building materials, such as wood.

Wood and wood-based materials used in construction have long lifespans and contribute to low carbon storage, resource efficiency, waste reduction, and support the Circular Economy (CE). By recycling and reusing products, we can decrease waste and minimize the harmful effects of human activity on the environment. Recycling and reuse are vital as they reduce greenhouse gas emissions, conserve natural resources, and limit the amount of waste sent to landfills and ecosystems. This approach is also cost-effective and reduces energy consumption. Overall, reuse and recycling are essential strategies for achieving a more sustainable future and promoting the CE (Dumitrica et al., 2023).

A combination of economic, environmental, technological, and societal factors is influencing the door market. The demand, supply and development of the wood sector are driven by these factors in a collective way. The main driver of the market is the construction industry. Doors are becoming more and more used due to a strong demand for housing and business building projects. Since wood is a renewable resource, there is a growing demand for wood doors as an eco-friendly and sustainable alternative to non-renewable materials. Wood is used in the furniture and interior design sectors for a variety of purposes. The demand is influenced by consumer preferences for wooden fixtures and furnishings. Wooden doors are used within buildings to divide rooms and offer solitude. They are renowned for their inherent beauty, warmth, and adaptability.

Life Cycle Assessment (LCA) is a commonly employed tool in many fields, such as research and development (R&D), vulnerability analysis, strategic planning, and comparing product and service systems. It provides a thorough insight into the environmental impacts linked with a product or process from start to finish. LCA help pinpoint alternative ways to enhance environmental performance by identifying potential improvements at every stage of the lifecycle.

The aim of the thesis

This thesis specifically aims to conduct a comparative analysis of three different end-of-life scenarios for four wooden interior doors with unsimilar construction, considering various materials used in their production, using the LCA approach in accordance with EN 15804+A2 standards. The evaluation of environmental impacts based on the results of the assessment will provide valuable insights into the sustainability of different materials and disposal methods.

Further, each stage of the product life cycle production will be analysed to determine which stage contributes the most to greenhouse gas emissions. This will help pinpoint where improvements can be made to reduce the environmental impact. Also, the environmental impact of different wooden materials by comparing their emissions will be assessed identifying the main material that contributes to emission results.

Additionally, the circularity perspective of the wood and wood-based materials used will be closely examined, exploring their potential contributions to the CE. This approach will offer valuable insights into optimizing environmental performance and promoting sustainable practices within the door production industry.

2. THEORETICAL OVERVIEW

2.1 Industry overview

In recent years, Europe has seen a steady increase in the need for doors. The region's booming construction industry is to blame for this expansion. Approximately 90% of the structures in the region were constructed before 1990, and more than 40% before 1960 (Grand View Research, Inc, 2023). This increased the number of buildings in Europe that needed to be renovated or completely rebuilt. Thus, the demand for doors in Europe is influenced by the region's thriving construction industry.

Wooden doors, integral components of the vast range of wood-based products, includes a combination of materials like wood, wood-based panels, adhesives, decorative papers or foils, coatings, and more. There are different types of interior wooden doors, namely wood-based composite doors, solid wood composite doors, and solid wood doors. These doors hold significant positions in both residential and commercial structures, with wood being the favoured material due to its aesthetic appeal, durability, anticipated performance, optimized waste generation, insulation qualities, and limited carbon emissions. Consequently, the wooden door sector secured a substantial 51.4% industry share in 2020, driven not only by consumer preferences but also by increasing wood production initiatives and the incorporation of natural materials by construction companies and architects. Forecasts indicate a 2.9% growth in the commercial European doors market from 2021 to 2027, driven by the multifunctional needs of facilities, preference for wooden doors, and the growing demand for energy-efficient and environmentally friendly materials (Graphical Research, 2021).

Within the European doors industry, major players contribute approximately 30% to the overall market share (Global Market Insights, 2023). To meet escalating consumer demands, manufacturers strategically pursue partnerships and collaborations. Long-term engagements with raw material suppliers and distributors serve to avoid material shortages and ensures prompt product delivery. In response to emerging competition existing companies diversify their product lines, enhancing sustainability. In 2023, wooden doors claimed a 43.8% share of all doors (Figure 2.1), while hinged doors held a 31% market share, anticipated to grow substantially through 2032, driven by their classic design, ease of use, and applicability across various architectural styles (Global Market Insights, 2023).

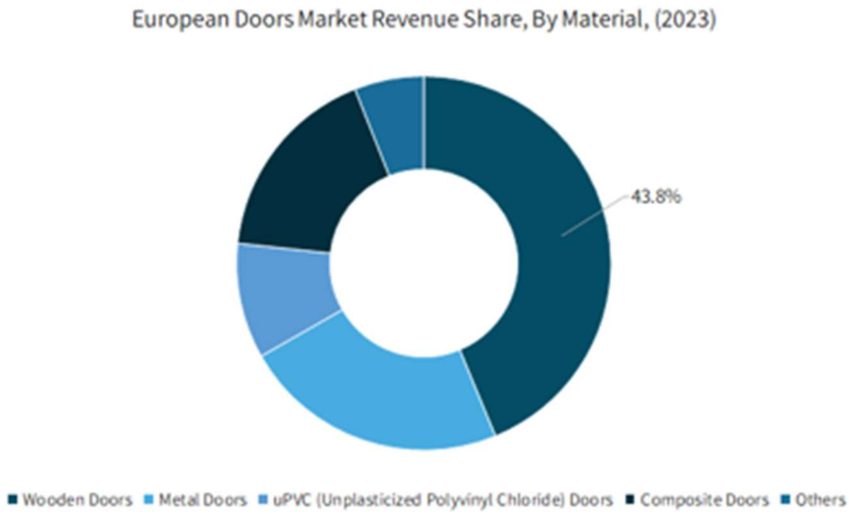

Figure 2.1 European doors market revenue share, by materials (Global Market Insights, 2023).

Sustainable strategies, aimed at enhancing environmental, economic, and social dimensions, pose a challenge in selecting the most fitting approach for each case (Iritani et al, 2015). LCA allows to address these challenges, the method of decision-making in industry processes. It is a widespread practice for evaluating environmental impacts starting from raw material extraction and reaching the end-of-life disposal becoming evident for both scientific research and industry processes (Sakib et al, 2024).

2.2 Regulations

The use of LCA is on the rise in policymaking (Sala et al, 2021). LCA findings serve various purposes within public administrations. Apart from informing the creation of laws and regulations, they are also used for law enforcement, internal and public communication, as well as consultancy tasks (Subal et al, 2024).

2.2.1 Mandatory LCA calculations for buildings

Proposed legislation within the European Union (EU) aims to mandate LCA calculations for buildings. This initiative seeks to advance sustainable construction practices by thoroughly evaluating the environmental impacts of buildings throughout their lifespan. The goal is to diminish the environmental footprint of buildings, enhance resource efficiency, and promote the transition to the CE by providing insights into design, construction, and renovation decisions. Under this proposal, developers and builders would be required to conduct LCA to measure and assess the environmental effects of buildings, from the extraction of raw materials to their eventual demolition and disposal.

This involves gathering data on energy consumption, resource utilization, emissions, and waste generation associated with every phase of a building's lifecycle. Standardized methodologies and criteria for conducting LCA will be established to ensure consistency and comparability of assessment results. Additionally, LCA reports must be submitted to regulatory authorities for review and verification, with potential consequences for non-compliance. (European Commission: Circular Economy Action Plan, 2020)

In response, door manufacturers are urged to take proactive measures. This includes collaborating with architects, engineers, and construction firms to develop door products that minimize environmental impacts across their entire lifecycle. Furthermore, investing in research and development endeavours to create sustainable materials and manufacturing processes aligned with LCA requirements is essential. Door producers should also work closely with suppliers to obtain materials with lower environmental footprints, ensuring transparency and traceability in the supply chain. Establishing procurement criteria based on LCA results to prioritize sustainable suppliers and materials is crucial. Moreover, conducting comprehensive environmental assessments and creating strategies to enhance the sustainability performance of door products based on LCA findings is essential.

2.2.2 European Green Deal

The European Green Deal is a robust and forward-looking legislative proposal put forth by the EU with the aim of forwarding sustainability, reducing greenhouse gas emissions, and nurturing economic growth. Embedded within the European Climate Law (European Commission: European Climate Law, 2024) is the ambition to reach climate neutrality by 2050, with interim goals for emission reduction by 2030. This initiative addresses the pressing need to resist climate change, preserve the environment, and foster sustainable economic development, in coherence to international commitments like the Paris Agreement. It promotes the shift towards a circular economy, aiming to minimize waste generation and enhance resource efficiency (European Commission: The European Green Deal, 2020).

Door manufacturers should include investing in research and development efforts aimed at producing environmentally friendly door products that align with the objectives of the Green Deal, such as energy-efficient doors made from sustainable materials. Moreover, manufacturers should adapt their manufacturing processes to minimize environmental impacts and promote circularity in product design and production. They should also take the lead in implementing Green Deal initiatives within their organizations, ensuring that these efforts are in sync with sustainability objectives and regulatory mandates.

2.2.3 Circular Economy Action Plan

The Circular Economy Action Plan, put forward by the EU, aims to encourage the careful use of resources, decrease waste, and promote a CE approach. It tackles the environmental and economic challenges linked to linear consumption habits, like running out of resources, piling up waste, and harming the environment. Its goal is to enhance resource efficiency and reduce resource extraction by favouring the reuse, repair, and recycling of products and materials. It sets goals for lessening waste and boosting recycling rates in various sectors such as packaging, electronics, etc. The plan also supports eco-friendly design principles to ensure products last long, can be fixed, and are recyclable, thus reducing their environmental impact throughout their lifespan. Furthermore, it supports innovation and investment in CE technologies and business models to foster sustainable economic growth and create jobs (European Commission: Circular Economy Action Plan, 2020).

Though the Circular Economy Action Plan might not directly talk about wooden products, it underscores forthcoming strategies concerning biodiversity and forests, emphasizing the importance of circular practices in achieving climate neutrality and maintaining competitiveness in the long run. Door producers should take specific steps starting with adjusting product design to include CE principles, like using recyclable materials and designing for disassembly and easy to repair. Additionally, they should integrate CE principles into their business strategies, operations, and product development processes. They should also explore market opportunities for eco-friendly door products in response to the increasing demand for CE solutions and sustainable building materials.

2.2.4 Construction Product Regulation

The Construction Product Regulation (CPR) is a legal structure adapted by the EU to standardize how construction products are evaluated and certified before entering the EU market. Its goal is to streamline the movement of these products across the EU Single Market while prioritizing safety, health, and environmental well-being. Manufacturers must attach the CE marking to their products as proof of meeting CPR standards (European Commission: Construction Products Regulation, 2019).

For door producers, following the CPR consider several actions. It requires ensuring that their products align with the performance criteria outlined by the CPR, potentially requiring further testing and certification. Collaboration with testing labs and authorized bodies is crucial to validate product conformity and secure necessary certifications. Processes and protocols must be established to guarantee compliance with CPR, including the upkeep of documentation and technical records. Furthermore, implementing quality checks becomes obligatory to oversee product performance and manage alignment with declared specifications.

2.2.5 Ecodesign for Sustainable Products Regulation

The Ecodesign for Sustainable Products Regulation (ESPR) is a proposal by the EU that is going to be implemented in 2024 aimed to encourage the manufacturing of environmentally friendly products across different industries. It establishes basic environmental standards for products, emphasizing energy efficiency, resource use, recyclability, and durability. The regulation introduces schemes where manufacturers are accountable for their products' environmental impact from production to disposal. Manufacturers must provide consumers with clear and accurate information about the environmental effects of products, including energy usage, resource consumption, and recyclability (European Commission: Ecodesign for Sustainable Products Regulation, 2024).

Door producers must integrate ecodesign principles into their product development, concentrating on energy efficiency, material choices, and recyclability at the end of the product's life. Collaborating with suppliers is crucial to procure eco-friendly materials and components for door manufacturing, ensuring compliance with ecodesign guidelines and encouraging sustainable sourcing methods. Additionally, conducting environmental assessments and life cycle analyses helps identify areas for enhancing the environmental performance of door products and production procedures.

2.2.6 EU Digital Product Passport

The EU Digital Product Passport is a proposed law by the EU under ESPR that aims to improve the traceability, openness, and sustainability of products through digital passports that accompany them from creation to disposal. It is due to start in 2026. Each product receives a unique digital ID, making it easy to follow and access information about it throughout its life. This includes details like design, materials, how it's made, energy use, and environmental impact. The passport also includes measures to mark the environmental, social, and economic aspects of the product, helping consumers and stakeholders make informed choices (European Commission: Ecodesign for Sustainable Products Regulation, 2024).

Door producers should gather and handle thorough product details, covering everything from design to environmental performance, to include in the Digital Product Passport. They also should develop sustainability measures for the passport, aligning with company goals and laws and use the passport to share the environmental and social features of door products with customers and stakeholders, promoting openness and trust.

2.2.7 Registration, Evaluation, Authorisation and Restriction of Chemicals

Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) stands as a comprehensive regulatory framework established by the EU with a purpose of ensuring the safe handling of chemicals and protecting both human health and the environment. It also aims to encourage innovation and support competitiveness within the chemical sector. By using stakeholder input and scientific insights, the EU can restrict or completely ban substances that it considers posing unacceptable hazards under REACH (European Commission: REACH Regulation, 2007)

Door manufacturers should assess the chemical composition of their products to ensure they comply with REACH regulations, particularly concerning substances categorized as very high concern (SVHCs) and collaborate with suppliers to identify and substitute hazardous chemicals with safer alternatives, if necessary, in order to fulfil REACH requirements. Additionally, they should conduct chemical risk assessments and devise strategies to minimize the environmental and health impacts associated with the chemical substances used in door production.

2.2.8 Regulations in Estonia

In Estonia, interior wooden door manufacturers must comply with several local regulations and legislation related to circularity and the environment. These regulations aim to ensure sustainable practices, reduce environmental impact, and promote the circular economy.

- Waste Management Act

The Waste Management Act is designed to regulate waste generation and management, promoting the principles of the waste hierarchy: prevention, reuse, recycling, recovery, and disposal. Implemented in 2004 and continuously updated, it aligns with EU waste directives. This legislation aims to minimize environmental impact by ensuring that waste is managed in an environmentally sound manner (Jäätmeseadus, 2004). Manufacturers should implement waste reduction strategies, such as optimizing material use and incorporating waste recycling programs. They should separate wood waste, packaging materials, and other recyclables. Partnering with certified waste management companies ensures compliance. Additionally, manufacturers can explore waste-to-energy options for non-recyclable waste. Regular training for staff on waste management practices and compliance with the act's requirements will further enhance sustainability efforts.

- Chemicals Act

The Chemicals Act regulates the use, handling, and storage of chemicals to protect human health and the environment. Implemented in 1998 and regularly updated, it enforces the EU REACH regulation. This legislation ensures that manufacturers use chemicals safely, preventing environmental contamination and health risks (Kemikaaliseadus, 1998/2015). Manufacturers should maintain an inventory of all chemicals used in production, ensuring proper labelling and storage. They must comply with safety data sheets (SDS) and implement safe handling procedures. Additionally, manufacturers should seek alternatives to hazardous chemicals, opting for eco-friendly adhesives, finishes, and treatments. Collaborating with suppliers to source safer chemical alternatives will further align with compliance and sustainability goals.

- Building Code

The Building Code establishes standards for construction products, focusing on safety, health, and environmental protection. Implemented in 2015, it mandates that construction products, including interior wooden doors, meet specific quality and performance criteria. This code ensures that buildings and their components are safe, sustainable, and energy efficient (Ehitusseadustik, 2015). Manufacturers should ensure that their products meet the Building Code's standards by using high-quality materials and production methods. Conducting regular product testing for durability, fire resistance, and environmental impact is crucial. Manufacturers should obtain necessary certifications and labels, such as CE marking, to demonstrate compliance. Adopting sustainable design practices, such as using certified sustainable wood and non-toxic finishes, will enhance product quality and marketability while ensuring adherence to the code.

- Sustainable Development Act

The Sustainable Development Act provides a framework for promoting sustainable development, balancing economic growth with environmental protection and social well-being. Implemented in 1995 and aligned with EU sustainability goals, it sets out principles and objectives to guide sustainable practices across all sectors, including manufacturing (Säästva arengu seadus, 1995). Manufacturers should integrate sustainability into their business strategies, focusing on resource efficiency, waste reduction, and eco-friendly product design. Implementing energy-efficient technologies in production processes and sourcing materials from sustainable forests are key steps. Engaging in continuous improvement practices and obtaining certifications like ISO 14001 for environmental management will help demonstrate commitment to sustainability.

- Climate Law

Climate Law is scheduled for implementation in January 2025, it aims to significantly reduce carbon emissions and promote sustainability across various sectors. This legislation mandates stricter regulations on industries, including manufacturing (Eesti kliimaseadus, 2025). Under Climate Law, door manufacturers must take proactive measures to mitigate their environmental impact. Sourcing wood from sustainably managed forests certified by recognized organizations like the Forest Stewardship Council (FSC) should be prioritized. Additionally, manufacturers should invest in energy-efficient production processes, such as using renewable energy sources and implementing energy-saving technologies. Manufacturers should optimize material usage, recycle, or repurpose waste whenever possible, and implement CE principles to extend the lifespan of their products.

2.3 Case studies

Several case studies have investigated the assessment of carbon footprints across a range of wood-based items, with a particular focus on understanding the complex production processes involved in crafting wooden doors and their potential to mitigate carbon emissions.

Wenker's (2015) study, "Life Cycle Assessment of Wooden Interior Doors in Germany," provides valuable insights in this field. Data collection research covers 19 door production sites, representing a significant 87% of total German door production. Employing generic data for wooden materials, the LCA highlighted critical findings. Notably, the most substantial environmental impacts were traced back to the manufacturing of semifinished wood products and fittings in the pre manufacturing stage, which activities include sourcing raw materials, logistics and distribution planning. Within the door manufacturing stage (module A3), energy demands emerged as a primary driver of environmental impacts. Despite the carbon neutrality of wood throughout its life cycle, differences in manufacturer-specific Global Warming Potential (GWP) categories remained consistent regardless of the wood content variation in the doors. However, significant differences were observed specifically during the cradle-to-gate life cycle phases (modules A1 to A3), indicating a dependency on wood content. Consequently, these differences should be taken with precaution, particularly for estimating the GWP of technical doors within sustainability assessments for buildings.

Furthermore, Cobut et al.'s (2015) “The environmental footprint of interior wood doors in non-residential buildings-Part 1: Life cycle assessment” exploration used LCA to evaluate wooden doors. The product under investigation in this case study was an internal wooden door used in non-residential buildings, with fibreboard and hardwood veneer being the primary skin components. Particleboard, hardwood, and structural composite lumber were the core materials. The investigation underscores the significance of raw material production, particularly the role of particleboard components, in driving environmental impacts. This was closely followed by the transportation of particleboard components to manufacturing facilities. To mitigate these impacts, alternative scenarios were proposed, targeting particleboard components, transportation, and final disposal techniques. With a growing global emphasis on low-carbon environments and evolving manufacturing technologies, enhancing process stages for wood products with high environmental impacts becomes imperative.

Deng's (2023) research, "Life Cycle Assessment and Optimization Scenario of Solid Wood Composite Doors: A Case Study in the East of China," adds depth to this discourse. This study evaluated a solid wood composite door using a LCA approach, drawing on field research to obtain production data. Focused on residential interiors, the functional unit for analysis was a solid wood composite door, with the LCA spanning from cradle to grave. Findings revealed that the raw material stage gave the most significant environmental impact, closely followed by the woodworking workshop stage. Regardless of the waste disposal method, the production stage consistently contributed 49% to 72% to all impact categories, with recycling emerging as the most environmentally friendly waste disposal option. Given the substantial electricity consumption during raw material production and woodworking workshop stages, the study promotes hydroelectricity as a preferable energy source. Moreover, considering a 20-year usage stage and wood wax oil maintenance, the study identified seven environmental impact categories surpassing 50% of their values during the production stage, emphasizing the need to explore alternative or environmentally friendly maintenance methods for wooden doors.

In the study conducted by Lao in 2023 “Environmental impacts evaluation and promotion measures of wood-based composite doors”, the carbon footprints of three distinct types of wooden doors manufactured in China were compared from the raw materials extraction to their disposal. The research investigated the cradle-to-grave assessment of carbon emissions associated with wood-based composite doors, solid wood composite doors, and solid wood doors, developing comprehensive models for analysis. Notably, the study also factored in the presence of biogenic carbon in the assessment. The investigation highlighted key findings regarding the carbon footprints of the examined wooden doors. It revealed that the procurement of raw materials and transportation stages are the primary contributors, accounting for 38% to 66% of the total carbon footprints across all door types. Interestingly, emissions during the product manufacturing stage were relatively modest in comparison. However, the treatment of waste disposal during the end-of-life phase, along with the disposal of wood materials in landfills, and the duration of their service life gave substantial impacts on the carbon footprints of the doors. Moreover, the study identified several points of emissions, known as "hotspots," within the life cycle of wooden doors. Fiberboard, laminated veneer lumber, sawn lumber, finger-jointed lumber, and electricity emerged as the primary sources of emissions, requiring closer attention for mitigation efforts. By offering a detailed comparative analysis, this study not only sheds light on the carbon footprints of wooden doors but also underscores the importance of considering various stages of the life cycle, from material acquisition to disposal, in assessing environmental impacts.

2.4 Contribution to circular economy

Circular Economy (CE) is described as an industrial model that aims to restore and regenerate resources intentionally and by design. It revolves around three key principles: preserving natural resources, optimizing resource output, and enhancing the effectiveness of systems (The Ellen MacArthur Foundation, 2015). This concept has garnered attention from policymakers, particularly in Europe (Bastianoni et al., 2023). However, the latest Circularity Gap Report highlights a concerning trend, showing that the global economy is only 7.2% circular. This is a decline from 9.1% in 2018 and 8.6% in 2020 (Circle Economy Foundation, 2023).

Research indicates that both LCA and circularity assessment can play roles as sustainability assessment methods for circularity strategies. However, neither approach can offer a complete overview of a system's environmental performance alone (Samani, 2023).

LCA can contribute to the development of more effective CE plans by considering both upstream and downstream effects, encompassing all relevant resources and impact areas (Rigamont et al., 2021). Initially, LCA focused on analysing a product's entire life cycle, from creation to disposal. It has since evolved to evaluate the benefits and impacts of reuse and recovery, broadening its scope from "cradle to grave" to "cradle to cradle". However, challenges persist, such as inconsistent modelling of open recycling loops and unclear guidelines for tracking multiple material uses with varying qualities (Haupt and Zschokke, 2017).

2.4.1 Circularity plan

The idea of a cycling plan is a comprehensive strategy intended to address the different obstacles that stand in the way of building a strong infrastructure for recycling products after they are first used. It explores the complexities of formulating plans intended to improve the circularity of products, all the while locating and making partnerships with organizations that are able to effectively recover and process these materials (Diaz et al, 2024). Cycling plan defines the producer's role in advancing circularity strategies (Figure 2.2).

Smarter product use and manufacture	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	R3	Reuse	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded products or its part in a new product with a different function
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recovery	Incineration of material with energy recovery

Figure 2.2 CE strategies (Morseletto, 2020).

Door is a product that is known for being more robust and long-lasting than other quickly moving consumer goods, is making sure that the cycling infrastructure can support these longer product lifespans. Although doors might last for fifteen to twenty years, the work of forming partnerships and figuring out the best routes for recycling and reclamation continues. This ongoing work demonstrates a dedication to sustainable methods and the ideas of the circular economy. The significance of standard operating procedures in recycling programs is highlighted by their capacity to disassemble doors in an organized manner, regardless of their unique structure. Each stage of the disassembly procedure calls for accuracy and cautious handling, starting with the removal of hardware and ending with the physical separation of rails, stiles, and core materials after the HDF skins have been peeled away. These facilities can effectively disassemble doors into its component pieces by using appropriate equipment and tools. This makes it possible to recycle and use the materials later on.

The circularity plan contributes to the following CE strategies (Moraga et al, 2019):

- Reuse, refurbish and repurpose parts to preserve the product's components.
- Preserve the materials through recycling and downcycling.
- Preserve the embodied energy through energy recovery at incineration facilities.

Return flows management must be designed appropriately to ensure the closing of the resource loops (Figure 2.3).

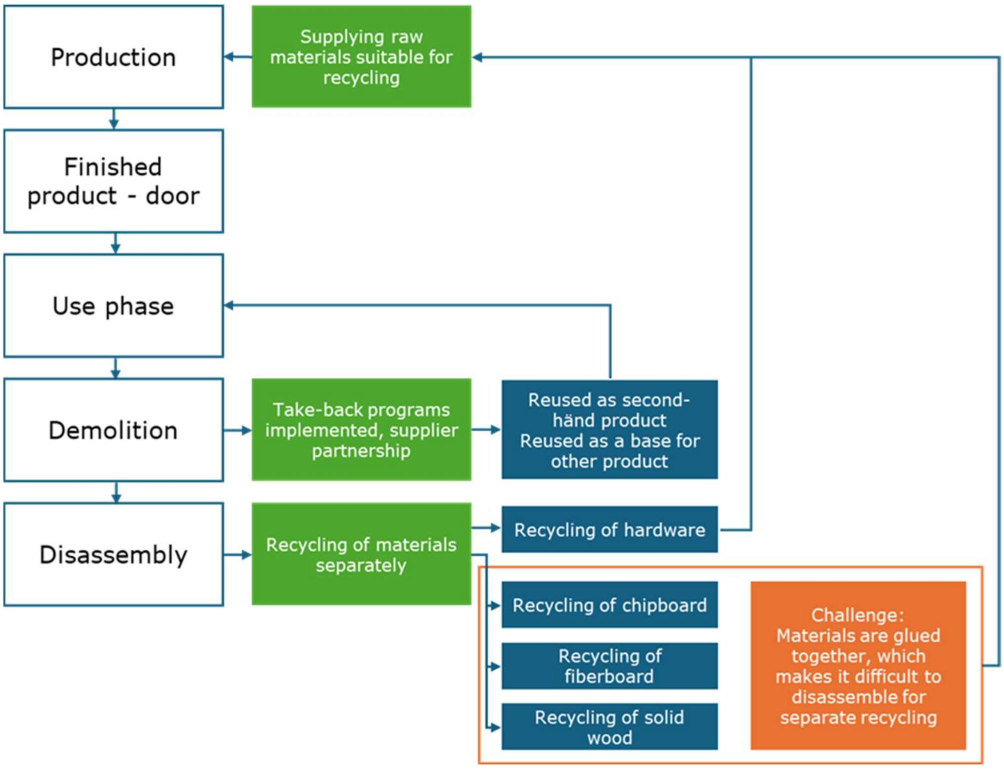

Figure 2.3 Circularity principles implemented to the door manufacturing processes.

It has been clarified that while recovery and recycling are widely used strategies in manufacturing, they don't always advance a circular economy, despite being the most commonly pursued goals so far. Due to their limited effectiveness, it's suggested that targets should prioritize other, more impactful CE strategies. These may include reducing waste, enhancing efficiency, closing production loops, and maximizing the retention of economic value in materials and products. Targets related to recovery and recycling (R8–R9) may not consistently drive a CE because these activities can compromise the integrity of products and fail to keep them within the economic cycle (Morseletto, 2020). Therefore, targets for R8–R9 should also emphasize minimal or physiological levels, directing attention towards more potent CE strategies (R0–R7). This shift in focus can better address the overarching goal of achieving sustainable and circular approaches to manufacturing and resource management.

2.4.2 Materials

Wood-based panels for doors are considered to be of non-construction non-structural use (no load-bearing structure) according to the type of application during the use stage of the product (Costa et al, 2024). The raw material for the panels can be both coniferous and non-coniferous tree species.

The door leaves consist of various wood-based materials (Table 2.1) which are bonded together with adhesives. This bonding complicates the demolition process, potentially leading to material breakage. Moreover, the surface treatment and adhesive are challenging to remove mechanically from the wooden components.

Table 2.1 Materials used in door construction (Costa et al, 2024).

Type	Sub-type	Definition	Use in the door
Veneer	Veneer	Thin sheets of wood peeled from blocks of wood using a slicing machine.	Skins
Particleboard or chipboard	Medium-density particleboard	Composed of wood pieces or other lignocellulosic materials (such as chips, splinters, shreds, and strands) that have been bonded by an organic binder and one or more processes (such as heat, pressure, humidity, or a catalyst)	Core Stiles and rails
	Oriented strand board		
	Flaxboard		
Fibreboard	Hardboard	Made from lignocellulosic materials, such as wood fibers, with the primary binding coming from the fibers' natural adhesive qualities and felting process	Core Skins Stiles and rails
	Medium-density fiberboard MDF		
	High-density fiberboard HDF		
	Softboard		

Recyclability

- MDF, HDF

Medium-density fibreboard (MDF) and particleboards are types of engineered wood made from leftover wood materials such as chips, shavings, and boards, combined with glues. These boards are manufactured using heat and pressure, along with additional adhesives. The main components of MDF and particleboards are wood and glues, which often contain toxic chemicals that raise sustainability concerns (Farjana et al., 2023).

MDF has traditionally been viewed as a non-recyclable waste product. However, MDF Recovery (MDF Recovery Ltd project, 2024) has created a technology that breaks down the glues in waste MDF, allowing the high-quality wood fibres to be reused in new, valuable applications. This innovation has led to partnerships with companies, including manufacturers, to ensure that scrap MDF is redirected towards more sustainable end-of-life solutions. Manufacturers will send waste MDF to a recycling facility where the recovered fibres are turned into natural fibre insulation products. The goal is to expand this recycling technology to other regions.

- Fibreboard, softboard, chipboard (particleboard)

Chipboard, also known as particleboard, is an engineered wood product made from wood chips, sawdust, and resin. It is widely used in furniture and construction due to its cost-effectiveness and versatility. Softboard, on the other hand, is lightweight and used for insulation, soundproofing, and as a backing material in furniture. It is a type of engineered wood product made from wood fibres bonded together using heat, pressure, and resin.

Recycling these boards is possible but challenging. The recycling process typically involves shredding the chipboard into small pieces, removing contaminants like nails and adhesives, and then processing these pieces into new particleboard. Advanced technologies, such as those developed by the EcoReFibre project (European Panel Federation, 2022), help streamline this process by separating materials and ensuring the quality of recycled wood fibres. One key focus area is mechanical recycling, which involves breaking down used wood-based panels into smaller pieces through processes like shredding or grinding. These smaller wood particles can then be reprocessed and formed into new panels or used as raw material for other wood products. Chemical recycling methods are also being explored, where the components of the wood-based panels are broken down into their molecular constituents using various chemical processes. This allows for the extraction of valuable materials that can be reused or repurposed.

- Flaxboard

Flaxboard is a type of engineered panel, similar to particleboard, but made from shives from flax plant stalks bonded with synthetic resin adhesive. These flax shives are a by-product of the linen industry. Flaxboard typically contains at least 70% flax and may also include other materials like wood particles. Although it shares some similarities with particleboard, flaxboard has unique properties and uses. Users should review its technical performance data for specific applications. Its lightweight nature, along with high fire resistance and good soundproofing, makes it ideal for fire-resistant door cores and partitions (Jones eta l, 2017).

Flax fibres break down in the soil within six months without harming the environment. They can be recycled three to five times before needing disposal (Timber Trade Federation, 2014). Currently, flaxboard manufacturers are recycling flaxboard and incorporating flaxboard waste as raw material in their production exploring the potential of incorporating flaxboard waste into their manufacturing processes, likely as a sustainable alternative or addition to their existing materials. Linex mentions on their website that any flaxboard rejected from their production lines is either turned into packaging blocks or recycled as raw material to make new boards (Linex Pro Grass BV, 2021).

2.4.3 Challenges

1. Establish partnerships with disassembly and recycling facilities, and cooperation for reuse options.

Building strong partnerships with disassembly and recycling facilities is essential, requiring significant coordination and agreement on processes and standards. Developing an in-house take-back and recycling system involves logistical, operational, and financial considerations. Manufacturers need to design efficient systems for collecting and processing used materials while working closely with chipboard producers to integrate recycled materials into new products. This cooperation can be complex due to differing production processes and quality standards (Wang et al, 2022).

Manufacturers must have detailed knowledge of the material's composition to maintain product standards and meet future material needs. As the demand for products with take-back systems increases, manufacturers must adapt their business models to include these options, which may involve additional costs and logistical planning.

Additionally, leveraging the second-hand market for refurbished doors requires an understanding of market dynamics and consumer preferences. This can be challenging but also offers potential revenue opportunities. Overall, the challenges revolve around creating an efficient, sustainable, and economically viable recycling and reuse system that aligns with both market demands and environmental goals (Uhrenholt et al, 2022).

2. Technology to separate materials from each other with minimum loss and investigate the recycling possibilities of these wooden materials.

Regarding technologies that facilitate the practical application of CE, there are various innovations that promote eco-friendly and more efficient production processes. Additionally, digital technologies play a role in enhancing material efficiency and managing waste. Specifically, sorting technologies aid in implementing waste management strategies, while other technologies help separate and analyse waste, making it possible to reintroduce waste as a valuable resource within the cycle. Furthermore, the adoption of the 3Rs (Reduce, Reuse, Recycle) principle is also facilitated by technological advancements. Technologies can be paired with methods like simulation. By using digital intelligence tools to develop circular scenarios, qualitative analysis is strengthened. This analysis can then be bolstered further by quantitative analysis using event simulation techniques, offering a promising approach for making economically advantageous decisions. This integration provides dependable decision support for advancing circular production and material consumption. Simulation techniques also hold potential for reducing production costs. For instance, they can help determine whether to engage in remanufacturing activities or not. Moreover, simulation techniques can assist in selecting the optimal strategy among the 3Rs for each product component, considering environmental impacts across different scenarios and the company's business model (Moreno, 2017).

3. Explore potential recycling pathway of wood-based materials.

Currently, the main pathway for all wood-based materials is chipboard production. The aim would be to learn more about if more valuable options and markets for single materials contained in this wood-based material exist and if it would be feasible to create a separate recycling stream for them.

If so, additional challenges arise. Various wood-based materials such as HDF, MDF, chipboard and solid wood, are bonded together. The bonding complicates the demolition process, potentially leading to material breakage. Identifying ways to ease disassembly through alternative glue options is already being investigated. Further, the surface treatment and adhesive are challenging to remove mechanically from the wooden components. Different types of wood-based materials like HDF, MDF, chipboard, and solid wood often undergo bonding during manufacturing, which can complicate the disassembly process and increase the risk of material breakage. To mitigate these challenges, alternative glue options can be explored to facilitate easier disassembly (Zimmer et al, 2023).

One approach is to use bio-adhesives that don’t consist of toxic chemical substances extracted from fossil resources (Hussin et al, 2022) or reversible adhesives that allow the separation of bonded components without causing damage. These adhesives can be designed to weaken or dissolve upon the application of specific conditions such as heat, moisture, or chemical agents. By employing reversible bonding techniques, the disassembly of wood-based materials becomes more feasible and less destructive.

3. LIFE CYCLE ASSESSMENT

3.1 Methodology

Life cycle assessment (LCA) is an effective method to assess environmental impacts and helpful tool for analysing performance of materials. LCA study includes calculating the environmental emissions that result from a product, process, or service as well as carefully tracking the energy and materials required across the supply and value chains. As a result, LCA assesses the possible cumulative environmental effects (Sala et al, 2021).

There are 4 stages in the LCA: goal and scope definition, inventory analysis, impact assessment and result interpretation. In Figure 3.1. it is shown the relationship between the stages that is defined in standard ISO 14040:2006+A1+A2:2020:Environmental management. Life cycle assessment. Principles and framework.

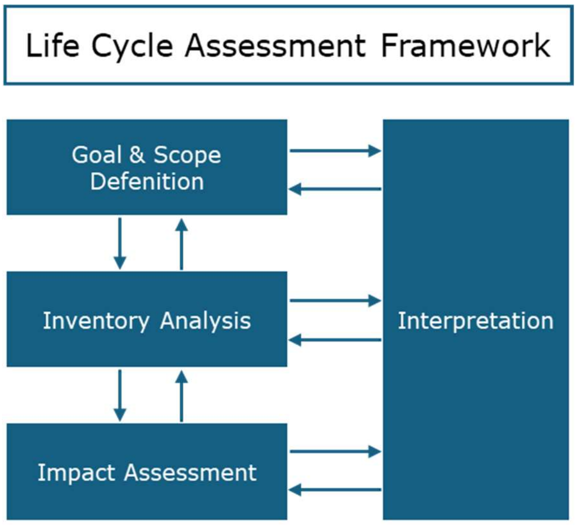

Figure 3.1 LCA stages (ISO 14040).

The goal definition addresses the main matters: why to perform LCA, who is the target audience and what is the product to assess. The scope definition includes specification of the product, which is going to be assessed, functional unit definition, the product system boundary explanation, intention for data quality and parameters. Inventory analysis stage includes the product process data collection such as definition of input and output flows. Consequently, LCI delivers quantifiable data on a product's environmental load over the course of its whole life cycle. Impacts on the environment caused on by a product's environmental burdens. The Life Cycle Impact Assessment (LCIA) assesses inventory systems. Impact categories are selected in order to quantify the impact, and then the equivalency approach is used to quantify the environmental impact within each impact category. The term "characterization" refers to this process. LCIA thus offers data on the product's environmental impact. Life cycle interpretation, the final stage of an LCA study, involves identifying environmentally major concerns and evaluating the accuracy and sensitivity of the LCA results. This phase additionally covers reporting, recommendations, and conclusions.

Cradle-to-grave analysis refers to the process of examining a product's effects across all five stages of its existence (A-C) (ISO 14040). The product's creation, when raw materials are sourced, is its "cradle," and its eventual disposal is its "grave." Also, transportation is considered in between any of the processes.

In 2004, the European Commission identified the need for EN standards to support the integrated multi-criteria assessment of buildings, civil structures, and construction products. These standards aimed to enhance transparency and communication about the environmental impacts over the entire life cycle of buildings and to address obstacles in the construction sector. Consequently, a series of standards was established to assess the sustainability of construction works, in accordance with EN ISO 14025 and EN ISO 14040/44. EN 15804, introduced in 2012, emerged as the key standard for developing reliable and verifiable LCA studies, which are documented as Environmental Product Declarations (EPDs). This standard outlines the core rules for construction products, services, and processes, encompassing modules A – D (Figure 3.2). EPDs have become an essential component of building LCA studies, routinely integrated through Building Information Modelling (BIM) models (Mirzaie, 2016). Today, EN 15804 stands as a pivotal sustainability standard for creating EPDs within the EU’s construction sector. The updated version, EN 15804 + A2, incorporates new calculations for end-of-life benefits in module D. This update provides detailed guidelines for assessing benefits and loads beyond system boundaries. Including the end-of-life phase in these calculations highlights the significance of circularity and recycling in evaluating environmental impact, thereby creating new opportunities for biobased materials (Ecochain, 2024).

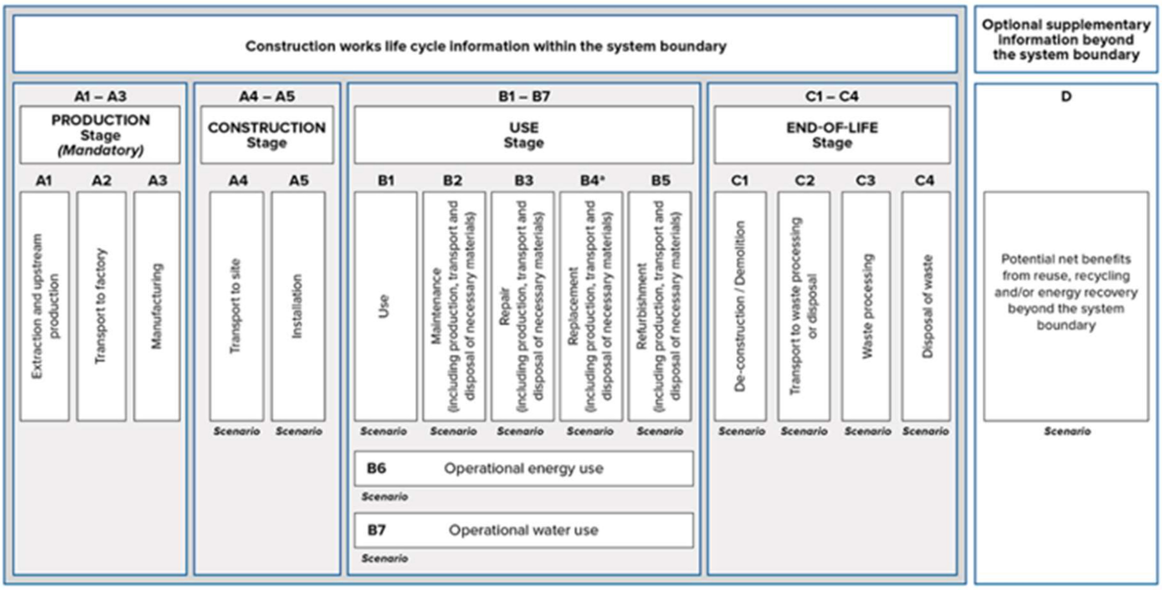

Figure 3.2 Modules A – D within the system boundary (EN 15804).

Building life cycle stages (Table 3.1) refer to the distinct phases a building goes through during its lifetime. In Europe, these stages are defined by the EN 15804 standard. Modules A1, A2, and A3 encompass the provision of materials, products, and energy, along with waste processing until waste is no longer waste or final residues are disposed of during the product stage. Stages A4 and A5 cover all impacts related to material losses during the construction process. The use stages B1 – B7 capture all impacts associated with the building's use throughout its entire life cycle, including the transport of materials and the impacts of energy and water usage. Note that stage B is not considered in this study. The end-of-life stages C1 – C4 include the deconstruction and demolition of the building, encompassing the impacts of transporting waste to processing sites and its disposal. This stage encourages design teams to consider environmental impacts early in the design process and to use recyclable or reusable materials to minimize these impacts. The 2019 update of EN 15804+A2 introduced Module D, which addresses the benefits and burdens from reusing products, recycling, or recovering energy from waste materials generated during the construction, use, and end-of-life stages.

Table 3.1 Modules A – D description (Masson, 2023).

Stage	Description
A1-A3 Construction Materials	The supply of raw materials (A1) encompasses emissions produced when raw materials are extracted from nature, transported to processing facilities, and processed. This stage also considers losses of raw material and energy. Transport impacts (A2) include emissions from transporting all raw materials from suppliers to the manufacturer's plant and the impacts of fuel production. Production impacts (A3) involve the manufacturing of materials and fuels used by machines and managing waste generated during production until it reaches an end-of-waste state.
A4 Transportation to site	Transport of building products from the manufacturer's plant to the construction site (A4) involves exhaust emissions and environmental impacts from fuel production.
A5 Construction/installation process	Site operations (A5) cover emissions from energy use, environmental impacts of fuel and energy production, water usage, and waste management until the end-of-waste state.
B1-B7 Maintenance and material replacement, energy and water consumption during use	Maintenance and material replacements (B1-B5) account for environmental impacts from replacing building products at the end of their service life.
C1-C4 Deconstruction	Deconstruction impacts include processing recyclable construction waste for recycling (C3) until the end-of-waste stage or pre-processing and landfilling non-recyclable waste (C4) based on material type. This stage also includes emissions from waste energy recovery.
D External impacts/end-of-life benefits	External benefits involve emission reductions from recycling building waste. Benefits of reused or recycled materials include the positive impact of substituting virgin materials with recycled ones, and the benefits of recovering materials for energy production, replacing other energy streams based on average energy production impacts.

3.1.1 Construction of a door

Doors can feature either a solid or hollow core and come in a range of styles and constructions (Figure 3.3). The frame of a door leaf includes horizontal rails at the top and bottom and vertical stiles on the sides. The core, which is the central panel filling the door frame, can be made from various materials such as wood, metal, or composite materials. The core panel is covered with skins, which in some designs also cover the stiles and rails for a uniform appearance. Hinges, typically made of metal for durability, are attached to allow the door to swing open and closed. The stiles, rails, and core panel are often crafted from different types of wood or wood-based materials, and they are glued together using various adhesives to ensure structural integrity. To enhance both protection and aesthetic appeal, the skins on the surface of the door undergo multiple treatments. These treatments include the application of layers of sealants to protect against moisture and wear, primers to ensure even paint application, and paint for colour and finish. This multi-layer treatment not only extends the life of the door but also provides a wide array of design options to suit different tastes and interior styles.

The materials chosen for each component of the door can significantly affect its performance and durability. For example, solid wood cores offer excellent strength and sound insulation, while hollow cores are lighter and more cost-effective. Composite materials can provide a balance between these qualities, offering both durability and affordability.

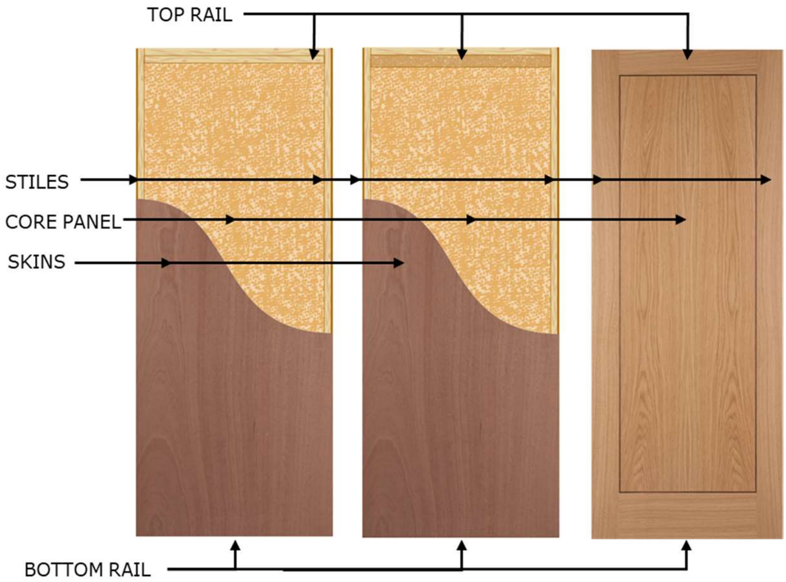

Figure 3.3 Construction of doors.

3.1.2 Software and data acquisition

The LCA calculation was done through OneClick LCA software. OneClick LCA is a leading global IT business which helps reducing the carbon footprint of manufacturing and construction. LCA software, which is automated, user-friendly, and globally accessible enable to assess and mitigate the environmental effects of construction, infrastructure, and renovation projects. Using OneClick LCA software aids in analysing assessment results effectively. The software features comparison tables and graphs, which help users understand the sources of impacts by viewing the results. On the results page, the cumulative impacts can be examined to determine which life-cycle stages produce the highest emissions. Once these stages are identified, the specific streams can be pinpointed in a detailed report, such as materials or energy sources, that contribute to these impacts. This detailed analysis allows for better targeting of areas for improvement in environmental performance.

Ecoinvent v3.8 and One Click LCA databases were used as sources of environmental data. The LCA depend on the accuracy and quality of initial data and LCA database. OneClick LCA is a reliable tool for conducting the assessment since the datasets are constantly reviewed, requirements for LCA data is set and detailed rules are used to apply them. There are different types of data. Inspected by the policy, including public EPDs, generic LCA data for key materials, energy and processes which is country specific or global adopted for EN 15804+A2, Ecoinvent datasets. The data is structured, reviewed and ready to use (Steven, 2023).

The input data was obtained by the constant monitoring of the production processes and research in the leading wooden door manufacturing company in Europe. The production quantities were taken from annual sales reports. Environmental data of the manufacturing site was obtained through internal annual EHS reports of the company. The most current available data should be used, however, any 12-month period in the last 5 years (EN 15804 2012+A2). The reference study period is calendar year 2022.

3.2 Case study

The case study is conducted in collaboration with one of the leading wooden doors manufacturing company in Europe. The data is provided by the manufacturing facilities based on the annual monitoring of production processes and considered to be accurate since the manufacturing company has the interest to use this case study for optimisation of the production processes.

3.2.1 Goal and scope definition

This case study consists of two parts. First part: evaluation of the environmental impacts of 4 interior wooden doors with different design and main materials, considering stages: production, construction, and end of life. The use stage considered not applicable since the product primary environmental impact occur during other stages of its life cycle. Three waste disposal scenarios are considered: (1) sorted waste to incineration or recycling 95% and to landfill 5% (current method of disposal); (2) as 100% to reuse; (3) 95% recycling and 5% to landfill of wooden materials, 100% of steel materials to reuse and 95% incineration of hazardous waste. Comparison and analysis of the environmental impact results. Second part: identification of the main contributing wooden material. The goal of the study is determining the most efficient disposal approach and identifying the environmental categories with possibilities for improvement through comparative LCA.

A door is a mechanism designed for specific function. Interior door is designed to be used inside a building as an entrance and exist between different rooms and spaces. It has light and thin construction, available in different designs, can be customized in any size, and can include various types of materials. The construction of a door consists of door leaf and a frame which are connected by moving mechanisms.

In this study 4 different types of interior door leaves will be studied that has a wood and wood-based panels as a main material (Table 3.2).

Table 3.2 Construction and materials used for each design.

Design	**WD1**	**WD2**	**WD3**	**WD4**
Construction	Stiles, rails, core covered by painted skin with veneer edgeband	Stiles and rails painted, thin panel painted	Stiles and rails painted, thin panel painted	Stiles, rails, core covered by painted skin with veneer edgeband
Core / panel material	Fiberboard, soft	Chipboard	Chipboard	Flaxboard
Stiles and rails (set)	MDF	MDF	Solid wood pine	Solid wood pine
			MDF	
			HDF	
Skin	HDF	-	-	HDF
Edgeband	Veneer	-	-	

3.2.2 Functional unit and system boundary

A functional unit is defined in EN 15804 as "quantified performance of a product system for a construction product or construction service for use as a reference unit in an EPD based on LCA that includes all stages of the life cycle". It refers to the product function and covers all data from cradle to grave.

In the case of interior wooden door, the functional unit is 1 square meter of door for specific use area. The reference unit is calculated with the reference product size. The size of door leaf is taken as the most common one (Table 3.3).

Table 3.3 Common size of the door.

Width, m	Height, m	Thickness, m	Area, m2
0,825	2,04	0,04	**1,683**

The production data was obtained from the one of largest door producers in Europe. The quantities of used materials were calculated for each design and given by the producer.

The set of processes that are considered for the assessment's subject are determined by the system boundaries (Figure 3.4). In order for the LCA results to be used for comparison and for better understanding and interpretation, an accurate representation of the system boundaries is required. The system boundary used in this study is "from cradle to grave," which includes all necessary stages from the extraction of raw materials to the end of life.

The system includes the finished door leaf with standard hardware: lock, hinges, screws; and surface treatment. To the scope is also added the packaging material that is used to protect the product during transportation to the customer. Since the product never leaves manufacturing site without the packaging, it is inevitable part of the product and is considered as unavoidable part of LCA.

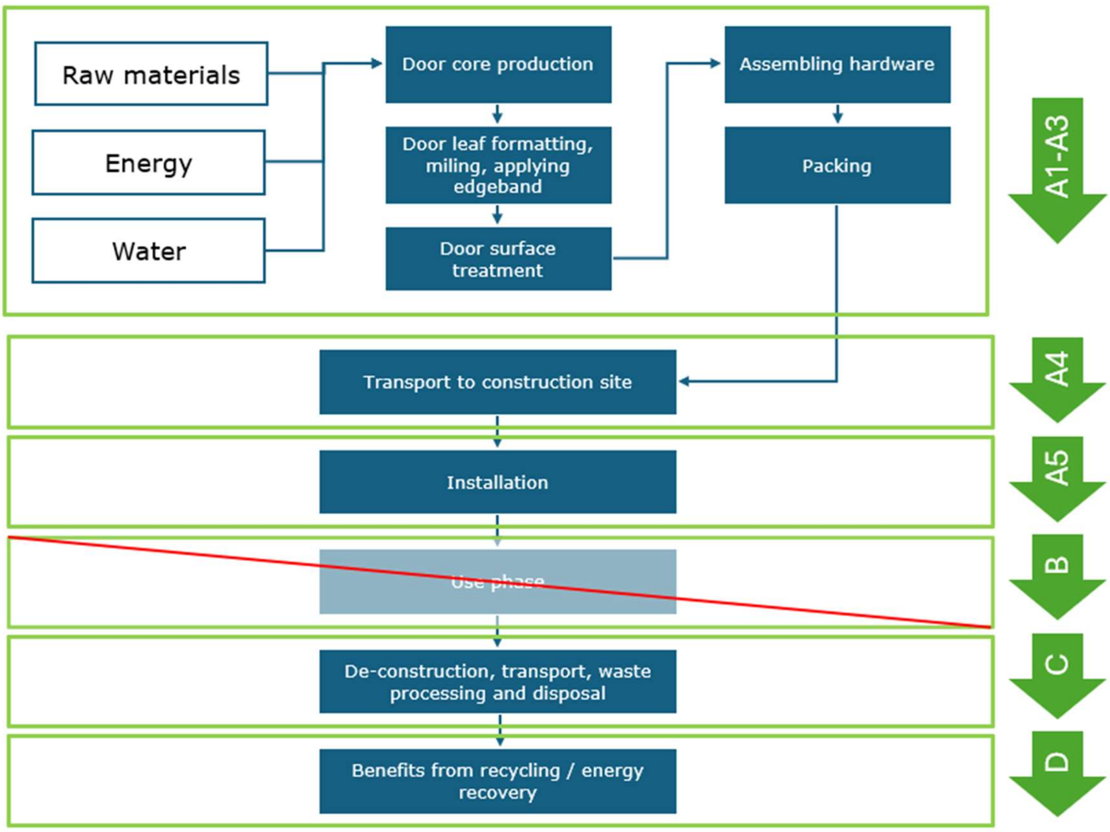

Figure 3.4 System boundary.

3.3 Life cycle inventory analysis

3.3.1 Life cycle inventory

The comprehensive Life Cycle Inventory (LCI) dataset contains information about the inputs and outputs during the production and distribution phases of a product. This dataset covers resource consumption, material usage, waste generation, and the final product itself. A detailed understanding of these elements is essential for conducting a thorough LCA that assesses the product's environmental impact throughout its entire lifespan.

Using the model, LCI calculations are formulated to gather and quantify every elementary flow throughout the related processes. Gathering the information needed to define each unit process within the system boundaries is crucial for LCI. Further processing of LCI data produces a set of indicator results for various impact categories. The final calculations, including data validation and allocation process application, are integrated into LCI (Table 3.4). The OneClick LCA software ensures the required level of data quality while simplifying the data collection process significantly. The datasets utilized for modelling are detailed in Appendix 1.

Table 3.4 Inventory table

Exact material specification/trade name/product number	Part weight (kg)	Weight per reference unit A1 kg/m2	Part volume A1 (m3/m2)	Ingoing Raw material (incl waste) kg/m2 A2	Production loss % A1	Total Weight (without waste) (kg)	Waste (kg/m2) A3	Waste (m3/m2) A3
WD1								
MDF	12,18	7,2371	0,0119	11,2029	35,4	12,18	3,965828	0,006501
HDF	5,80	6,8925	0,0081	7,3168	5,8	11,60	0,424376	0,000499
Fiberboard, soft	10,20	6,0606	0,0253	6,3462	4,5	10,20	0,285578	0,001190
Veneer edgeband	0,01000	0,0059	0,0000089	0,0061	2,6	0,01	0,000159	0,000000
Glue PVA	0,01	0,0059	-	0,0060	1,1	0,01	0,000066	-
Glue EVA	0,63	0,3743	-	0,3831	2,3	0,63	0,008812	-
Hotmelt	0,03	0,0178	-	0,0180	0,9	0,03	0,000162	-
Sealant	0,09	0,0535	-	0,0559	4,3	0,09	0,002403	-
Primer	0,00	0,0018	-	0,0028	35,6	0,00	0,000985	-
Paint + Hardener + Thinner	0,69	0,4100	-	0,7481	45,2	0,69	0,338160	-
Mass per declared unit, kg/m2		**21,06**						
Total weight of door (without hardware), kg						**35,44**		
WD2								
MDF	21,28	12,6441	0,0207	15,7657	19,8	21,28	3,1216077	0,005117
Chipboard	6,15	3,6542	0,0061	3,8999	6,3	6,15	0,2456925	0,000409
Glue EVA	0,14	0,0832	-	0,0842	1,2	0,14	0,0010103	-
Glue PVA	0,12	0,0713	-	0,0726	1,8	0,12	0,0013069	-
Primer	0,31	0,1842	-	0,2499	26,3	0,31	0,0657303	-
Paint + Hardener + Thinner	0,29	0,1723	-	0,2676	35,6	0,29	0,0952529	-
Mass per declared unit, kg/m2		**16,81**						
Total weight of door (without hardware), kg						**28,29**		
WD3								
Solid wood Pine	8,28	4,9198	0,0102	5,1516	4,5	8,28	0,2318224	0,000483
MDF	5,31	3,1551	0,0052	4,7374	33,4	5,31	1,5822775	0,002594
HDF	2,93	1,7409	0,0020	1,8560	6,2	2,93	0,1150727	0,000135
Chipboard	8,46	5,0267	0,0084	5,2802	4,8	8,46	0,253449	0,000422
Glue EVA	0,25	0,1468	-	0,1486	1,2	0,25	0,0017828	-
Glue PVA	0,12	0,0713	-	0,0721	1,1	0,12	0,000793	-
Primer	0,53	0,3149	-	0,4830	34,8	0,53	0,1680828	-
Paint + Hardener + Thinner	0,78	0,4635	-	0,8321	44,3	0,78	0,3686031	-
Mass per declared unit, kg/m2		**15,84**						
Total weight of door (without hardware), kg						**26,66**		
WD4								
Flaxboard	16,33	9,7029	0,0277	11,0638	12,3	16,33	1,3608416	0,003888
HDF	5,38	6,3933	0,0075	6,7016	4,6	10,76	0,3082745	0,000363
Solid wood Pine	3,80	2,2579	0,0047	2,3422	3,6	3,8	0,0843189	0,000176
Glue EVA	0,11	0,0654	-	0,0662	1,2	0,11	0,0007938	-
Glue PVA	0,01	0,0059	-	0,0060	1,3	0,01	7,826E-05	-
Sealant	0,06	0,0357	-	0,0368	3,1	0,06	0,0011405	-
Primer	0,09	0,0535	-	0,0777	31,2	0,09	0,0242507	-
Paint + Hardener + Thinner	0,47	0,2793	-	0,4678	40,3	0,47	0,1885144	-
Mass per declared unit, kg/m2		**18,79**						
Total weight of door (without hardware), kg						**31,63**		
Hardware								
Lock	0,275	0,1634						
Hinge	0,14	0,0832						
Screws	0,114	0,0677						
Mass per declared unit, kg/m2		**0,3143**						
Packaging								
Pallet		0,0155						
Plastic stretchwrap	0,1500	0,0891						
Cardboard edges	0,5098	0,3029						
Mass per declared unit, kg/m2		**0,4075**						

3.3.2 Allocation

Allocation is required if some material, energy, and waste data cannot be measured separately for the product under investigation (ISO 14040). Allocation by mass or volume was used for manufacturing environmental data: heat, electricity, and water consumption.

Environmental data is allocated using 4 allocation factors (Table 3.5):

1. Factor depends on the share of the factory environmental data depending on the product category (door and frame production 95% and thresholds 5%) since there are different processes involved in the production of threshold.

2. Factor depends on the number of doors produced in 2022 at the factory.

3. Factor that depends on the product category produced at the factory (Table 3.6) valid for all case study doors.

4. Factor that depends on the line of standard interior door (Table 3.7) valid for WD1, WD2, WD3.

Table 3.5 Allocation factors, including number of produced doors (year 2022) and allocated amounts of heat, electricity, and water consumption.

	Number of doors produced in 2022	Allocation factor 1	Allocation factor 2	Allocation factor 3	Allocation factor 4	Heat MWh	Heat MWh/m2	Electricity MWh	Electricity MWh/m2	Water m3	Water m3/m2
WD1	2164	0,95	0,0062	0,54	0,54	4,3847	2,6053	3,3588	1,9957	4,5430	2,6994
WD2	1975	0,95	0,0057	0,54	0,35	2,6031	1,5467	1,9941	1,1848	2,6971	1,6026
WD3	3569	0,95	0,0103	0,54	0,54	7,2316	4,2968	5,5396	3,2915	7,4926	4,4519
WD4	1946	0,95	0,1016	0,03	-	7,3547	4,3700	5,6339	3,3475	7,6202	4,5277

Table 3.6 Product categories produced at the factory (year 2022).

Category	Quantity	% for allocation	
interior frames	175105	27,20%	95 % of the factory environmental data (what remains to be allocated after the threshold production)
HP frames	74313	11,54%	
various - without chemicals, hardware and thresholds	27215	4,23%	
Standard Interior Doors (including WD1, WD2, WD3)	348094	54,06%	
HP doors (including WD4)	19147	2,97%	
thresholds, interior	103803	77,46%	5 % of the factory environmental data
thresholds, exterior	30198	22,54%	

Table 3.7 Lines of standard doors produced at the factory (year 2022), valid for designs WD1, WD2, WD3.

Standard Interior Doors Lines	348094	
Advance (WD1, WD3)	186621	53,61%
Clever (WD2)	121396	34,87%
Superior	1027	0,30%
Others	39050	11,22%

3.3.3 Assumptions

For more accurate comparison results the following assumptions were made:

- Products are produced at the same factory.
- Suppliers of raw materials are the same for each design, that means transportation distances from supplier of raw materials are considered to be the same.
- Since the size of each door design is the same, then the packaging used is similar.
- Transportation distances to the sorting and incineration facilities and landfill are taking according to One Click LCA recommendations.
- Distance from the factory to the building site is the same (transported to the same building site)
- Production loss (data given by engineering department, calculated based on drawings and factory data monitoring)
- Hardware used is the same, cutoffs for hardware are the same.
- Since the studied product is final item, the life span of a product is considered to be long and actions for maintaining the product as installed during service life is

close to zero, the impact of the use stage is assumed to be not applicable and is not included in the study.

- During the demolition process, energy and natural resource consumption appears insignificant.

3.3.4 The product stage A1-A3

Environmental impacts referred to the production phase involve the extraction and processing of raw materials, packaging materials, ancillary materials and supplementary data. Furthermore, waste management practices within manufacturing facilities and material losses incurred during production processes are considered necessary components of the investigation. The assumed way of the transportation is a lorry.

The manufacturing process initiates with the bonding and compression of door leaf components, followed by multiple milling operations to attain precise dimensions, and place hardware installation holes and selected edge profiles. Subsequently, surface treatment procedures are executed, followed by painting and installation of hardware such as locks and hinges. The electricity consumption is modelled as "residual mix", which is LCA study for country specific residual electricity mixes based on AIB 2022 and calculated by One Click LCA 2023 (AIB, 2023). The combination of energy sources, associated CO_2 emissions, and radioactive waste that is gathered from countries with excess energy resources is known as the European Attribute Mix (EAM). The EAM for 2022 is 9,22% renewable, 17,02% nuclear and 73,76% fossil. For heating purposes, incineration of woodchips is employed. The heat of combustion of chips from post-consumer wood is based on the low heating value of mixed wood chips and furnace efficiency. Only waste related to the production process is produced and managed through incineration. Finally, for logistical purposes, doors are set on pallets up to 20 units each, with protective cardboard and plastic wrapping ensuring product integrity during transportation.

3.3.5 The construction stage A4-A5

The transportation impacts that are caused by delivering final items to building sites (A4) includes emissions connected to fuel generation, related infrastructure emissions, and direct exhaust emissions from fuel. The transportation distances used is a weighted average, which is measured considering previous transportation records. Transportation data was averaged, taking into account historical logistics records. This analysis identified destinations most frequently involved in transporting the products. As a result, calculations were made based on this information and average distance was further considered. The assumed way of the transportation is a lorry, with the vehicle capacity value of 1. Empty returns are considered to be out of scope.

Packaging waste is produced when the products' packaging is removed after installation. Since the finished product is simply installed, neither material loss during the installation phase nor the requirement for such building techniques are anticipated. Hand tools can be used for the mounting and fastening elements of the installation process. No further supplies are required for the installation process. Because of its small size and the impact, it has on this life-cycle stage, the energy consumption for installing therefore qualifies as zero.

3.3.6 The end-of-life stage C1-C4

All system outputs are considered as waste at the end-of-life (EoL) phase until they enter the "end-of-waste state" (Antunes et al, 2021). Any material or output that fits the following requirements is in the end-of-waste state:

- It is used for particular purposes.
- There is an existing market or demand for it.
- It meets technical requirements for specific purposes.
- There won't be any general negative effects from using it.

The net benefits and loads resulting from product reuse, recycling, or energy recovery from "end-of-waste state" materials from the construction stage (A4–A5) and end-of-life stage (C1–C4) are covered in Module D. Only materials or products that have reached the "end-of-waste state" and are used to replace other materials or fuels in another product system are covered by Module D.

In this case study 3 options of end-of-life scenarios are examined (Tabel 3.8). The datasets and calculations are demonstrated in Appendix 2.

Tabel 3.8 End-of-life scenarios

Material	Scenario 1	Scenario 2	Scenario 3
Wood	95% incineration 5% to landfill	100% to reuse	95% to recycling 5% to landfill
Paint and glue	95% incineration hazardous waste 5% to landfill	100% to reuse	95% incineration hazardous waste 5% to landfill
Steel	95% to recycling 5% to landfill	100% to reuse	100% to reuse

The percentages of materials that take the various treatment paths are included in the scenarios. Each material's proportion at each stage will always add up to 100%, which represents the entire amount of the material that entered that stage. The EoL scenarios are based on available information regarding material treatment at the product EoL.

Scenario 1

For scenario 1 the EN17213 Annex B's end-of-life scenario for wooden door sets is studied. The paint, glue, metal, and wood have been sorted. Energy and resource inputs for treating and sorting these waste streams in preparation for recycling and energy-recovery incineration are taken into account in Module C3. In accordance with the timber door sets end-of-life scenario (EN17213 Annex B Figure 3.3), 5% of the wood waste is disposed of in landfills along with 5% of metal and 5% of paint and glue waste. In addition, burned hazardous waste is covered by Module C4 (not by Module D for benefits received outside of the system boundary). Assumptions about waste management are made with regard to the sorting processes and the distance of transportation. It is believed that the waste comes from the mixed construction waste industry and that a lorry is the waste collecting vehicle. The truck that is delivering the waste is expected to travel 50 km from the demolition site to the waste disposal facility. Upon arrival to the waste management plant, recyclables and/or materials that can be recovered for energy are separated from the waste and used appropriately.

As specific national data is not used for timber / wooden products, then according to the end-of-life scenario of timber windows and door sets (EN17213 Annex B), 100% of sorted timber materials goes to incineration. The wooden pallet, wooden board, cardboard packaging, and plastic packaging used during transportation are also incinerated for energy recovery or recycled (module A5).

The benefits and loads of incineration and recycling are included in Module D. Amount of recycled material put into the system (A1-A3) minus amount of recycled material leaving the system (C3) that is how to get net recycled material used as the quantity for the loads and benefits in module D (Graham, 2021). Plastic and steel parts hold potential for recycling and material recovery for secondary material production purposes, that reduce the need for virgin raw materials (D). The wooden content of the door leaf has great heating value and are applicable for energy production upon used as a fuel in the incineration process (D), decreasing the demand for virgin fuel production and use. Use of Exported Energy datasets are required for EoL option for incineration with energy recovery. The formula to calculate Exported Energy is:

Exported Energy = Quantity of incinerated material * Lower Heating Value * Efficiency

Lower heating value is taken from dataset. Efficiency values 62% for thermal efficiency, 11% for electricity efficiency (so-called "Nordic scenario"). It is calculated separately for each material, since materials has different lower heating value, then summed up and the result is put to the D module.

Scenario 2

For scenario the option of reuse of the whole product is considered. The total 100% of materials are going to reuse. Basically, the product is discarded after installation as it is and taken to the refurbishing facility, where minor renovation is made, and then moved to the next point of operation. Assumption on the transportation distances from the disassembly site to the reuse facility is considered to be 50 km and the transportation is done by the lorry.

For modelling reuse scenario in OneClick LCA software "dummy" dataset is used – "Materials for re-use". Dummy dataset "materials for recycling" is also used but only for mass balance purposes. These "dummy" datasets in OneClick LCA software facilitate the simulation of various scenarios and provide standardized set of data that can be applied to evaluate outcomes. If we use "materials for recycling" dataset, it will populate materials for recycling in output flows table 1 kg/kg. Reuse dataset doesn't populate any environmental indicators, so both of them should be used in conjunction. Therefore, the outcomes of these "dummy" datasets are demonstrated in the EoL output flows – how much material is going for reuse, indicating the benefits in the D module and providing overview of materials circularity. There are no waste treatment processes for either of materials, the product is being reused 100%, so there are any burdens in C3. The C4 module is empty, nothing is sent for landfill or energy recovery.

For module D there are no loads from the product materials because there is no treatment process for materials used in the product, only benefit for avoided material production The benefits and loads of recycling the packaging plastic are included in Module D. Plastic packaging parts hold potential for recycling and material recovery for secondary material production purposes, that reduce the need for virgin raw materials (D).

Scenario 3

For scenario 3 the possibility of full recycling of output wooden materials is reviewed. Since the circularity plan of the manufacturer includes such scenario and different beneficial options are examined, the quantifying the potential of this scenario is valuable for comparable reasons. Wooden materials are going to recycle with 95%, 5% of wooden materials are still considered to end up at the landfill considering scrap, mechanical removal of paint or glue, and other residuals. Steel materials are assumed to be 100% reused. The paint and glue with 95% go to incineration of hazardous waste. The remaining 5% of wood and paint and glue is assumed to be the amount of material that can't be mechanically separated and considered to be a scrap and end up at a landfill. The wooden material is efficiently recycled and functions as a primary material substitute. The challenges of such scenario for the present situation are stated in chapter 2.4.3.

The paint, glue, metal, and wood have been sorted. Energy and resource inputs for treating and sorting these waste streams in preparation for recycling are taken into account in Module C3. Burning of hazardous waste is covered in Module C4 (not by Module D for benefits received outside of the system boundary). There are assumptions made regarding disposal of waste with regard to the sorting processes and the distance of transportation. It is assumed that a lorry is the waste collection vehicle. From the demolition site to the waste handling point, the truck carrying the waste is expected to drive 50 km. Recyclable materials are separated from the waste upon arrival at the waste management facility and put to the intended purpose. Wooden materials are sent to recycling with the benefit for the wooden pallet production.

3.3.7 Biogenic carbon

Analysing the removal and emission of biogenic CO_2 is important throughout the life cycle of products manufactured with wood or wood-based materials. Through photosynthesis, CO_2 is taken from the atmosphere and incorporated into biomass as it grows. Until it is released back into the atmosphere through decomposition or burning at the end-of-life stage, this carbon remains in the wood-based panels.

Negative = Stored in product Positive = emissions due to decomposition / combustion

In LCA for buildings, a big debate is about how to deal with biogenic carbon, which is carbon released or taken in by plants during their growth and later released when they're used or disposed of (Hoxha et al, 2020). There are two main ways to handle this. The first way, called the '0/0 approach' or 'carbon neutral approach,' assumes that any CO_2 released from a bio-based product is balanced out by the CO_2 absorbed during the plant's growth. As a result, there is no consideration for the absorption (0) and emission (0) of biogenic CO_2 and it is not considered in any module of the system boundary (A-D). The second approach, used in this study, is called the '-1/+1 approach.' It tracks all the flows of biogenic carbon throughout the building's life. This means it looks at both the carbon absorbed (-1) and released (+1) by the building, as well as any transfers of carbon between different systems. For example, when trees grow, they absorb CO_2, and when they're used in building materials, that carbon is transferred to the building. But when the building is demolished, or if materials are recycled, that carbon is released again. This approach aims to make sure the balance of biogenic carbon is zero for all parts of the building. For this case study the -1/+1 approach was used. Compared to the 0/0 approach, the -1/+1 approach gives a better picture of all the biogenic carbon flows. The calculations for biogenic carbon were conducted for modelling in OneClick LCA software and are demonstrated in Appendix 3.

4. RESULTS AND DISCUSSION

The primary focus in this case study is comparison of the results obtained through LCA of four interior wooden doors with different designs. The main points to compare:

- Impact categories allow us to compare different EoL scenarios and see how much these scenarios affect the overall environmental impact. By changing the disposal method, we can measure the difference in impact. Four EoL scenarios will be compared to determine which option is the most environmentally friendly. This comparison helps to understand which disposal method results in the least harm to the environment, guiding toward more sustainable management practices.

- Different stages of a product's life cycle will be examined to see which ones have the most significant environmental impact and why. GWP category will be compared of each stage such as production, transportation, usage, and disposal. This comparison helps to identify which stage contributes most to greenhouse gas emissions. By understanding the specific reasons behind these impacts, improvements can be targeted more effectively to reduce the overall environmental footprint.

- To determine the environmental impact of different materials, the percentage contribution of various wooden materials will be compared from the beginning of their life cycle to the point where they are ready for use (known as cradle to gate). By focusing on the raw materials stage, specifically the A1-A3 modules, it can be identified which materials are the main emission hotspots. This means finding out which materials produce the most emissions. Understanding these hotspots helps us pinpoint where we need to make changes to reduce the environmental impact.

4.1 Life cycle impact assessment

In the manufacturing of interior wooden doors, various processes contribute to different environmental impact categories. An impact category (Table 4.1) brings together various emissions to assess their overall effect on the environment. Emissions vary widely depending on their source; for instance, those from harvesting raw materials are quite different from those generated by electricity production. Impact categories help organize these diverse emissions by categorizing them based on their environmental effects. During the Life Cycle Impact Assessment phase of a LCA, emissions are converted into standardized, actionable figures. Emissions contributing to the same environmental impact are combined into a single unit, often expressed in kilograms of CO_2 equivalents (kg CO_2-eq). This method allows different types of greenhouse gases, regardless of their original measurement units, to be grouped into a single impact category. This unification simplifies the assessment process, making it easier to evaluate and compare the environmental impacts of different activities or products. By using a common metric for climate change, such as CO_2-eq, it's possible to create a clear and comprehensive picture of the overall impact. This approach helps identify the most significant sources of emissions and prioritize efforts to reduce the environmental footprint effectively. It also aids policymakers, businesses, and researchers in making informed decisions to achieve sustainability goals and mitigate climate change (Ecochain Technologies, 2024).

Table 4.1 Environmental impact categories that will be compared in this case study (Ecochain Technologies, 2024).

Impact Category	Abbr	Unit	Description
Global warming potential - total	GWP total	kg CO_2-eq	An indicator of potential global warming is linked to the emissions of greenhouse gases into the atmosphere. Categorized into 3 subcategories based on their source: (1) fossil Resources, (2) bio-based Resources and (3) land use.
Global warming potential - fossil	GWP fossil	kg CO_2-eq	The GWP fossil indicator considers the global warming potential of greenhouse gas emissions and sequestration in all forms, resulting from the oxidation or reduction of fossil fuels or substances containing fossil carbon, such as during combustion or landfilling.
Global warming potential - biogenic	GWP biogenic	kg CO_2-eq	Carbon dioxide is produced when organic material undergoes combustion or decomposition.
Global warming potential – land use and land use change	GWP luluc	kg CO_2-eq	The greenhouse gas emissions and compounds (CO_2, CO, and CH4) that result from changes in the designated carbon stock due to land use and land use change are included
Ozone depletion	ODP	kg CFC-11-eq	An indicator of emissions into the air leads to the depletion of the stratospheric ozone layer.
Acidification	AP	kg mol H+	An indicator of potential soil and water acidification arises from the release of gases like nitrogen oxides and sulfur oxides.
Eutrophication – freshwater	EP	kg PO4-eq	An indicator of freshwater ecosystem enrichment with nutrients stems from emissions of nitrogen or phosphorus-containing compounds.
Photochemical ozone formation	POCP	kg NMVOC-eq	Indicators of gas emissions influencing the formation of photochemical ozone in the lower atmosphere (smog) catalyzed by sunlight.
Depletion of abiotic resources – minerals and metals	ADPE	kg Sb-eq	An indicator of natural non-fossil resource depletion.
Depletion of abiotic resources – fossil fuels	ADPF	MJ, net calorific value	An indicator of natural fossil fuel resource depletion.

GWP, or Global Warming Potential, encompasses four key indicators: GWP Total, GWP Fossil, GWP Biogenic, and GWP Luluc. GWP Total represents the collective impact of fossil, biogenic, and land use and land use change (Luluc) activities. GWP Fossil focuses on the greenhouse gas emissions and sequestration resulting from the oxidation or reduction of fossil fuels and carbon-containing substances. This includes processes like combustion and landfilling, as well as interactions with inorganic materials such as those found in cement or lime-based building materials. GWP Biogenic accounts for carbon dioxide emissions stemming from the combustion or decomposition of organic matter. It's essential for transparency within GWP assessments to separately present GWP Fossil and GWP Biogenic data. GWP Luluc specifically addresses the impact of land use and land use change on greenhouse gas emissions and bonds. It considers changes in carbon stocks associated with land use activities, like deforestation or afforestation.

In assessments, GWP Total tends to show lower results due to the inclusion of GWP Biogenic (Table 4.2 Figure 4.1). This indicator factors in the carbon dioxide absorbed during biomass growth and its subsequent storage over the material's lifespan. It also considers emissions from biomass oxidation or decay, including those resulting from combustion. The transfer of biogenic carbon between product systems, such as wood recycling, must be considered in these assessments. The uptake of biogenic CO_2 and transfers from previous product systems are represented as negative values in LCA, while emissions from biomass are characterized as positive values. This distinction helps accurately capture the overall impact of biogenic carbon within product systems (LCA.no AS, 2024).

Table 4.2 Results environmental impact (%) for 10 impact categories (data taken from OneClick LCA model).

Category	WD1 EoL sc1	WD1 EoL sc2	WD1 EoL sc3	WD2 EoL sc1	WD2 EoL sc2	WD2 EoL sc3
GWP-total	100,0000	89,7630	99,9852	73,9664	67,8561	73,9451
GWP-fossil	100,0000	89,7132	99,9852	74,2123	68,0725	74,1909
GWP-biogenic	66,1952	66,1952	66,1952	41,0411	41,0411	41,0411
GWP-luluc	87,6816	87,4121	87,6771	18,1848	17,9831	18,1797
ODP	85,5992	82,1509	85,5911	75,1637	73,1524	75,1475
AP	62,7507	61,7669	62,7306	50,2402	49,6171	50,2176
EP	33,7727	31,5976	33,7644	25,6190	24,0411	25,6100
POCP	85,2982	84,3432	85,2823	74,5259	73,9028	74,5080
ADPE	85,3531	83,9911	84,9292	100,0000	98,9945	99,5735
ADPF	100,0000	96,7160	99,9859	85,7663	83,7241	85,7451

Category	WD3 EoL sc1	WD3 EoL sc2	WD3 EoL sc3	WD4 EoL sc1	WD4 EoL sc2	WD4 EoL sc3
GWP-total	65,7915	54,0686	65,7767	87,2738	81,9681	87,2590
GWP-fossil	65,8404	54,0600	65,8256	87,1215	81,7904	87,1067
GWP-biogenic	99,7264	99,7264	99,7264	100,0000	100,0000	100,0000
GWP-luluc	40,0203	39,7887	40,0158	100,0000	99,7856	99,9955
ODP	100,0000	95,9577	99,9919	59,0407	57,3416	59,0326
AP	38,3057	37,2370	38,2856	100,0000	99,4285	99,9798
EP	18,1178	16,1685	18,1095	100,0000	98,3548	99,9917
POCP	54,7764	53,7766	54,7604	100,0000	99,4105	99,9841
ADPE	64,3481	62,8929	63,9242	74,4425	73,4920	74,0186
ADPF	65,0161	61,4091	65,0020	69,1885	67,3369	69,1744

The results of comparison of 4 wooden door designs are displayed in Figure 4.1.

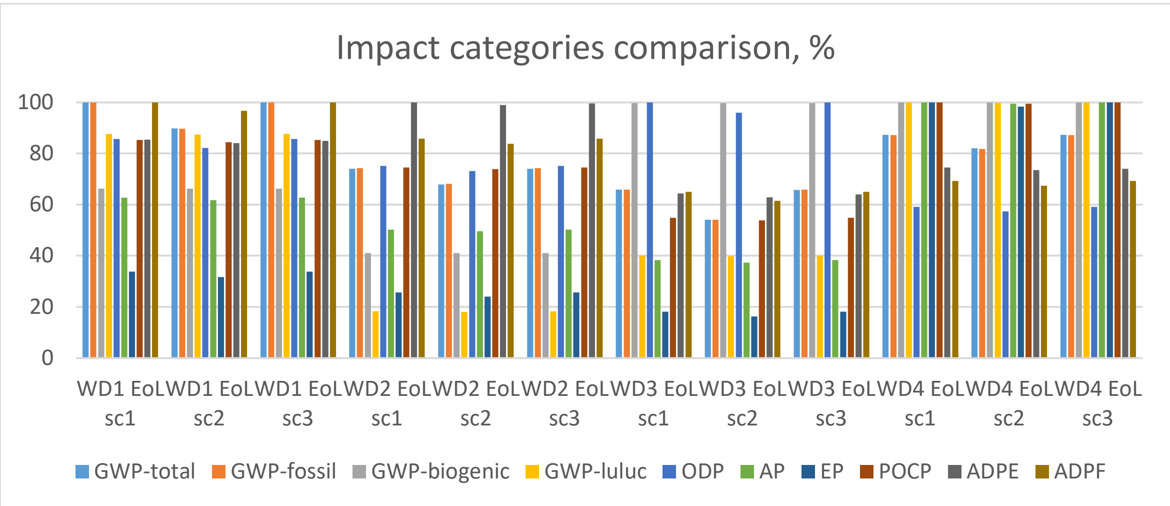

Figure 4.1 Comparison of impact categories.

The initial stage of door production, involving the acquisition and processing of raw materials like wood and metals, has a significant impact on various environmental aspects. This includes greenhouse gas emissions (GWP) resulting from carbon dioxide released during the extraction and processing of raw materials. Moreover, the utilization of energy sources like thermal power generation adds to categories such as acidification potential (AP) and abiotic depletion potential (ADP) due to the emission of pollutants during energy production.

During the manufacturing process, the painting workshop notably affects eutrophication potential (EP), which measures the risk of water bodies becoming excessively enriched with nutrients, leading to harmful algal blooms. Wastewater from painting operations contains nitrogen oxides and other pollutants, contributing significantly to the potential for eutrophication by elevating nutrient levels in water bodies, thereby disrupting aquatic ecosystems.

Transportation also plays a crucial role in distributing finished products, impacting categories like AP, EP, and photochemical ozone creation potential (POCP). Emissions from transportation activities, including nitrogen oxides and volatile organic compounds (VOCs), contribute to acidification and eutrophication potentials. Furthermore, the combustion of fossil fuels during transportation releases pollutants that contribute to the creation of photochemical ozone.

Additionally, waste disposal practices in door manufacturing, such as incineration of wood waste and residues, release harmful substances like carbon monoxide (CO), VOCs, polycyclic aromatic hydrocarbons (PAHs), nitrogen oxides (NOx), and heavy metals. These emissions contribute to various environmental impact categories, including GWP, AP, EP, and abiotic depletion potential of fossil fuels (ADPF).

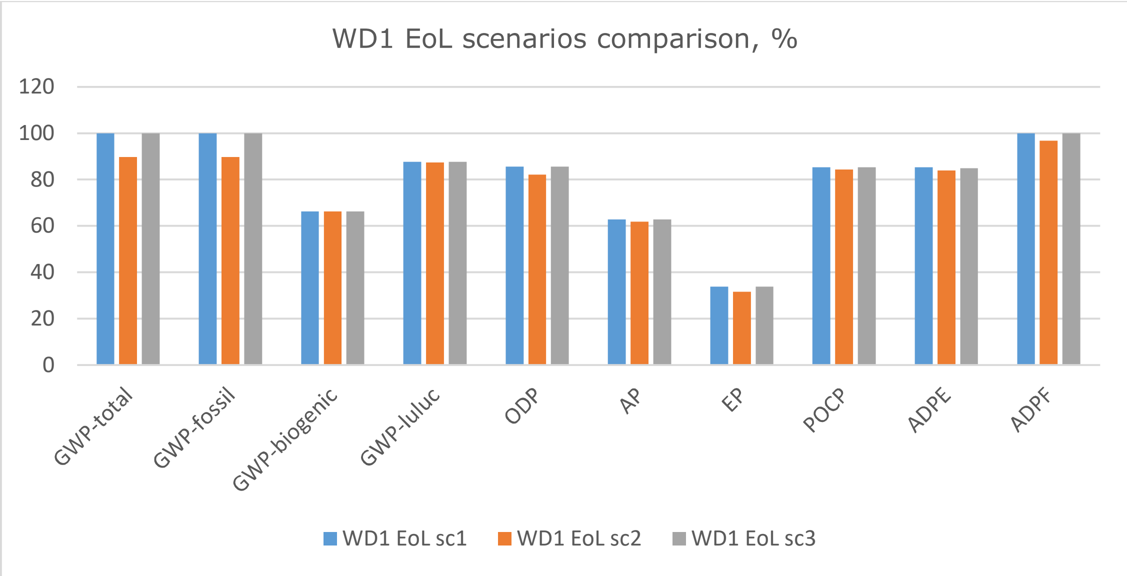

Figure 4.2 Comparison of impact categories of WD1 design based on EoL scenarios.

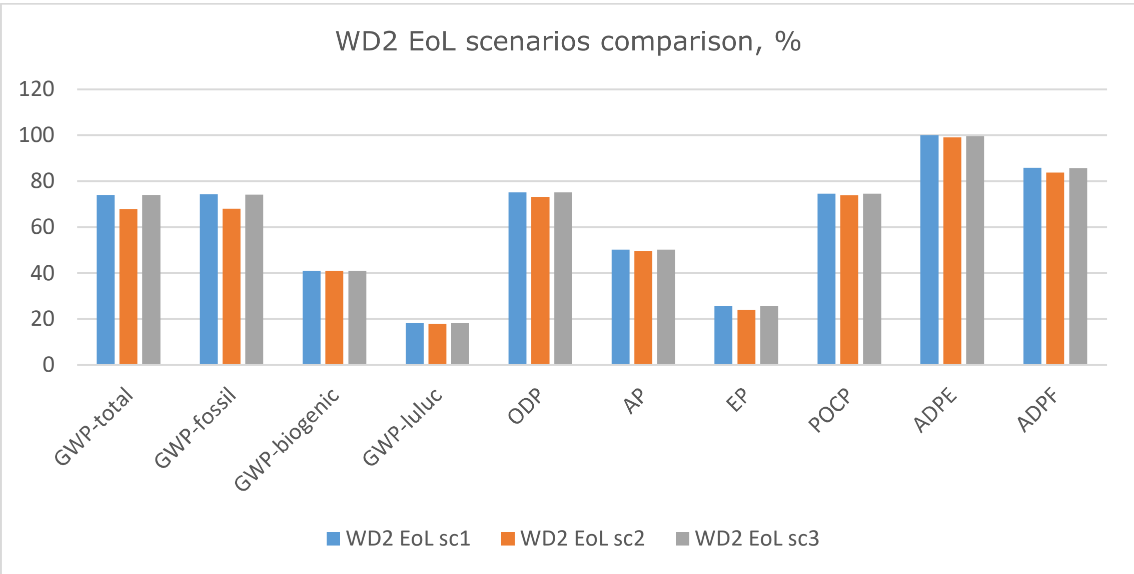

Figure 4.3 Comparison of impact categories of WD2 design based on EoL scenarios.

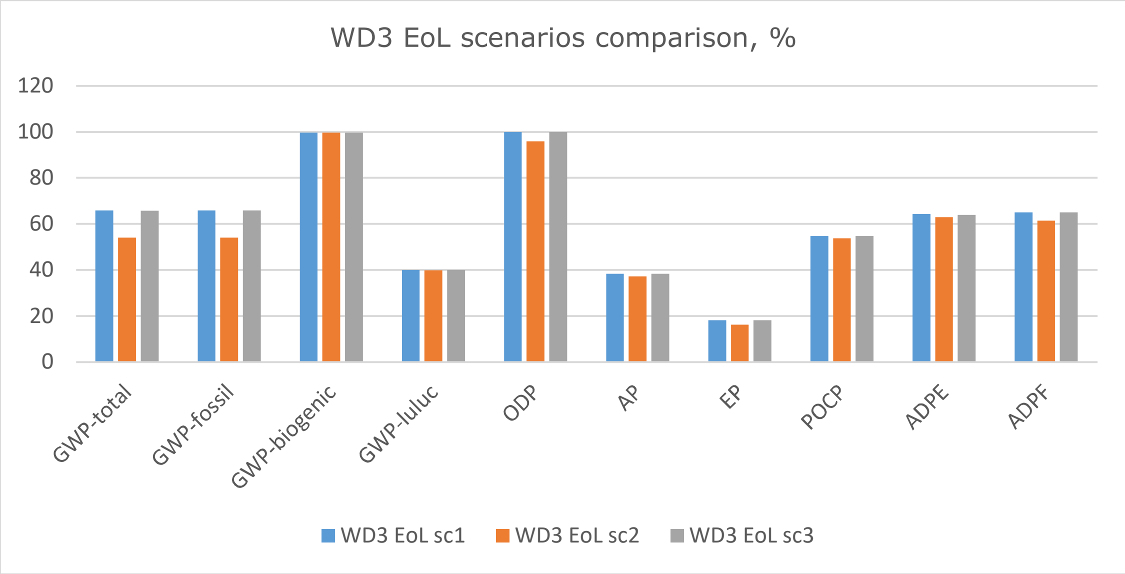

Figure 4.4 Comparison of impact categories of WD3 design based on EoL scenarios.

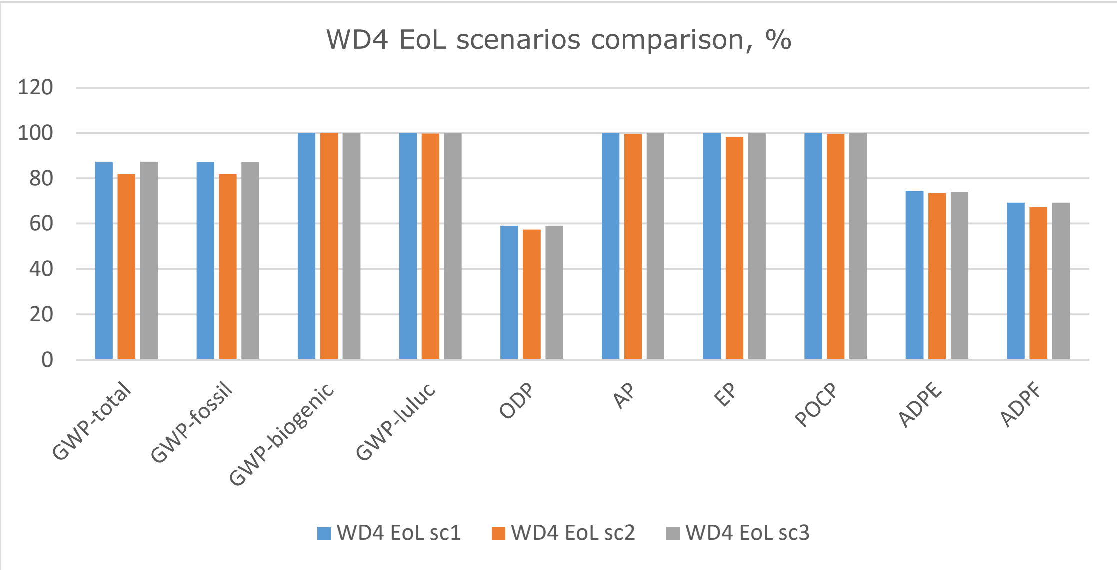

Figure 4.5 Comparison of impact categories of WD4 design based on EoL scenarios.

The graphs (Figures 4.2 – 4.5) indicate that scenarios 1 and 3 have very similar environmental impacts. This similarity arises from the recycling benefits accounted for outside the system boundary in module D. The C1, C2, and C3 stages use the same data sets for disassembly, transport, and waste processing, reflecting consistent contributions across these phases. Recycling's impact can be observed in the waste output flow and module D. However, recycling engineered wood products like MDF and HDF often results in downcycling (Farjana et al, 2023), meaning the material's quality and value decrease with each recycling cycle. Consequently, the benefits of avoided material for recycling scenario in module D are relatively small.

In contrast, the reuse scenario shows clear advantages across all impact categories, mainly because the EoL treatment impacts are minimal. The graphs (Figures 4.2-4.5) illustrate that mostly EoL scenarios affect Global Warming Potential (GWP), GWP fossil, and GWP total categories. It shows that the most contributing life cycle stage is raw material production, and it has the most impact on each category. Designing products with reuse in mind can significantly extend their lifespan and reduce impact on environmental categories.

4.2 Discussion

Research conducted by Cobut et al. (2015) and Wenker et al. (2016) underscores the significant role of the raw material stage in shaping the environmental impact, particularly in terms of Global Warming Potential (GWP), during the production of wooden doors. Cobut et al. (2015) emphasized that the production of raw materials stands out as the primary determinant affecting the environmental footprint of wooden doors. Similarly, Wenker et al. (2016) highlighted the noteworthy environmental consequences associated with the production of semi-finished wood and metal components, which are integral to the raw material stage. Several factors contribute to the heightened impact of the raw material stage. Firstly, the manufacturing process involved in creating density boards consumes a substantial amount of electricity. Additionally, the utilization of urea-formaldehyde resin adhesives in this process exacerbates environmental impacts. These adhesives significantly contribute to categories such as GWP due to emissions generated during their production process. Consequently, the raw material stage emerges as a critical focal point for addressing environmental concerns linked to wooden door production. Efforts aimed at enhancing sustainability in this stage may encompass various strategies. These include sourcing materials from renewable and low-impact sources, optimizing production processes to minimize energy consumption, and exploring alternative adhesive options with reduced environmental footprints. By implementing such measures, the environmental impact associated with the raw material stage of wooden door production can be effectively mitigated, contributing to overall sustainability efforts within the industry.

Similarly, in this case study it was obtained that the most contribution was from producing such materials as MDF, HDF, chipboard and flaxboard - designs WD1, WD2 and WD4 - with ratios shown on Figure 4.6. On the contrary, the design with solid wood shows much lower contribution to GWP.

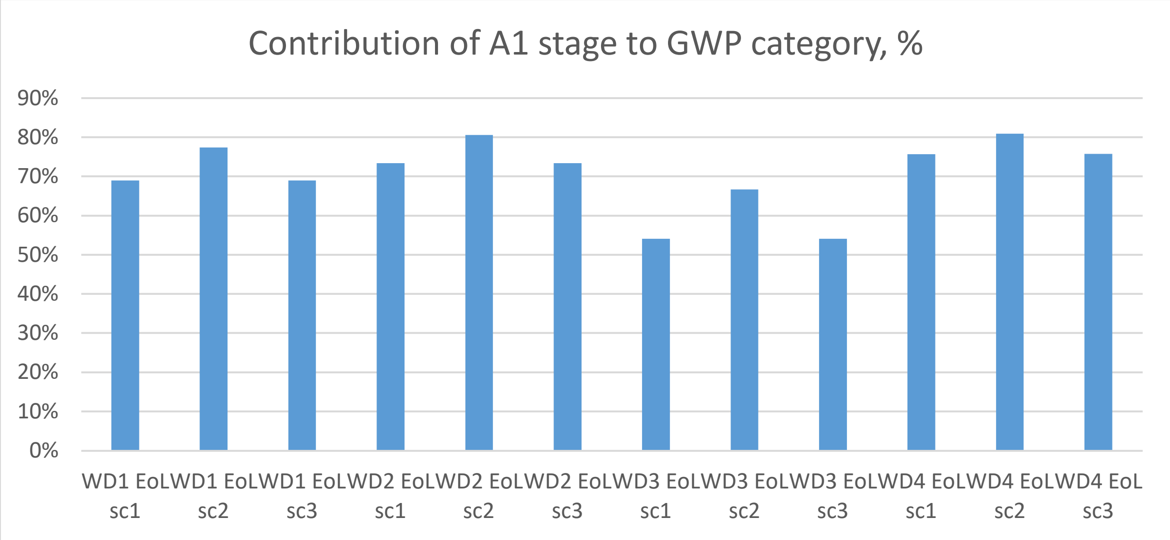

Figure 4.6 Contribution of A1 stage to GWP category.

The raw materials transport stage A2 contribution to GWP purely depended on the distance of transportation and have low contribution due to the usage of diesel-powered lorries.

The impact of manufacturing stage A3 is significantly lower than the material production stage and was determined by the number of produced doors and resources spent such as heat, electricity and water consumption. Also, the impact depended on the amount of the waste treated for energy recovery. Therefore, the production losses played a significant role in this stage. The largest ratio of production losses had MDF and flaxboard due to the design entities, and primer and paint due to surface treatment processes. Throughout the manufacturing process of wooden products, significant amounts of dust are generated, especially during cutting operations. Therefore, it is recommended to conduct these cutting activities in well-ventilated environments (Farjana et al, 2023).

The transportation to the site stage A4 had a lower impact in the GWP category and depended on the transported mass.

The installation process of the interior door is quite simple: fitting the hinges to the door and hanging it in place. It does not require any energy, the A5 stage consists only of the packaging disposal: cardboard and pallet for energy recovery and plastic packaging for recycling.

The deconstruction process consists only of physically removing the door off the hinges, thus the demolition stage C1 is considered to be negligible.

In this case study the stages C2 – D is where the difference of the end-of-life scenarios for each design is reflected.

In the transportation to the disposal facility stage C2 the transportation distance and the disposal way is taken into account. Smaller contribution to the stage is from the EoL scenario 2 (the reuse scenario) due to only transportation the uninstalled door as a whole to the site for the next use. For the same reason the waste processing and disposal stages for EoL scenario 2 do not have any impact on the environment, thus reuse EoL scenario being the most environmentally friendly way of product disposal.

In the deconstruction waste treatment stage C3 it is necessary to categorise waste wood components according to the types of materials they contain and choose proper treatment process. Comparing the EoL scenarios 1 and 3 that have contribution to this stage, the difference is in the hardware disposal way, wood and surface treatment chemicals have the same waste processing scheme (Appendix 2).

Residual materials and waste from C3 should be clarified in the waste disposal stage C4. Therefore, considering the defined EoL scenarios (Appendix 2) for this case study the C4 stage has the same impact besides hardware: 95% recycling and 5% landfilling for scenario 1 and 100% to reuse in scenario 3.

In order to address the net benefits and loads coming from product reuse, recycling, or energy recovery from waste materials resulting from the construction, use, and end of life stages, Module D was added to the EN15804+A2 2019 version. If taking into consideration module D then the impact is reduced drastically, especially due to biogenic carbon consideration. For EoL scenario 1 the benefit consists of thermal energy and electricity coming from the incineration of wooden based products. Scenario 2 obviously benefits from sending materials and components for reuse, thus reducing the impact on the environment. Analysing the stage D for scenario 3 the benefit significantly depends on the further use of the recycled material. Modelling stage D for this case study the next purpose for the material is wooden pallet production from recycled wood, which demonstrated not significant amount of benefit.

In conclusion, the reuse scenario has a lesser impact on greenhouse gas emissions (Table 4.3) than the landfill or incinerator methods of waste disposal (Figure 4.7). Furthermore, it contributes a little percentage, whether through incineration or landfilling. It becomes evident that optimising the manufacturing stage of the wooden door's life cycle needs to be paid greater emphasis. Also, the proper way of further use of recycled material should be chosen to benefit the environmental impact, even if the D stage is considered to be out of the assessment boundaries.

Table 4.3 Table of results on GWP-total.

Category	A1 Raw material extraction and processing	A2 Transport to the manufacturer	A3 Manufacturing	A4 Transport to the building site	A5 Installation into the building	C1 Deconstruction	C2 Waste transport	C3 Waste processing	C4 Waste disposal	D External impacts (excluded from totals)	GWP excluding D	GWP with D
WD1 EoL sc1	23,46044	3,74421	2,58094	0,35858	0,06537	0,00000	0,10308	0,75730	2,95541	-14,97665	34,02533	19,04868
WD1 EoL sc2	23,46044	3,74421	2,58094	0,35858	0,06537	0,00000	0,09925	0,00000	0,00000	-18,62256	30,30879	11,68623
WD1 EoL sc3	23,46044	3,74421	2,58094	0,35858	0,06537	0,00000	0,10454	0,75087	2,95533	-0,66453	34,02027	33,35574
WD2 EoL sc1	18,39141	2,35652	1,63681	0,28861	0,06537	0,00000	0,08178	0,48442	1,76543	-14,98708	25,07035	10,08328
WD2 EoL sc2	18,39141	2,35652	1,63681	0,28861	0,06537	0,00000	0,07951	0,00000	0,00000	-13,20191	22,81823	9,61632
WD2 EoL sc3	18,39141	2,35652	1,63681	0,28861	0,06537	0,00000	0,08099	0,47798	1,76535	-0,66453	25,06304	24,39851
WD3 EoL sc1	11,97183	2,00081	3,56548	0,27264	0,06537	0,00000	0,07942	0,80754	3,37897	-13,09565	22,14205	9,04640
WD3 EoL sc2	11,97183	2,00081	3,56548	0,27264	0,06537	0,00000	0,07501	0,00000	0,00000	-6,26532	17,95113	11,68582
WD3 EoL sc3	11,97183	2,00081	3,56548	0,27264	0,06537	0,00000	0,08088	0,80111	3,37889	-0,66453	22,13700	21,47247
WD4 EoL sc1	23,26679	2,57437	2,42592	0,32128	0,06537	0,00000	0,09069	0,45123	1,53551	-15,55178	30,73116	15,17938
WD4 EoL sc2	23,26679	2,57437	2,42592	0,32128	0,06537	0,00000	0,08876	0,00000	0,00000	-20,56379	28,74248	8,17869
WD4 EoL sc3	23,26679	2,57437	2,42592	0,32128	0,06537	0,00000	0,09215	0,44480	1,53543	-0,66453	30,72610	30,06158

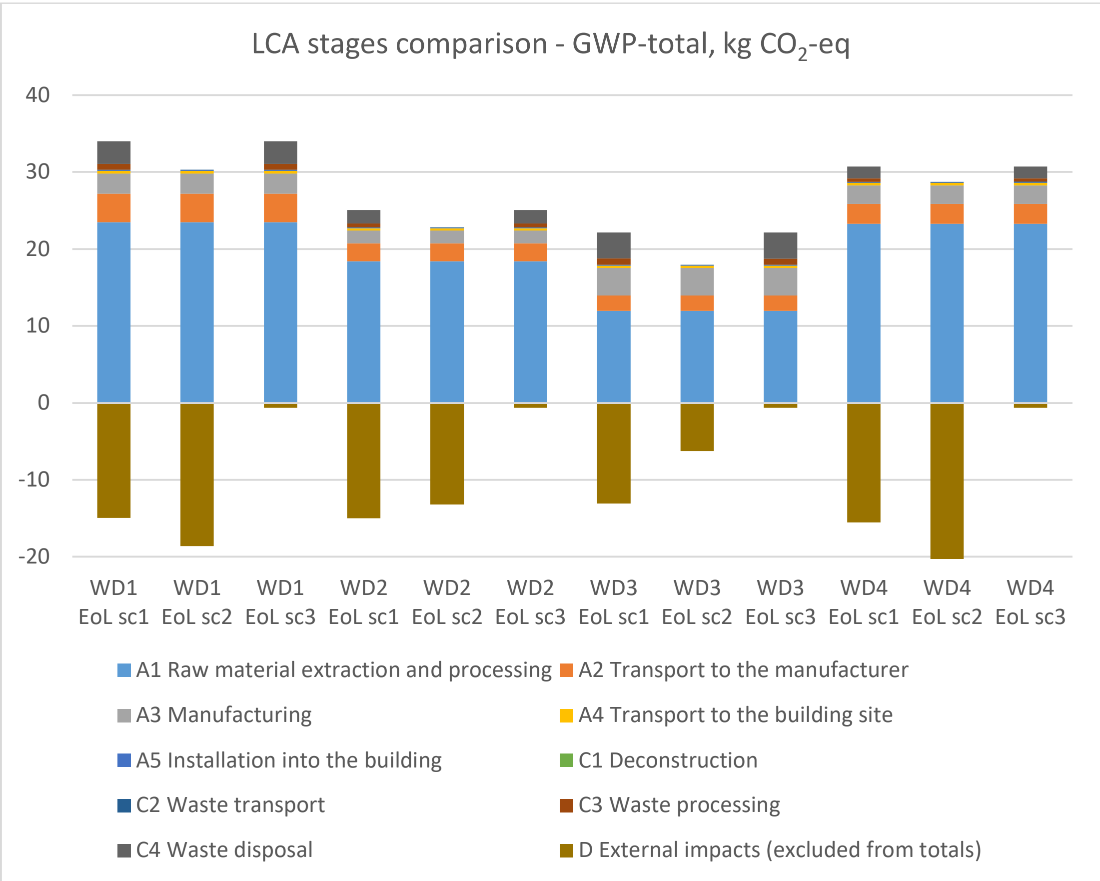

Figure 4.7 Comparison of impact on GWP-total LCA stages.

4.3 Material contribution

In most case the contribution of materials to the environmental impacts are proportional to the amount of material used as raw materials. The only exception is the use of solid wood pine. The percentage of used solid wood in the door leaf is 18,46% (Table 4.4) and the impact in stages A1-A3 is only 6,8% (Table 4.5) in comparison with chipboard material which content is 18,86% of the door leaf and the impact is 23,7%.

Solid wood pine generally has a lower environmental impact (Table 4.6) because it is a natural material that requires less energy-intensive processing compared to engineered wood. The manufacturing processes of engineered wood (chapter 2.4.2) are more energy-intensive and has higher associated emissions, this results in the environmental impacts being less proportional to the amount of solid wood pine used.

Table 4.4 Materials share for the door leaf.

Material	Dataset	WD1	WD2	WD3	WD4
MDF	Medium density fibreboard production, uncoated	20,42%	44,69%	11,84%	
HDF	Fibreboard production, hard	19,45%		6,53%	20,21%
Fiberboard soft	Fibreboard production, soft, from wet & dry processes	17,10%			
Chipboard	Particleboard production, uncoated, average glue mix		12,92%	18,86%	
Solid wood pine	Sawnwood production, softwood, dried (u=20%), planed			18,46%	7,14%
Flaxboard	Fibre production, flax, retting				30,68%
Veneer edgeband	Market for residual wood, dry	0,02%			

Table 4.5 Contribution of materials, % of cradle to gate (A1-A3).

Material	Dataset	WD1	WD2	WD3	WD4
MDF	Medium density fibreboard production, uncoated	36,8%	82,4%	31,6%	
HDF	Fibreboard production, hard	35,3%		17,6%	31,0%
Fiberboard soft	Fibreboard production, soft, from wet & dry processes	18,9%			
Chipboard	Particleboard production, uncoated, average glue mix		11,2%	23,7%	
Solid wood pine	Sawnwood production, softwood, dried (u=20%), planed			6,8%	1,5%
Flaxboard	Fibre production, flax, retting				58,5%
Veneer edgeband	Market for residual wood, dry	0,0%			

Table 4.6 Contribution of materials, cradle to gate (A1-A3) impacts, kg CO_2-eq

Material	Dataset	WD1	WD2	WD3	WD4
MDF	Medium density fibreboard production, uncoated	7,4	13,0	3,2	
HDF	Fibreboard production, hard	7,1		1,8	6,6
Fiberboard soft	Fibreboard production, soft, from wet & dry processes	3,8			
Chipboard	Particleboard production, uncoated, average glue mix		1,7	3,4	
Solid wood pine	Sawnwood production, softwood, dried (u=20%), planed			0,69	0,32
Flaxboard	Fibre production, flax, retting				12,0
Veneer edgeband	Market for residual wood, dry	0,0			

5. CONCLUSIONS AND RECOMMENDATIONS

Managing wooden products sustainably at the end of their lifespan poses significant challenges, especially with engineered wood, which is largely non-biodegradable. The separation of wooden fibres from adhesives presents a major obsticle to effectively recycling engineered wood. Additionally, incineration, a common disposal method, is unsustainable as it releases heat energy into the atmosphere and contributes to ozone layer depletion. Recovered wood from discarded products is often used in low-value applications like particleboard manufacturing, wooden pallet production, animal bedding, and landscaping. However, these applications typically represent downcycling rather than true recycling, as the recovered wood is not utilized in high-value products or processes. This limited reuse underscores the need for more sustainable end-of-life management practices for wooden products. Efforts to address this issue may involve developing innovative recycling technologies capable of separating wood fibres from adhesives, as well as promoting the use of biodegradable adhesives in engineered wood production. Additionally, exploring alternative disposal methods that minimize environmental impacts, such as composting or innovative forms of biomass conversion, could help improve the sustainability of managing wooden products at the end of their life.

Further examination reveals that integrating additional CE strategies into a manufacturer's business model is not only possible but necessary. Beyond mere reuse and recycling, expanding the cycling plan to include other CE strategies can enhance sustainability efforts and reduce waste generation. The Refuse strategy, particularly concerning materials like plastic used in packaging, holds promise in preventing unnecessary waste generation. Reduction, as a less extreme form of refusal, aims to minimize material consumption during production processes. Analysis of production waste underscores the urgent need for improvement. Prioritizing minimal material usage while maintaining product functionality and aesthetics can significantly reduce waste generation, emphasizing efficiency and optimization across all production stages. The Rethink strategy, when implemented at the corporate level, can lead to substantial improvements in design, material selection, and energy efficiency. Design plays a crucial role in facilitating product reuse and disassembly, supporting circularity. Extending product lifespan through repair strategies is another important aspect. Circular design practices, rooted in life cycle thinking, ensure that products are designed with future end-of-life considerations in mind, fostering a more sustainable product lifecycle.

However, transitioning to a circular business model necessitates robust data and information to guide decision-making. Adequate data collection and analysis are crucial for aligning design decisions with broader business strategies and sustainability goals, highlighting the importance of integrating environmental considerations into all aspects of business operations.

SUMMARY

Building and construction activities are major contributors to global carbon emissions, accounting for a significant 39%. This significant carbon footprint underscores the urgency to adopt sustainable practices within the construction industry. One area where sustainability can be improved is in the materials used for construction. Wood and wood-based materials are gaining attention for their potential to mitigate carbon emissions. Unlike traditional construction materials, wood possesses a unique capacity to store carbon over its long lifespan. This means that not only does wood contribute less to carbon emissions during production, but it also actively sequesters carbon from the atmosphere, making it a valuable asset in the fight against climate change. Furthermore, the principles of reuse and recycling play a crucial role in achieving a more sustainable future. By extending the lifespan of materials and products, we can reduce the demand for virgin resources and minimize waste generation. This aligns with the concept of the Circular Economy, which aims to maximize resource efficiency and minimize environmental impact. In recent years, Europe has witnessed a surge in the demand for doors, driven primarily by the booming construction industry. Doors are essential components of both residential and commercial buildings, serving functional and aesthetic purposes. This increased demand presents an opportunity to incorporate sustainable practices into door manufacturing. Wood, as a renewable resource, has emerged as a preferred material for door production due to its eco-friendly properties. Unlike non-renewable materials, such as metal or plastic, wood can be sustainably harvested and replenished. To assess the environmental impact of wooden doors throughout their lifecycle, a comparative analysis was conducted using Life Cycle Assessment (LCA) methodology. LCA is a widely accepted tool for evaluating the environmental performance of products and processes. By analysing the cradle-to-grave environmental impacts of wooden doors, insights can be gained into areas for improvement and optimization. The study involved evaluating the environmental impacts of four different wooden interior doors with varying designs and materials. Three end-of-life scenarios were considered: (1) sorted waste to incineration or recycling 95% and to landfill 5% (current method of disposal); (2) as 100% to reuse; (3) 95% recycling and 5% to landfill of wooden materials, 100% of steel materials to reuse and 95% incineration of hazardous waste. The findings revealed that while all scenarios had their specifics, reuse demonstrated clear advantages in terms of environmental impact. By extending the lifespan of doors through reuse, the need for new materials and waste generation can be minimized. In addition to assessing environmental impacts, the study also identified the main contributing wooden material. Challenges were highlighted in the study as the need for proper recycling infrastructure

to support sustainable practices. Doors, with their longer lifespans compared to other consumer goods, require specialized recycling processes. Standard operating procedures for disassembling doors and separating materials are essential for effective recycling. By using OneClick LCA software, the study was able to accurately quantify environmental impacts and identify areas for improvement. Collaboration with a leading European door manufacturer provided valuable insights and data for the case study. The functional unit of analysis is defined as one square meter of door for a specific use area. The study evaluates the removal and emission of biogenic CO2 throughout the life cycle of wood and wood-based materials, employing the -1/+1 approach. This approach provides a comprehensive picture of biogenic carbon flows compared to the 0/0 approach. Scenarios 1 and 3 demonstrated very similar environmental impacts. This similarity rise from the recycling benefits that are accounted for outside the system boundary in module D. The C1, C2, and C3 stages utilize consistent data sets, reflecting uniform contributions across these phases. The impact of recycling is evident in the waste output flow and module D. However, recycling engineered wood products like MDF and HDF often results in downcycling, where the material's quality and value decrease with each recycling cycle. Consequently, the benefits of avoided material for the recycling scenario in module D are relatively small. In contrast, the reuse scenario 2 shows clear advantages across all impact categories. This is mainly because the EoL treatment impacts are minimal. By reusing materials, the need for new raw materials is significantly reduced, leading to lower overall environmental impacts. This scenario demonstrates the potential of designing products with reuse in mind to extend their lifespan and minimize their environmental footprint. The study found that mostly EoL scenarios affect Global Warming Potential (GWP), GWP fossil, and GWP total categories. The most contributing life cycle stage is raw material production, which has the highest impact on each category. The study revealed that producing materials such as MDF, HDF, chipboard, and flaxboard contributes most to the environmental impacts. On the contrary, the design with solid wood shows much lower contributions to GWP. The manufacturing processes for engineered wood are more energy-intensive and have higher associated emissions. The study's comparative analysis of different end-of-life scenarios for wooden doors demonstrates the environmental benefits of reuse over recycling and disposal methods. By prioritizing reuse and optimizing production processes, we can create a more sustainable construction industry that significantly reduces its impact on global carbon emissions.

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APPENDIX 1: TABLE DATASETS USED FOR MODEL IN ONECLICK LCA SOFTWARE

Stage	Input/outout	Dataset
A1	MDF	Medium density fibreboard production, uncoated
	HDF	Fibreboard production, hard
	Fiberboard soft	Fibreboard production, soft, from wet & dry processes
	Chipboard	Particleboard production, uncoated, average glue mix
	Solid wood pine	Sawnwood production, softwood, dried (u=20%), planed
	Flaxboard	Fibre production, flax, retting
	Veneer edgeband	Market for residual wood, dry
	Glue for stiles and rails	Ethylene vinyl acetate copolymer production
	Glue for layers	Vinyl acetate production
	Glue for edgeband	Ethylene vinyl acetate copolymer production
	Paint	Waterborne alkyd primer paint, 1.284 kg/L, average coverage 8-9 m2/L, Pinja Protect G
	Primer	Waterborne alkyd primer paint, 1.284 kg/L, average coverage 8-9 m2/L, Pinja Protect G
	Sealer	Acrylic varnish production, product in 87.5% solution state
	Hardware	Hot rolling, steel
	Hardware	Steel production, electric, low-alloyed
A2	Transportation	Transported mass
A3	Packaging wood, pallet	EUR-flat pallet production
	Packaging plastic, PE	Packaging film production, low density polyethylene
	Packaging cardboard	Corrugated board box production
	Water consumption	Market for tap water
	Heat produced from bricket	Heat production, wood chips from post-consumer wood, at furnace 300kW
	Electricity	Market for electricity, medium voltage
	Treatment of waste wood	Treatment of waste wood, untreated, municipal incineration
	Treatment of waste glue, hazardous	Treatment of waste paint, hazardous waste incineration
	Treatment of waste paint, primer, sealer, hazardous	Treatment of waste paint, hazardous waste incineration
	Treatment of wastewater	Treatment of wastewater, average, capacity 1E9l/year
	Heat from incineration	Exported Energy: Thermal
	Electricity from incineration	Exported Energy: Electricity
A4	Final product + packaging transportation to site	Transported mass
A5	Treatment of wooden pallet	Treatment of waste wood, untreated, municipal incineration
	Treatment of packaging plastic	Treatment of waste polyethylene, for recycling, unsorted, sorting
	Treatment of packaging cardboard	Treatment of waste paperboard, municipal incineration
	Heat from incineration	Exported Energy: Thermal
	Electricity from incineration	Exported Energy: Electricity
C1	Electricity for deconstruction	Market for electricity, medium voltage
C2	Transportation	Transported mass
C3	Sorting and chipping of wooden waste	Wood chipping, industrial residual wood, stationary electric chipper
	Hardware sorting, to recycling	Sorting and pressing of iron scrap
	Glue, paint sorting, to hazardous waste	Treatment of waste paint on wall, sorting plant
C4	Wood landfill	Treatment of waste wood, untreated, sanitary landfill
	Hardware to landfill	Treatment of scrap steel, inert material landfill
	Paint and glue, to landfill	Treatment of waste emulsion paint, inert material landfill
	Paint and glue, to incineration	Treatment of waste paint, hazardous waste incineration
	Materials for re-use	Materials for re-use
	Materials for recycling	Materials for recycling
D	Avoided virgin materials, hardware, benefit	Steel production, converter, low-alloyed
	Plastic wrap recycling, load	Packaging film production, low density polyethylene
	Plastic wrap recycling, benefit	Packaging film production, low density polyethylene
	PENRM recycled plastic wrap	Non Renewable Energy as Material
	MDF benefit	Medium density fibreboard production, uncoated
	HDF benefit	Fibreboard production, hard
	Fiberboard soft, benefit	Fibreboard production, soft, from wet & dry processes
	Chipboard benefit	Particleboard for indoor use, 600 kg/m3, P1 (Byggelit AB (2023))
	Solid wood pine benefit	Sawnwood production, softwood, dried (u=20%), planed
	Flaxboard benefit	Fibre production, flax, retting
	Pallet production from recycled wood benefit	Wooden pallet, skid, 1200x800 mm (Euro-pallet), 22.96 kg/unit

APPENDIX 2: END-OF-LIFE SCENARIOS, DATASETS AND CALCULATIONS FOR MODELLING IN ONECLICK LCA

		Unit		WD1	WD2	WD3	WD4										
	Weight of wood	kg		20,1961	16,2983	14,8425	18,3541										
	Weight of paint and glue	kg		0,8633	0,5110	0,9965	0,4397										
	Weight of steel	kg		0,3143	0,3143	0,3143	0,3143										
Stage			**Scenario 1**	**WD1**	**WD2**	**WD3**	**WD4**	**Scenario 2**	**WD1**	**WD2**	**WD3**	**WD4**	**Scenario 3**	**WD1**	**WD2**	**WD3**	**WD4**
C1	Demolition	kg		21,3737	17,1236	16,1533	19,1081		21,3737	17,1236	16,1533	19,1081		21,3737	17,1236	16,1533	19,1081
C2	Transportation distance (to waste treatment and/or landfill)	km		50	50	50	50		50	50	50	50		50	50	50	50
	Transported mass	kg		21,3737	17,1236	16,1533	19,1081		21,3737	17,1236	16,1533	19,1081		21,3737	17,1236	16,1533	19,1081
C3	Sorting of wood	kg	95% incineration	19,1863	15,4834	14,1004	17,4364						95% to recycling	19,1863	15,4834	14,1004	17,4364
	Sorting of paint and glue	kg	95 % incineration hazardous was	0,8202	0,4854	0,9466	0,4177						95 % incineration hazardous was	0,8202	0,4854	0,9466	0,4177
	Sorting of steel	kg	95 % to recycling	0,2986	0,2986	0,2986	0,2986						100 % to reuse	0,3143	0,3143	0,3143	0,3143
	Materials for reuse	kg						100 % to reuse	21,3737	17,1236	16,1533	19,1081					
C4	Landfill of wood	kg	5 % to landfill	1,0098	0,8149	0,7421	0,9177						5 % to landfill	1,0098	0,8149	0,7421	0,9177
	Landfill of paint and glue	kg	5 % to landfill	0,0432	0,0255	0,0498	0,0220						5 % to landfill	0,0432	0,0255	0,0498	0,0220
	Landfill steel	kg	5 % to landfill	0,0157	0,0157	0,0157	0,0157										
	Incineration of paint and glue	kg	95% to incineration	0,8202	0,4854	0,9466	0,4177						95 % to incineration	0,8202	0,4854	0,9466	0,4177
D	Incineration for energy recovery, wood	kg		19,1863	15,4834	14,1004	17,4364										
	MDF - Exported Energy: Thermal	MJ	0,62*(MJ/m3)*(m3*0.95)	67,2020	117,4104	29,2974											
	MDF - Exported Energy: Electricity	MJ	0,11*(MJ/m3)*(m3*0.95)	11,9229	20,8309	5,1979											
	HDF - Exported Energy: Thermal	MJ	0,62*(MJ/m3)*(m3*0.95)	58,4942		14,7748	54,2584										
	HDF - Exported Energy: Electricity	MJ	0,11*(MJ/m3)*(m3*0.95)	10,3780		2,6213	9,6265										
	Fiberboard soft - Exported Energy: Thermal	MJ	0,62*(MJ/m3)*(m3*0.95)	28,2589													
	Fiberboard soft - Exported Energy: Electricity	MJ	0,11*(MJ/m3)*(m3*0.95)	5,0137													
	Chipboard- Exported Energy: Thermal	MJ	0,62*(MJ/m3)*(m3*0.95)		37,3068	51,3196											
	Chipboard- Exported Energy: Electricity	MJ	0,11*(MJ/m3)*(m3*0.95)		6,6190	9,1051											
	Solid wood Pine - Exported Energy: Thermal	MJ	0,62*(MJ/m3)*(m3*0.95)			39,3300	30,5657										
	Solid wood Pine - Exported Energy: Electricity	MJ	0,11*(MJ/m3)*(m3*0.95)			6,9779	5,4229										
	Flaxboard - Exported Energy: Thermal	MJ	0,62*(MJ/m3)*(m3*0.95)				75,6096										
	Flaxboard - Exported Energy: Electricity	MJ	0,11*(MJ/m3)*(m3*0.95)				13,4146										
	Veneer edgeband - Exported Energy: Thermal	MJ	0,62*(MJ/m3)*(m3*0.95)	0,0419													
	Veneer edgeband - Exported Energy: Electricity	MJ	0,11*(MJ/m3)*(m3*0.95)	0,0074													
	Thermal energy from wood incineration	**MJ**	**Total**	**153,9971**	**154,7173**	**134,7219**	**160,4338**										
	Electricity from wood incineration	**MJ**	**Total**	**27,32207**	**27,44984**	**23,90228**	**28,46406**										
	Recycling steel	MJ															
	Loads: steel recycling	MJ															
	Benefit, avoided steel	MJ															
	Biogenic carbon content (product+packaging)	kg	95% incineration	8,0144	6,6412	6,1730	7,6912										

APPENDIX 3: TABLE OF BIOGENIC CARBON DATAPOINTS AND CALCULATION

Raw Material	Datapoint	GWP-bio	Unit	WD1			WD2			WD3			WD4		
				Qty	Unit	kg C	Qty	Unit	kg C	Qty	Unit	kg C	Qty	Unit	kg C
MDF	Medium density fibreboard production, uncoated	-986	kg CO2e/m3	0,01186	m3	3,19035	0,02073	m3	5,57395	0,00517	m3	1,39087			
HDF	Fibreboard production, hard	-1580	kg CO2e/m3	0,00811	m3	3,49414				0,00205	m3	0,88257	0,00752	m3	3,24112
Fiberboard, soft	Fibreboard production, soft, from wet & dry	-254	kg CO2e/m3	0,02525	m3	1,74931									
Chipboard	Particleboard for indoor use, 600 kg/m3, P1 (Byggelit AB (2023))	-853	kg CO2e/m3				0,00609	m3	1,41683	0,00838	m3	1,94900			
Solid wood Pine	Sawnwood production, softwood, dried (u=20%), planed	-814	kg CO2e/m3							0,01025	m3	2,27540	0,00470	m3	1,04427
Flaxboard	Fibre production, flax, retting	-1,44	kg CO2e/kg										9,70291	kg	3,81060
Veneer edgeband	Market for residual wood, dry	-997	kg CO2e/m3	0,00001	m3	0,00241									
				Total product		**8,44**			**6,99**			**6,50**			**8,10**
Pallet	EUR-flat pallet production	-35,9	kg CO2e /unit	0,01547	unit	0,15148									
Cardboard	Corrugated board box production	-1,48	kg CO2e / kg	0,30290	kg	0,12226									
				Total packaging		0,2737									
				Total (with packagi		**8,71**			**7,26**			**6,77**			**8,37**