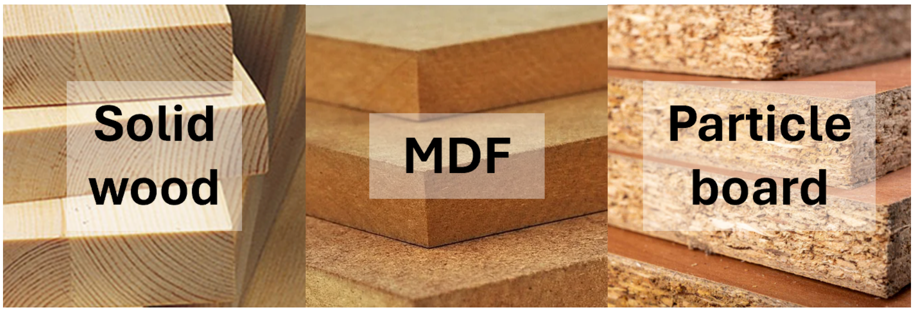
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Kim Kluin

Life-cycle assessment of Solid Wood and Engineered Wood Tables

Master's thesis in Industrial Ecology
Supervisor: Johan Berg Pettersen
Co-supervisor: Kamila Krych
January 2024



KPM, n.d.; NWT, n.d.; Steven Fox and Vila,2020

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Preface

This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Industrial Ecology at NTNU. The research was conducted under the supervision of Johan Berg Pettersen in Department of Energy and Process Engineering at NTNU, from the 15th of January 2024 to the 10th of June 2024.

The motivation behind this research is to contribute to the field of sustainable production and consumption. As society becomes more conscious of environmental impacts, it is crucial to develop methodologies that provide a comprehensive understanding of these effects. This study focuses on evaluating the environmental impacts associated with wooden tables.

I extend my gratitude to my supervisor, Johan Berg Pettersen , for their expertise, patience, and insightful feedback. I am also thankful to my co-supervisor Kamila Krych for their knowledge and assistance. My appreciation goes to my fellow students for their willingness to engage in valuable discussions and their support throughout the thesis writing process.

Special thanks to my family and friends for their support and understanding throughout my studies.

I hope this thesis contributes to environmental sustainability and provides a foundation for future research.

Kim Kluin
NTNU
10.06.2024

Abstract

This thesis evaluates the environmental impacts of medium-density fiberboard (MDF), particleboard (PB), and solid wood tables using a comprehensive Life Cycle Assessment (LCA) to understand how furniture lifetimes influence the environmental impacts associated to them. The thesis highlights the importance of integrating durability and recyclability into LCAs for accurate environmental assessments. The research addresses three key questions: the comparison of environmental impacts between engineered wood and solid wood tables, the methodologies for accurately estimating table lifespans, and the differences in environmental impacts when lifetime considerations are integrated into LCA. The LCA was conducted using Brightway 2.0, incorporating Ecoinvent 3.8 data, and calculated with the ReCiPe 2016 method. Thirty tables from Norway's leading furniture stores were analyzed across three system boundaries: cradle-to-gate, cradle-to-grave, and full lifecycle including repair and lifespan considerations. Key findings include that solid wood tables generally have lower environmental impacts than MDF but do not outperform PB, largely due to high Agricultural Land Occupation and transport emissions. System Boundary 1, focusing on cradle-to-gate impacts, shows this comparison. System Boundary 2, incorporating cradle-to-grave impacts, reveals that MDF tables have the highest impacts across most indicators, while PB tables perform best in categories like Particulate Matter Formation Potential and Global Warming Potential. The end-of-life treatment significantly affects certain indicators, notably Global Warming Potential and Freshwater Ecotoxicity Potential, but scaling incineration emissions based on heating values introduces uncertainties. System Boundary 3, addressing lifespan and repairability, shows that solid wood tables exhibit the lowest environmental impacts across all categories due to their significantly longer lifespans—more than 19 times that of MDF and PB tables. The thesis concludes that selecting tables with longer lifespans, especially solid wood, is the most effective strategy for reducing emissions per year of use. Future research should focus on developing LCAs that include durability and quality considerations, along with precise methodologies for estimating product lifetimes.

Key words: Environmental impact indicators, product lifetime, solid wood, engineered wood, Life Cycle Assessment, durability, product longevity, recyclability, sustainable consumption

Sammendrag

Denne avhandlingen evaluerer miljøpåvirkningen fra bord av MDF, sponplater og heltre ved hjelp av en omfattende livssyklusanalyse (LCA) for å forstå hvordan møblenes levetid påvirker miljøpåvirkningen. Studien viser hvor viktig det er å integrere holdbarhet og resirkulerbarhet i LCA-analyser for å få nøyaktige miljøvurderinger. Forskningen tar for seg tre hovedspørsmål: sammenligning av miljøpåvirkningen mellom bord i konstruert tre og bord i heltre, metoder for nøyaktig estimering av bordenes levetid og forskjellene i miljøpåvirkning når hensynet til levetid integreres i LCA. LCA-en ble utført ved hjelp av Brightway 2.0, med data fra Ecoinvent 3.8, og beregnet med ReCiPe 2016-metoden. Tretti bord fra Norges ledende møbelbutikker ble analysert på tvers av tre systemgrenser: vugge-til-port, vugge-til-grav og hele livssyklusen, inkludert reparasjoner og levetidsbetraktninger. De viktigste funnene er at bord i massivt tre generelt har lavere miljøpåvirkning enn trefiberplater med middels tetthet, men ikke bedre enn PB, hovedsakelig på grunn av høye utslipp fra landbruk og transport. Systemavgrensning 1, som fokuserer på vugge-til-port-virkningen, viser denne sammenligningen. Systemavgrensning 2, som inkluderer vugge-til-grav-virkninger, avslører at bord av trefiberplater med middels tetthet har de høyeste virkningene på de fleste indikatorene, mens sponplatebord gjør det best i kategorier som potensial for partikkeldannelse og potensial for global oppvarming. Behandlingen ved slutten av levetiden har betydelig innvirkning på visse indikatorer, særlig potensial for global oppvarming og økotoksisitetspotensial for ferskvann, men skalering av forbrenningsutslipp basert på oppvarmingsverdier introduserer usikkerhet. Systemgrense 3, som tar for seg levetid og reparasjonsmuligheter, viser at bord i massivt tre har den laveste miljøpåvirkningen i alle kategorier på grunn av den betydelig lengre levetiden - mer enn 19 ganger så lang som for bord i fiberplater med middels tetthet og sponplater. Studien konkluderer med at valg av bord med lengre levetid, spesielt bord i massivt tre, er den mest effektive strategien for å redusere utslippene per bruksår. Fremtidig forskning bør fokusere på å utvikle LCA-er som tar hensyn til holdbarhet og kvalitet, samt presise metoder for å estimere produktlevetiden.

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1 Introduction

Furniture constitutes a significant portion of bulky waste, which encompasses items too large for standard waste containers or bins, such as appliances, mattresses, electronics, and other sizable household items, carrying considerable environmental implications. Cooper et al. (2021) estimated that approximately 10 million tonnes of furniture waste are generated annually within the European Union (EU), with much of it being potentially reusable at the time of disposal. Despite its substantial environmental footprint, furniture has received relatively less attention compared to other consumer durables, partly due to the misconception that it has minimal energy requirements for operation and that its primary material, wood, is renewable (Cooper et al., 2021).

However, contemporary furniture often incorporates engineered wood-based composite materials like fiberboard or particleboard, which pose challenges for maintenance and recycling in comparison to solid wood counterparts (Russell et al., 2022). Medium-density fiberboard (MDF) and Particle Board (PB) are among the most widely used panel materials globally, with a combined production volume exceeding 200 million cubic meters annually (Lao and Chang, 2023). Despite their prevalence, MDF and PB are considered lower-quality materials compared to solid wood (Lao and Chang, 2023).

The rapid growth of the wood-based panel industry, primarily driven by the furniture and construction sectors (Lao and Chang, 2023), suggests a continued rise of furniture made from wood or engineered wood variants, leading to an increased need for bulky waste disposal in the future.

Current waste management practices cause environmental concerns, with a significant portion of wood waste from furniture being incinerated rather than recycled (Tina Wågønes et al., 2019). Incineration contributes to emissions of greenhouse gases, particulate matter, dioxins, and other pollutants thereby worsening air pollution (Tangri, 2023). Therefore, the expansion of the wood-based panel industry and the consequently higher volumes of furniture does not only increase resource consumption but may intensify adverse environmental impacts from both production and end-of-life treatment of wood-based panels.

Understanding the environmental implications of furniture materials is crucial in this context, and the life cycle assessment (LCA) method serves as the most commonly used approach for evaluating such impacts across all stages of product life cycles, from raw material extraction through production, use, and disposal (Lao and Chang, 2023)

In order to mitigate the escalating resource consumption and environmental impacts associated with the wood-based panel industry, various measures can be employed. These measures range from extending product lifetimes to implementing efficient recycling systems (Glöser-Chahoud et al., 2021).

Extending the lifetime of products, such as furniture, is particularly notable as it facilitates keeping materials within the usage loop, thereby reducing resource consumption and waste. Product lifetime refers to the total lifespan of a product during which it remains economically viable or is used by a single owner (Russell et al., 2022).

The extension of a piece of furniture's lifespan can be realized through repair interventions upon breakage or regular maintenance to mitigate wear and tear. Alternatively, choosing furniture with longer lifespans from the beginning is another way to reduce resource use and environmental impacts in the wood-based panel industry. This approach alleviates the need for consumers to engage in maintenance or repair activities, thus potentially reducing their burden.

Achieving prolonged furniture lifespans necessitates prioritizing durability, which pertains to an item's ability to withstand the test of time (Iraldo et al., 2017). Enhancing durability involves the utilization of high-quality materials and judicious design choices.

Despite its significance, durability remains relatively underexplored within the furniture sector (Iraldo et al., 2017). Presently, the predominant focus of LCA studies within this sector involves the analysis of environmental impacts stemming from raw material extraction, production processes, and end-of-life treatment. However, such analyses often neglect to account for the lifespan of a product, potentially resulting in misleading conclusions. For instance, a product with a short lifespan, necessitating frequent replacement, might erroneously appear to have lower environmental impacts compared to a product with higher impacts in raw material extraction and production but a longer overall lifespan. This discrepancy stands in stark contrast to assertions by numerous scholars who advocate for extending the lifespan of durable goods as a means to mitigate the adverse effects of consumerism in present-day 'throwaway societies' (Gnanapragasam et al., 2018).

This thesis aims to fill this research gap by evaluating the influence of furniture lifespan on the environmental footprint of furniture pieces through Comparative Life Cycle Assessment, with a focus on data from the Norwegian context. The following three research questions shall be answered:

1. How do the environmental impacts of engineered wood tables compare to those manufactured from solid wood, considering both production and end-of-life treatment?

2. What methodologies can be employed to accurately estimate the lifespan of various table variants, and what are the distinguishing factors influencing their expected lifetimes?

3. To what extent do environmental impacts differ between average engineered and solid wood tables when lifetime considerations are integrated into the Life Cycle Assessment (LCA), and what are the implications of these findings?

In order to achieve the aim of the thesis the environmental impacts of solid wood tables will be compared with those of engineered wood tables, while also examining how different product lifespans and recyclability factors contribute to these impacts.

The specific focus on tables as representative furniture items was chosen due to the tables' inherent comparability, stemming from their relatively straightforward construction compared to items such as sofas or kitchens as well as their utilization of fewer components. The approach used to achieve the research aim will further be explained in the Methodology section.

The subsequent chapters of this thesis will begin with a comprehensive literature analysis aimed at understanding the life cycles of tables and the environmental impacts attributed to them, while also exploring the influence of durability on these impacts. Subsequently, the assessed system and the assumptions made in association with the conducted Life Cycle Assessment (LCA) will be laid out. This will be followed by the presentation and discussion of the findings obtained, along with the responses to the research questions.

2 Literature review

To gain deeper insights into the life cycles of tables crafted from solid or engineered wood, as well as to identify the environmental impacts associated with them and assess the influence of durability on these impacts, a comprehensive literature review was conducted. This review encompasses an analysis of 10 LCAs focusing on various furniture items and wooden materials, alongside examination of 4 Environmental Product Declarations (EPDs) pertaining to Particle Board (PB) and Medium-Density Fiberboard (MDF), and consideration of 4 articles discussing eco-innovation, emission reduction in the furniture sector, product lifetimes, and consumer perceptions.
The choice of literature was influenced by its direct relevance to the thesis topic and its availability, and it was subjectively curated by the author. The literature surveyed encompasses diverse geographic regions, including Brazil, China, USA, and Europe.

The synthesis of these studies and articles reveals significant consensus on specific environmental assertions and focal points, which will be further discussed in the subsequent analysis. This consensus provides a foundational framework for anticipating the outcomes of the LCA conducted within the scope of this master's thesis.

Various studies point towards a nuanced understanding of the relationship between product durability, material choices, and their environmental impacts. Russell et al. (2022) suggest that while durable wood furniture may have a longer lifespan, the increased use of wood and other materials required in circular design approaches could lead to higher costs and greater environmental impacts compared to less-durable "fast furniture" alternatives. Meanwhile, Brunet-Navarro et al. (2017) propose that utilizing more wood in furniture, combined with design strategies to enhance product lifespan and facilitate recycling, could offer a significant opportunity for mitigating climate change, particularly if implemented at scale.

The selection of impact categories for LCAs in furniture production is crucial for understanding and addressing environmental impacts. Different studies have utilized various impact categories to assess the environmental performance of wooden furniture. For instance in the literature review performed by Cordella and Hidalgo (2016) the focus was on standard impact categories specified in Product Category Rules (PCRs) for furniture products, including "Acidification Potential, Global Warming Potential, Freshwater Eutrophication, Ozone Layer Depletion, and Photochemical Ozone Formation". Such a comprehensive approach provides insights into key environmental impacts associated with furniture production.
Similarly, Piekarski et al. (2017) evaluated impact categories including the previously mentioned "Acidification Potential, Global warming potential, Freshwater Eutrophication, Ozone Layer Depletion, and Photochemical Ozone Formation" but expanded their analysis by "Ecotoxicity and Human Toxicity".
In another study by Bianco et al. (2021), impact categories like "Global Warming Potential, Acidification Potential, Freshwater Eutrophication, and Human toxicity-carcinogenics" amongst others were considered relevant to the wooden furniture sector.

The decision to exclude certain impact categories in previous studies was based on specific challenges and limitations within the field of LCA for furniture production.
For example, in the study by Cordella and Hidalgo (2016), the assessment category for resource depletion was omitted due to significant methodological differences in how resource depletion impacts are evaluated. This discrepancy highlighted the need for further consensus and improvement in assessment methods.

Similarly, the ecotoxicity impact category was not considered in the LCA due to its absence in Product Category Rules (PCRs) for furniture and the lack of "recommended and satisfactory" assessment methods as noted by the European Commission's Joint Research Centre. Furthermore, the assessment of Water Depletion (WD) was deemed unreliable and therefore excluded from consideration in the study by Bianco et al. (2021). The variability of water consumption in the wooden furniture sector, influenced by factors like tree varieties, cultivation techniques, and local climate, contributed to significant data uncertainty, particularly during the forestry phase.

Given these challenges and limitations identified in previous research, the LCA for this master thesis will also exclude resource depletion, ecotoxicity, and water depletion as impact categories. Instead, the focus will be on impact categories which are recognized as relevant to the wooden furniture sector by the European Commission, including "Global Warming Potential, Acidification Potential, Freshwater Eutrophication, Particulate matter/respiratory inorganics, Human toxicity-carcinogenics, Freshwater ecotoxicity and land use" (Bianco et al., 2021).

2.1 Comparison of furniture materials

In assessing environmental impacts across different materials, researchers have consistently found that metals and plastics generally impose higher environmental burdens compared to wooden materials (Cordella and Hidalgo, 2016; Wenker et al., 2018). Cordella and Hidalgo (2016) suggest that while plastics offer relatively better environmental profiles than metals due to lower weight and energy use during production, their primary impacts stem from non-renewable resources like oil consumption.

Additionally, Cordella and Hidalgo (2016) emphasize the energy-intensive nature of metals, especially primary aluminum, which significantly contributes to their environmental impacts. Wenker et al. (2018) further illustrate the significant influence of non-wood components, especially metals, on the Global Warming Potential (GWP) of furniture during raw material extraction and manufacturing, underscoring the comparably high environmental impacts associated with metals in furniture production.

These findings align with research by Maureen Puettman (2019), who highlights the lower environmental impacts of wood-based composite panels compared to non-wood alternatives across various impact categories, reinforcing the environmental benefits of using wood-based materials in various applications, as emphasized in the analysis by Cordella and Hidalgo (2016). Figure 1 shows which wood-based materials are assessed during this master thesis LCA.

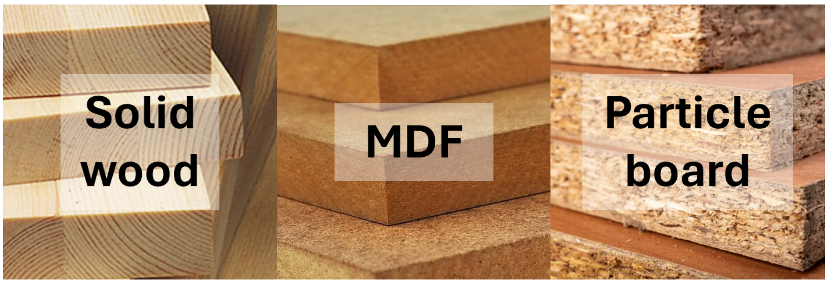

Figure 1: Different table material types (KPM, n.d.; NWT, n.d.; Steven Fox and Vila, 2020)

Despite the advantages of wood-based composite panels compared to non-wood alternatives, Cordella and Hidalgo (2016) note environmental burdens related to land resource demands associated with wood materials, including embodied energy and chemical additives used in the manufacturing of wooden panels and boards.

Furniture incorporating mixed materials see a higher contribution from material production and supply stages, particularly evident in solid wood furniture, where other life cycle stages become relatively more significant.

Wood-based materials like wood panels demonstrate comparatively reduced environmental impacts per mass fraction when contrasted with non-wooden components. Nonetheless, because wood components are predominant in furniture items, their production significantly influences the LCA outcomes during the cradle-to-gate phase of the declared units (Wenker et al., 2018).

2.2 Furniture life cycle steps with the highest environmental impacts per category and material type

Previous LCAs have revealed crucial insights into the environmental impacts associated with solid wood panels and engineered wood panels like particle board (PB) and medium-density-fiberboard (MDF), highlighting consistent findings across diverse studies.

Specifically, Lao and Chang (2023) emphasize that regardless of the panel type, the most significant environmental effects occur during raw material and auxiliary material production, followed by board manufacturing. This includes notable environmental hotspots such as the production of urea-formaldehyde (UF) resin and electricity consumption, which are essential components in PB and MDF production. Similarly, findings from Piekarski et al. (2017) confirm these trends, attributing a substantial portion of MDF's acidification impacts to its production phase, particularly focusing on wood transport, UF resin production, and electric power consumption. Additionally, studies on PB production by González-García et al. (2012) and Thomas P. Gloria (2018) also echo these conclusions, highlighting the significant environmental impacts of raw material production, electricity generation, and resin production. Moreover, Cooper et al. (2021) emphasize in their life cycle analysis of wooden furniture that material production and supply contribute significantly to environmental impacts, underscoring the importance of material selection and product durability. Notably, both Lao and Chang (2023) and Maureen Puettman (2019) identify energy production and material manufacturing as critical environmental hotspots in PB and MDF production, with MDF notably emitting higher greenhouse gas (GHG) emissions compared to PB due to fossil fuel combustion.

Wood panel production, including cutting and drying, requires substantial energy, particularly during painting and coating stages where drying alone can account for up to 70% of the energy demand (Cordella and Hidalgo, 2016). Adhesives, solvents, and coatings used in these processes release substances that contribute to photochemical ozone formation (Cordella and Hidalgo, 2016).

In furniture manufacturing and distribution, environmental impact is less significant compared to the impact of material supply and production (Cordella and Hidalgo, 2016).

During the use phase of furniture, environmental impacts from cleaning and maintenance are minimal, while the durability of furniture has a great influence on the item's overall environmental footprint as well as the end-of-life stage which influences especially eutrophication and ozone depletion impact categories (Cordella and Hidalgo, 2016).

Overall, the findings from previous LCAs underscore the significant environmental impacts of raw material extraction, auxiliary material production, and specific manufacturing processes in the production of PB and MDF furniture (Cordella and Hidalgo, 2016). Similarly Lao and Chang (2023) demonstrate in their comparative study, as depicted in the Figure 2 "Contribution analysis of particleboard", the distribution of environmental impacts across different stages of particleboard production in China. Their findings underscore that the primary contributors to these impacts are the production of raw and auxiliary materials, followed by PB manufacturing and transportation. This pattern mirrors the results observed for MDF according to their study. The dominance of raw and auxiliary material production in contributing to environmental effects across various indicators can be attributed to the substantial consumption of urea-formaldehyde (UF) (Lao and Chang, 2023). The PB manufacturing stage is particularly influential in terms of water use (78%) and human toxicity (94%) generation.

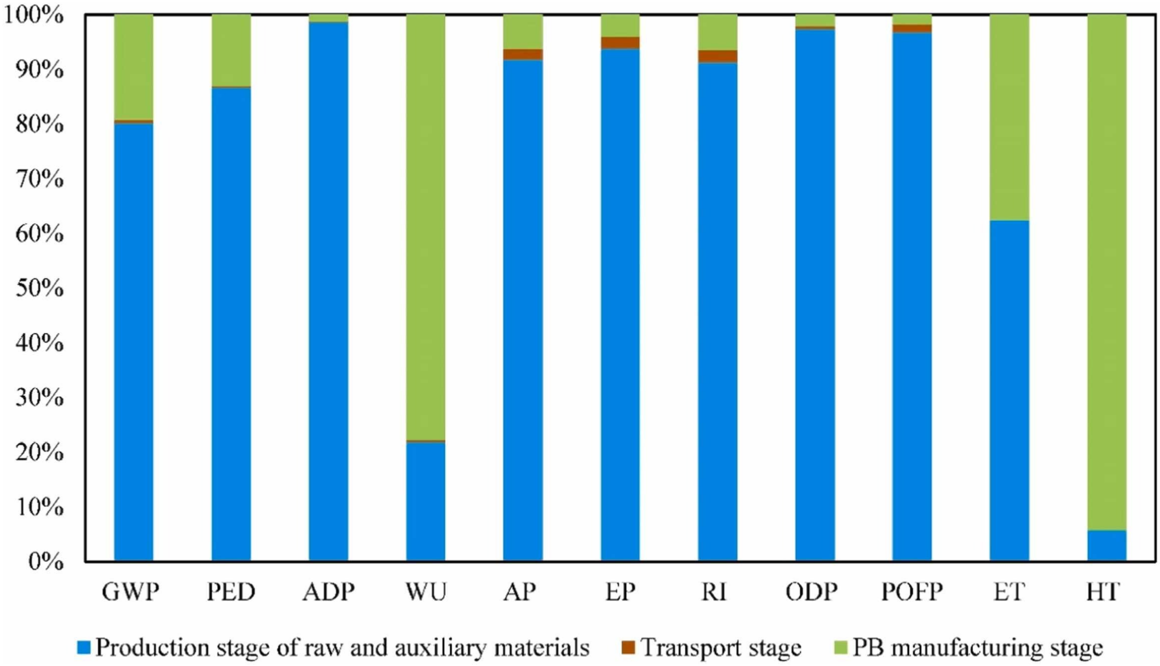

Figure 2: Contribution analysis of particleboard (Lao and Chang, 2023)
GWP= Global Warming Potential, ADP= Abiotic Depletion Potential, ODP= Ozone Depletion Potential, PED= Primary Energy Demand, RI= Respiratory Inorganics, WU= Water Use, EP= Eutrophication Potential, POFP= Photochemical Oxidation Formation Potential, AP= Acidification Potential, EC= Ecotoxicity, HT= Human Toxicity

The findings for PB and MDF are consistent with environmental hotspots identified in the production of solid wood furniture, as demonstrated in a study by Wang et al. (2016). The study compared the life cycle environmental impacts of three solid wood-based furniture items: a beech desk, a white oak and fabric sofa, and a rubber wood wardrobe. The analysis revealed that the production of wooden materials emerged as the primary "hot spot" process, contributing 50% or more to the total impact of all three items, followed by raw material transportation and electricity production.

2.3 Influence of product lifetime on environmental impacts

Transitioning to considerations of product durability in LCA, the literature underscores a consistent theme regarding the environmental benefits associated with extending product lifespans. Iraldo et al. (2017), Cox et al. (2013), Cooper et al. (2021), and Russell et al. (2022) all emphasize the positive impact of increasing product durability on reducing environmental impacts. Specifically, extending product lifetimes leads to avoided environmental impacts associated with the materials used and the subsequent manufacturing-, transport- and disposal life cycles stages as well as reductions in carbon emissions (Iraldo et al., 2017, Cox et al., 2013, Cooper et al., 2021, Russell et al., 2022).
Cooper et al. (2021) further suggest that longer furniture lifetimes not only reduce waste but also contribute significantly to carbon emission reduction. Russell et al. (2022) expands on this concept by proposing that designing products with extended lifespan, incorporating voluntary return

programs (VRPs), and recycling materials like wood can facilitate additional product or material service life cycles, thereby reducing carbon emissions.

The academic literature addressing the consideration of product durability within LCA remains limited; however, researchers who have integrated this aspect into their analyses typically assign specific lifetimes to the assessed products. For instance, the study conducted by David V. Spitzley et al. (2006) employed a uniform nominal lifetime across all systems studied, under the assumption of negligible impacts occurring during the use phase. Similarly, Babarenda Gamage et al. (2008) determined the specific lifetime of the unit item under examination by referencing the product warranty terms.

In addition to designing furniture for increased durability, product lifespan can also be extended through practices like reuse, repair, and refurbishment. Reuse involves using an item again in its current state and is a viable option considering that many products are discarded prematurely due to technological obsolescence or changing fashion trends, as indicated by research (Cox et al., 2013; O. Dictionary, n.d.). The reasons behind premature disposal are often emotional or social, in addition to design and functionality considerations.

Repair is necessary when a product becomes flawed or broken, involving the restoration of an object by replacing or fixing damaged parts to restore functionality (Merriam, n.d.). On the other hand, refurbishment refers to the process of improving and revitalizing an object's appearance and functionality (F. Dictionary, n.d.). While both repair and refurbishment aim to enhance products, repairs are targeted at specific issues to maintain functionality, whereas refurbishment involves more extensive modifications to improve overall condition and appearance.

Research by Russell et al. (2022) suggests that reusing wooden furniture has the lowest environmental impact, while the impacts of repair and refurbishment vary in terms of the benefits they provide (Russell et al., 2022). Notably, the study found that with increasing design complexity, repair and refurbishment processes result in higher process energy use and emissions (Russell et al., 2022).

2.4 Aspects from assessed LCAs to be included in the system boundary definition

Several system boundary definitions identified in the reviewed LCAs exhibit a common aspect that will be adopted in the LCA of the master thesis. Specifically, a noteworthy decision made by certain studies involves the exclusion of biogenic carbon consumption associated with tree growth. This exclusion is a reasonable approach aimed at focusing on fossil CO_2 emissions rather than incorporating the complex dynamics of biogenic CO_2 storage and release during the life cycle of wooden materials (González-García et al., 2012; Wenker et al., 2018). Biogenic CO_2 is temporarily stored in wooden products but is ultimately released into the environment upon disposal, whether through combustion or landfill. By excluding biogenic carbon consumption from the analysis, these studies aim to maintain clarity and avoid potential misinterpretations in assessing the environmental impacts of wooden product life cycles (González-García et al., 2012; Wenker et al., 2018). This systematic approach ensures a more focused and accurate evaluation of the environmental performance of wooden products within the defined system boundaries of the LCA

2.5 Gaps identified in assessed LCAs

Several of the LCAs reviewed omit the use-phase and end-of-life phase of furniture items in their system boundary, often due to challenges in tracking these phases and uncertainties in end-of-life data. For instance, Piekarski et al. (2017) excludes these phases citing difficulties in tracing the end-use and final destination of the product, particularly given the widespread application of medium-density-fiberboard (MDF) in furniture and interior architecture, leading to diverse disposal possibilities.

Similarly, Wang et al. (2016) justifies excluding the use phase due to minimal energy inputs required by furniture and the unavailability of maintenance data, while uncertainties surrounding end-of-life data further warrant its exclusion from assessment. Additionally, Cordella and Hidalgo (2016) notes that impacts related to the use phase, such as maintenance and cleaning, appear negligible without considering factors related to durability.

In contrast to traditional product LCAs that primarily focus on material types and production impacts, this master's thesis LCA prioritizes assessing how durability and furniture lifetime influence the environmental impacts associated with furniture items. Consequently, both the usage and end-of-life phases of the furniture items must be integrated into the analysis. The Methodology chapter will provide detailed insights into how these phases will be included within the system boundary.

2.6 Key Insights from Literature Review

1. Some literature indicates that durable furniture made from wood may increase material usage and costs, potentially amplifying environmental impacts compared to "fast furniture" alternatives while other literature suggests that increasing wood usage in furniture could significantly contribute to mitigating climate change.

2. Metals and plastics exert greater environmental burdens compared to wood per kilogram in furniture manufacturing, while wood composite materials, attributed to chemical additives, exhibit higher environmental impacts than solid wood counterparts.

3. The primary environmental impacts associated with furniture for most impact categories occur during the life cycle stages of raw material and auxiliary material production, irrespective of the material type, encompassing medium-density fiberboard (MDF), particle board (PB), and solid wood.

4. The literature consistently underscores the environmental benefits of prolonging product lifespans, linking extended product lifetimes to reduced environmental impacts and significant reductions in carbon emissions as well as waste, thereby strengthening the motivation for posing research questions 2 and 3.

5. The literature which considers product durability in LCA is limited, but studies integrating this aspect typically assign specific lifetimes to assessed products based on warranty terms or other factors.

6. Extending product lifespan through practices such as reuse, repair, and refurbishment, alongside designing for increased durability, is feasible, with wooden furniture reuse demonstrating the lowest environmental impact, while the environmental impacts of repair and refurbishment vary based on design complexity.

7. Previous studies have excluded certain impact categories in LCA for furniture production due to methodological discrepancies and limitations, such as resource depletion, ecotoxicity, and water depletion, emphasizing the need for consensus and improvement in assessment methods, leading to similar exclusions in the LCA for this master thesis.

8. The reviewed LCAs commonly exclude biogenic carbon consumption associated with tree growth from their system boundaries, aiming to focus on fossil CO_2 emissions and ensure clarity and accuracy in assessing the environmental impacts of wooden product life cycles, a decision that will be adopted in the LCA of the master's thesis.

9. Several LCAs reviewed exclude the use-phase and end-of-life phase of furniture items from their system boundary due to challenges in tracking these phases and uncertainties in end-of-life data, with this master's thesis LCA prioritizing the integration of both phases into the analysis to assess how durability and furniture lifetime influence environmental impacts.

3 Methodology

3.1 Goal

The objective of this lifecycle analysis is to evaluate how the lifetime of furniture influences its environmental impacts. This study focuses on comparing a simple piece of furniture, specifically a table, made from various materials with different levels of durability and recycling potential.
By conducting this comparison, the analysis aims to demonstrate that in addition to considering the environmental impacts associated with different life-cycle stages of a furniture item, factors such as durability and recyclability—determined by material choices and design—must be integrated to comprehensively assess its environmental impacts.
The findings of this study will be disseminated within the academic community and potentially published to share insights with the public.

3.2 Scope

This lifecycle analysis covers a range of thirty tables, including the top ten most popular dining table models sourced from each of Norway's leading furniture wholesale stores: Ikea, Bohus, and Jysk (Knut Erik Rekdal, 2019). The tables, along with their attributes such as wood material, table area, and weight, are shown in Table 1. As observed, 18 tables are predominantly made of medium-density fiberboard, 7 are made of particleboard, and 5 are made of solid wood.
Each of the tables is intended to accommodate six people simultaneously, aiming to suit a wide range of household sizes and remain functional for an extended period of time. This capacity is considered representative of Norwegian households, covering a majority of potential users.

Table 1: The 30 tables assessed in this LCA

Wholesale Company	Table name	Predominant table top material	Table surface area [m^2]	Table weight [kg]
Bohus	SOUTHAMPTON	MDF	2.2	83
	GOTLAND	MDF	2.2	76
	NOLA	MDF	1.7	65
	ZION	MDF	2.0	63
	FRIBURG	MDF	1.9	89
	QUEBEC	MDF	2.2	105
	BRIXTON	MDF	1.8	51
	TRONDHEIM	PB	1.6	27
	SKOVBY	Solid wood	2.1	97
	PIRO	Solid wood	2.2	75
Ikea	TRANEBO	MDF	2.2	55
	MELLANSEL	MDF	2.1	47
	EKEDALEN	MDF	1.0	36
	VANGSTA	PB	1.4	33
	YPPERLIG	PB	1.8	42
	STRANDTORP	PB	1.4	56
	VOXLÖV	PB	1.6	36
	LISABO	PB	1.6	49
	RÖNNINGE	PB	1.4	73
	SKOGSTA	Solid wood	2.4	84
Jysk	TERSLEV	MDF	1.2	27
	JEGIND	MDF	1.0	46
	KALBY	MDF	1.2	40
	AABENRAA	MDF	1.0	26
	SKOVLUNDE	MDF	1.4	44
	MARSTRUP	MDF	1.8	37
	BANNERUP	MDF	0.9	19
	SKAGEN	MDF	1.4	44
	VISLINGE	Solid wood	1.4	29
	ROSKILDE	Solid wood	1.9	57

System boundaries :
In order to answer the research questions while properly assessing the influence of the table lifespans on the environmental footprint of the tables, the LCA was split into three system boundaries which shall shed light on the tables from different viewpoints. Each system boundary has an associated functional unit and reference flow. Figure 3 illustrates the table lifecycle stages encompassed within each system boundary.

System Boundary 1 - Cradle-to-gate: will contrast the environmental impacts of producing engineered wood tables with the impacts of tables made from solid wood. It therefore encompasses cradle-to-gate life-cycle stages for all 30 tables, covering raw material extraction, auxiliary material production, furniture manufacturing, and distribution. To facilitate comparability across the thirty tables of varying dimensions and styles, a **functional unit** was defined as the dining table surface area used by one person. This was operationalized into a **reference flow** of one square meter of table surface area, representing the typical use area for one person. Consequently, the environmental impacts will be normalized to one square meter of table surface area, serving as the reference flow.

System Boundary 2 - Cradle-to-grave: will expand the comparison of environmental impacts of producing engineered wood tables and solid wood tables to include recyclability factors. Consequently System Boundary 1 is expanded to include cradle-to-grave life-cycle stages, incorporating use-phase and end-of-life treatment. The primary focus is on the significant environmental concerns associated with these materials. To isolate and highlight the direct emissions and waste management impacts associated with the disposal of the tables, the benefits of energy recovery during incineration are excluded from the scope of this analysis. This approach ensures a more straightforward assessment of the environmental impacts directly attributable to the materials themselves, without the distorting influences of potential energy recovery benefits. This boundary specifically highlights three tables constructed from the predominant tabletop materials (MDF, PB, and solid wood), as detailed in Table 2. Each table's composition is an average derived from the complete component list of 30 tables. The **functional unit** from system boundary 1 is expanded to encompass the dining table surface area used and discarded by one person. This does not change the **reference flow**, which continues to normalize the environmental impacts associated with production and end-of-life treatment to one square meter of table surface area.

Table 2: Average MDF, PB and solid wood table inventory

Lifecycle inventory								
Average MDF table			Average PB table			Average solid wood table		
Material	Amount	Unit	Material	Amount	Unit	Material	Amount	Unit
Steel	2.7438	kg	Steel	4.0960	kg	Steel	2.588	kg
Carton	0.8051	kg	Carton	0.7430	kg	Carton	0.820	kg
HDPE	0.0011	kg	HDPE	0.0023	kg	HDPE	0.001	kg
Teflon	0.0299	kg	Teflon	0.0088	kg	Teflon	0.015	kg
Bamboo culm	-	-	Bamboo culm	0.2580	kg	Bamboo culm	-	-
Beech wood	0.0001	m^3	Beech wood	0.000006	m^3	Beech wood	0.00001	m^3
Birch wood	0.0020	m^3	Birch wood	0.0015	m^3	Birch wood	-	-
Oak wood	0.0038	m^3	Oak wood	0.0002	m^3	Oak wood	0.037	m^3
MDF	0.0357	m^3	MDF	-	-	MDF	-	-
Pine wood	0.0012	m^3	Pine wood	-	-	Pine wood	0.009	m^3
Particle board	0.0005	m^3	Particle board	0.0369	m^3	Particle board	-	-
Transport	35.4189	tkm	Transport	6.4563	tkm	Transport	39.534	tkm

System Boundary 3 - Cradle-to-grave, including lifetime factors: will analyze the entire product life cycle of engineered and solid wood tables, while also taking into account their lifespan and repairability. It also includes cradle-to-grave life-cycle stages like System Boundary 2, with the key difference lying in the use-phase treatment. In System Boundary 3, the lifetime for one of the three tables can be extended through repair. Since this system boundary includes considerations of furniture lifetime, the **functional unit** must reflect that. Therefore, the functional unit is defined as the dining table surface area used and discarded by one person per year of table use. The **reference flow** will normalize the environmental impacts associated with production and end-of-life treatment to one square meter of table surface area divided by the anticipated years of table lifespan. This approach enables a comprehensive assessment of environmental impacts associated with the selected dining table models throughout their operational lifespan.

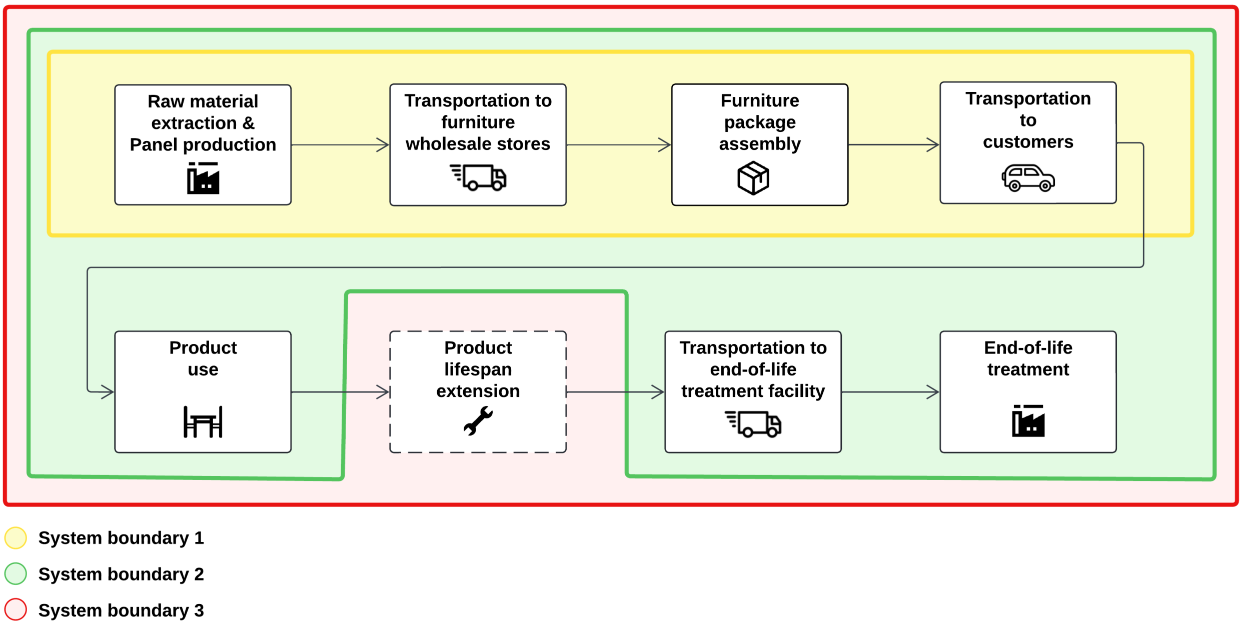

Figure 3: System boundaries used in LCA

Despite variations in design complexity across the assessed tables, they generally comprise distinct components including table tops, legs, cross bars, and auxiliary items like screws, brackets, assembly tools, and packaging materials. The identified tables predominantly consist of the materials of Medium-density fiberboard, particleboard, and solid wood, supplemented by auxiliary materials such as aluminum, steel and carton. An example of such a table can be seen in Figure 4.

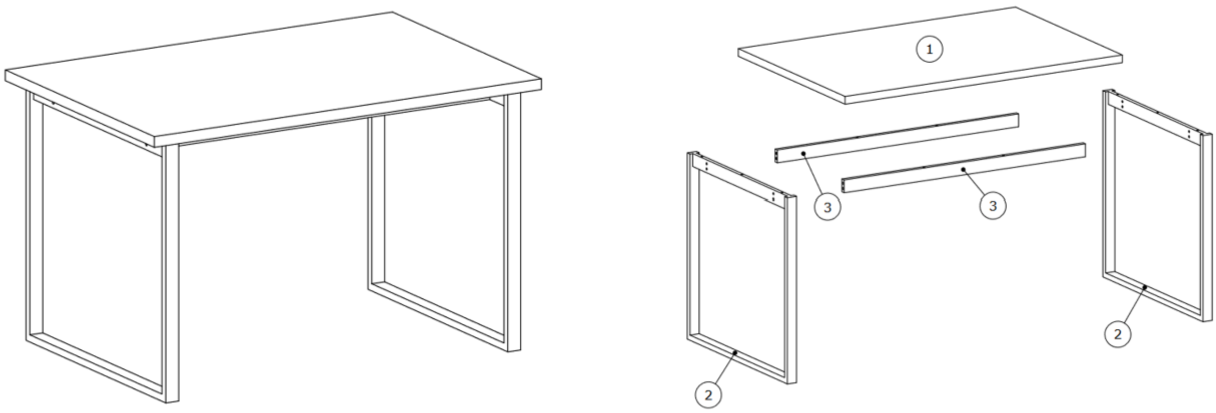

Figure 4: Example of dining table design and components
(1= table top, 2= table legs, 3= cross bars)
(Jysk, n.d.-b)

The LCA was conducted utilizing Brightway 2.0 as software tool incorporating Ecoinvent 3.8 and calculated with the ReCiPe 2016 v1.03, midpoint (H) method. As previously described in Section Literature review the impact categories which are assessed in this LCA are "Global Warming Potential, Acidification Potential, Freshwater Eutrophication, Particulate matter/respiratory inorganics, Human toxicity-carcinogenics, Freshwater ecotoxicity and land use". The results obtained from the LCA were consequently analyzed using Python in Visual studio code as well as Microsoft Excel.

3.3 Life cycle inventory

3.3.1 Data collection

The tables selected from the three most popular furniture wholesale stores were accessed online, where information about the amount and type of components comprising the main tables and the overall package weight of each table was provided. This online data, along with the setup manuals containing information on all auxiliary parts, served as the basis for identifying equivalent components with similar attributes or functionalities.

For the purpose of conducting the LCA, it was imperative to determine the weight and material composition of each individual component. Despite efforts to obtain precise part specifications through email correspondence with the wholesale stores, exact details were not obtainable. Consequently, in cases where an exact match for a component could not be found online, the next best available option was selected, and assumptions were made to scale the component to closely resemble the original part. Due to the extensive content that would exceed the format constraints of the appendix, a list of all components assessed for each of the 30 tables, along with detailed descriptions of the underlying assumptions, is provided in the attached files accompanying this master thesis.

The assumptions made during this process varied and included methods such as scaling component weight by length, surface area, and the quantity of parts within a package. Some table setup manuals did not contain sufficient information on part dimensions, which meant that visual estimations of dimensions or derivations from parts with known dimensions had to be made. The different approaches used for estimating the weight or volume of the table components and how often they proportionally have been applied is shown in Figure 5. An exact description of the assumptions made, along with the qualitative uncertainty assigned to the approach, is provided in Figure 6 and will be discussed in more detail in the Uncertainty section. Additionally, the Appendix contains one figure, summarizing the methodologies applied to estimate the physical properties of the components, for each wholesale store. This inclusion was necessary due to the varying levels of detail provided by the wholesale stores in their setup manuals and dimension specifications.

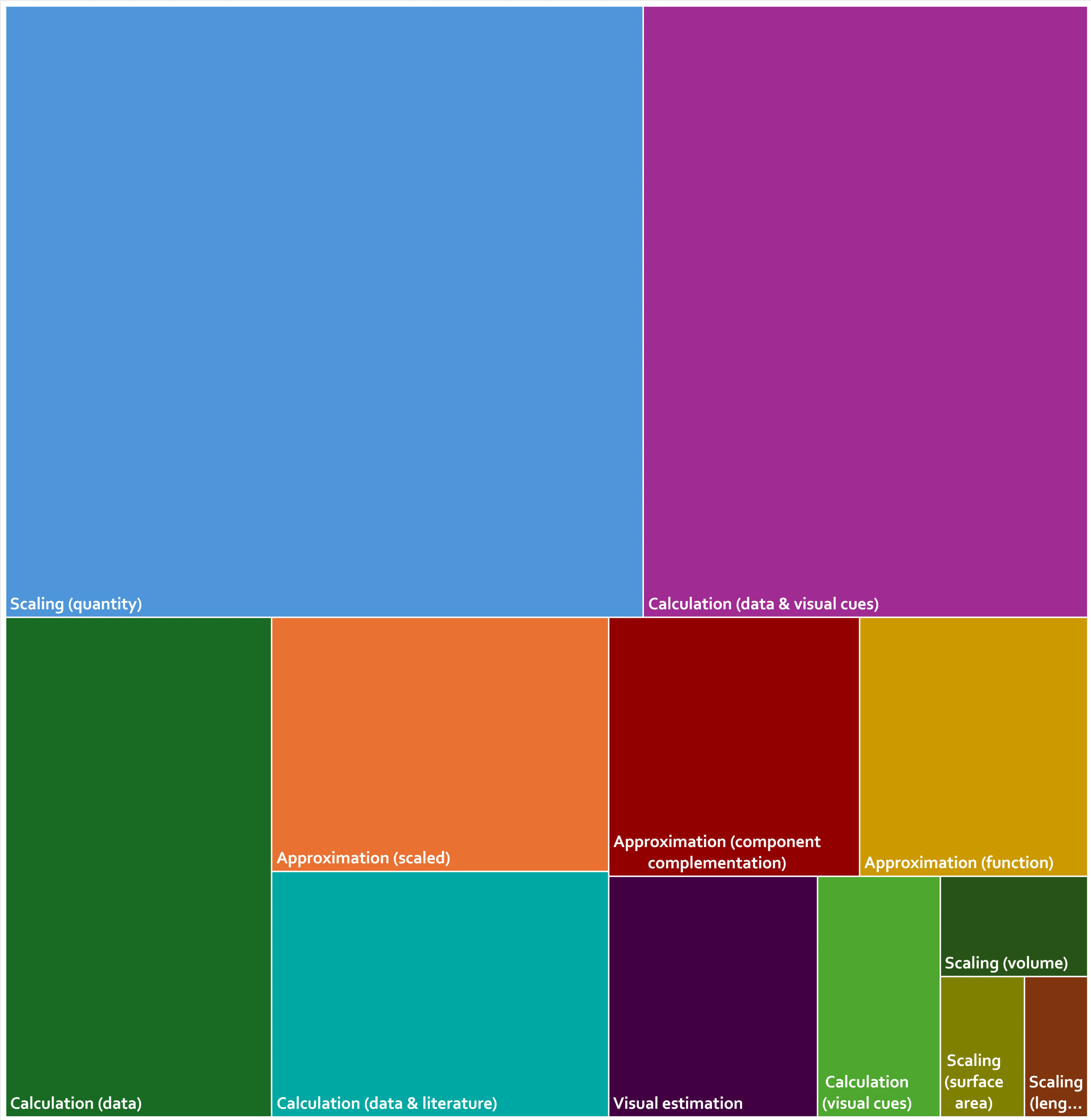

Figure 5: Applied estimation approaches for physical properties of table components

		Uncertainty
Scaling (quantity)	Standard of part was identified based on the table setup manual. The weight of the part sold by an online supplier was found and scaled by quantity of the pieces sold.	Low
Calculation (data)	The dimensions of the part were identified based on the setup manual or the webpage of the wholesale store. The weight or volume of the part was then directly calculated.	Low
Scaling (length)	The dimensions of the part were identified based on the setup manual or the webpage of the wholesale store. An exact match for the part with the required dimensions was not available from online suppliers. Consequently, the weight of an existing part was adjusted to account for the difference in length.	Low
Scaling (surface area)	The dimensions of the part were identified based on the setup manual or the webpage of the wholesale store. An exact match for the part with the required dimensions was not available from online suppliers. Consequently, the weight of an existing part was adjusted to account for the difference in surface area.	Low
Scaling (volume)	The dimensions of the part were identified based on the setup manual or the webpage of the wholesale store. An exact match for the part with the required dimensions was not available from online suppliers. Consequently, the weight of an existing part was adjusted to account for the difference in volume.	Low
Approximation (component complementation)	The dimensions of the part were only partially available from the setup manual. Therefore, the missing dimension was deduced from another part with sufficient indications, as the setup manual clearly indicated that both parts would be used together complementarily.	Low
Calculation (data & literature)	The dimensions of the part were only partially available from the setup manual. The calculation was therefore supplemented with an average value specific to that part from literature sources.	Medium
Calculation (data & visual cues)	The dimensions of the part were only partially available from the setup manual. The missing dimensions were visually estimated by comparing the size of its depiction in the setup manual to another part depicted with known dimensions.	Medium
Calculation (visual cues)	All dimensions of the part were visually estimated by comparing the size of its depiction in the setup manual to another part depicted with known dimensions.	Medium
Approximation (function)	The standard of the part was not specified in the setup manual, and its exact design could not be found online. Consequently, the weight of a part with a different design but fulfilling the same purpose was used as a proxy	High
Approximation (scaled)	The standard of the part was not specified in the setup manual, and its exact design could not be found online. Consequently, the weight of a part with a different design but fulfilling the same purpose was used as a proxy and scaled to match the estimated length.	High
Visual estimation	All dimensions of the part were visually estimated by comparing the size of its depiction in the setup manual to other parts without indicated dimensions.	High

Figure 6: Legend corresponding to the applied estimation approaches

After identifying the materials, weights, and volumes for each table, corresponding datasets with background inventory data on raw material extraction, transport, and production were sourced from the Ecoinvent database. Generally, processes representative of European or global average technologies were preferred to ensure relevance to the Norwegian context of this LCA.

In instances where foreground processes were not covered by the Ecoinvent database, additional data was collected through literature review and an expert interview. This included processes such as transport from material production to the wholesale store, transportation from the wholesale store to the customer, resource utilization for table repairs, and transport from the customer to end-of-life treatment facilities. The specific assumptions made in each unit process will be discussed in detail in the subsequent section.

3.3.2 Unit processes

The unit processes comprising the assessed system are illustrated in Figure 7. The life cycle stages of the tables encompass several key phases: raw material extraction and panel production, transportation to furniture wholesale stores, furniture package assembly, transportation to customers, product use, product lifespan extension, transportation to end-of-life treatment facilities, and end-of-life treatment. The assumptions underlying each unit process in the LCA will be elaborated upon in the following.

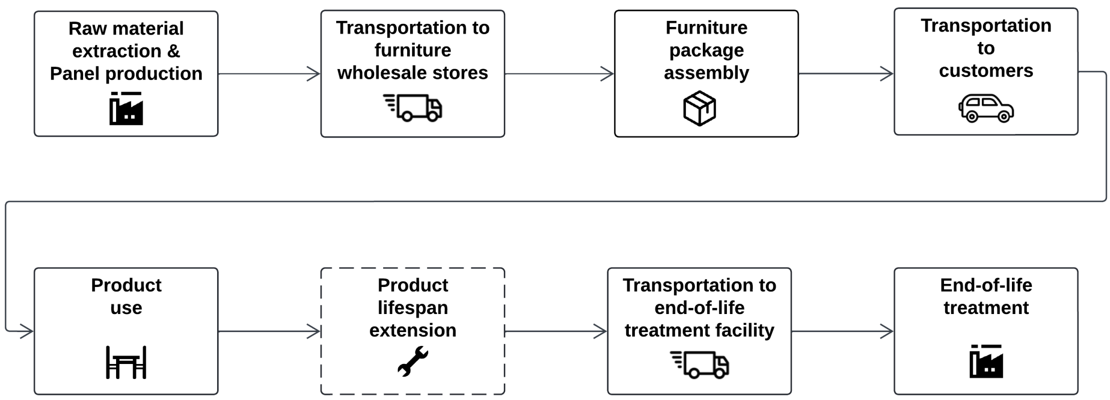

Figure 7: Unit processes included in the LCA system

Raw material extraction and panel production

The raw material extraction and panel production data utilized in this master's thesis for Medium Density Fibreboard (MDF), Particle Board (PB), and solid wood panels are derived from processes documented in the Ecoinvent database. Specifically, the data for MDF adheres to the standard EN 622-5, with specified density ranging from 500 kg/m³ to 1000 kg/m³ and average thickness between 1.8 mm and 60 mm whereas the data for PB adheres to standard EN312, with specified density ranging from 650 to 750 kg/m³, and average thickness between 3 mm and 40 mm. This information agrees with documented Environmental Product Declarations (EPDs) for MDF and PB reviewed in the Literature review (Thomas Gloria, 2024; Thomas P. Gloria, 2018) and is therefore applicable for inclusion in this LCA.

The selection of Ecoinvent processes for MDF, PB, and solid wood panels was guided by the need to reflect the Norwegian context. For MDF, data sourced from Germany was considered acceptable as Germany is the major exporter of MDF in Europe, the key region relevant to the Norwegian market (Mark Irle, 2023). Due to the absence of domestic production facilities Norway relies solely on imports for MDF (FAOSTAT, n.d.). Similarly, the selection of PB data from Germany aligns with central European conditions, suitable for comparative analysis within the European context.

The choice of specific Ecoinvent processes for solid wood panels was tailored based on tree type and geographical relevance, ensuring alignment with European datasets to accurately reflect the Norwegian scenario. The typical density range of oak wood, falling between 600 to 900 kg/m^3, is used as metric for subsequent calculations, given its prevalent use in the evaluated tables (E.T., n.d.). Auxiliary materials such as steel, boxboard carton, and aluminum were also sourced from Ecoinvent, emphasizing compatibility with European standards and original part specifications to maintain consistency and reliability in the LCA. These considerations ensure that the data used in this study is robust, contextually relevant, and conducive to meaningful analysis within the scope of the research objectives.

Transport to furniture wholesale store

The transport distances specified in the Ecoinvent processes for auxiliary materials are deemed sufficient for this LCA due to their reasonable representation of the import and export dynamics involving the countries concerned. However, for wooden materials, adjustments to transport distances were made based on assumptions specific to this LCA to better align with the Norwegian context, as opposed to a broader European perspective.

The transportation of wooden panels to the wholesale store was assumed to be conducted via lorry and quantified in ton-kilometers. For the ton kilometer calculation, the distance between the country of panel production and wholesale logistic centers situated in Norway was required. Initially, the locations of wholesale logistic centers and panel production facilities were identified, as detailed in Tables 3 and 4. Notably, the assessed furniture wholesale stores are situated in the vicinity of Oslo, ensuring comparability across locations.

For Medium-Density Fiberboard (MDF), the panel supplier was assumed to be situated in Germany, given Norway's reliance on MDF imports (FAOSTAT, n.d.). Germany, being a prominent MDF exporter in Europe, led to the selection of Kronospan, the largest MDF producer in Germany, as the reference point for this LCA (Birgit Fingerlos, 2012). Particleboard (PB) sourcing was assumed to be domestic to Norway, given Norway's net production surplus of particleboard (FAOSTAT, n.d.). Forestia AS, a major particleboard producer in Norway, was selected as the reference point due to its prominence in the market. For solid wood, Poland was identified as the panel supplier based on Ikea's supply data, highlighting Poland as a significant source of virgin wood for Ikea's operations (E.T., n.d.). Among Poland's numerous production facilities, a representative location was chosen for this study.

Table 3: Logistic center location per wholesale store

Furniture wholesale store	Logistic center location
Ikea	Guldlisten 35, 3048 Drammen, Norway
Bohus	Heiaveien 8, 1900 Fetsund, Norway
Jysk	Tevlingveien 23, 1081 Oslo, Norway

Table 4: Location of panel production per material type

Panel material	Panel production company	Location of panel production
MDF	Kronospan GmbH	Leopoldstalerstrasse 195, 32839 Steinheim, Germany
PB	Forestia AS	Damvegen 31, N-2435 Braskereidfoss, Norway
Solid wood	Ikea Sp.zo.o	Kargowska 59, 66-110 Babimost, Poland

Ton-kilometers were calculated for each table by multiplying the distance between the panel production site and the wholesale logistics center by the table's weight (converted to tons). This value was then divided by the table's surface area to reflect the functional unit. These calculations serve to inform adjustments to the transport processes within Ecoinvent to enhance the accuracy of the LCA.

Furniture package assembly

The absence of furniture assembly data in the LCA can be attributed to several factors related to the nature of the assessed wholesalers (Ikea, Bohus, and Jysk) and their sales approach, which involves the distribution of furniture in flat package format requiring manual assembly by consumers. Specifically, the assembly of furniture packages would require data regarding the elec-

Table 5: Ton kilometers per panel material and logistics center

Panel material	Wholesale logistics center	Distance panel production to wholesale logistics center [km]
MDF	Ikea	1 032
	Bohus	1 101
	Jysk	1 079
PB	Ikea	209
	Bohus	128
	Jysk	134
Solid wood	Ikea	1 163
	Bohus	1 172
	Jysk	1 148

tricity consumption during the assembly process. However, due to a lack of available literature on this subject and the wholesalers' unwillingness to provide relevant data for this LCA, no energy consumption data during package assembly was incorporated to mitigate uncertainties arising from potentially inaccurate estimations. It was therefore assumed that no energy is utilized during the package assembly phase. Furthermore, the absence of information regarding the glues or adhesives used to bond components together, or the paints used for aesthetic purposes, in the material components list of the assessed tables contributed to the decision not to include assembly-related data. As a result, it was assumed that the raw and auxiliary material as described in Ecoinvent already possess the desired design and coating upon arrival at the wholesale logistics center, further supporting the exclusion of specific assembly-related information from the LCA.

Transport to the customer

In order to quantify the emissions associated with the transportation of the table package from the wholesale logistics center to the private consumer household, certain assumptions were necessary. Firstly, it was assumed that consumers typically travel to the wholesale center using their private vehicles and have the capacity to transport the table package within their cars. This assumption is supported by a study on private car demand in Norway, which highlights the predominant use of private cars for retail and service trips due to the country's low population density (Rokseth et al., 2021). Secondly, estimating the distance traveled by car required referencing findings from the Norwegian national travel survey of 2013/14, which reported that the average daily travel distance per Norwegian citizen is 47.2 kilometers, with approximately 27% of this distance attributed to shopping activities. Consequently, this equates to an estimated 12.7 kilometers traveled per day for shopping purposes. This figure closely aligns with the average daily travel distance of 14.5 kilometers identified in another study (Randi Hjorthol et al., 2014).

For consistency and comparability, it was assumed that the distance between the wholesale logistics center and the consumer household is the same for all three wholesalers.

Product use

The decision to exclude data inputs related to the furniture use phase is based on specific characteristics of the assessed tables and assumptions regarding consumer behavior. Firstly, the product use phase of the assessed tables does not necessitate any energy inputs to fulfill their intended purpose. Unlike certain appliances or electronic devices, these tables primarily serve functional and structural roles that do not require ongoing energy consumption during typical use. Therefore, no energy-related data inputs were deemed necessary for this phase of the life cycle assessment. Secondly, it is assumed that regular maintenance activities typically associated with furniture use in households are minimal or nonexistent. This assumption aligns with prevailing societal attitudes characterized by a "fast furniture" mentality, where furniture items are often perceived as disposable or replaceable rather than subject to routine maintenance (Cooper et al., 2021). As a result, considerations such as maintenance-related energy consumption or materials usage were not included in the assessment, reflecting the assumed patterns of consumer behavior in relation to these furniture pieces.

Product lifetime prolongation

In the context of this LCA, the system boundary 3 examines the assumption that a table's lifespan can be extended through repair actions. Solid wood is valued for its durability and ability to withstand multiple sanding or refinishing processes, whereas engineered wood, despite its improved resistance to warping and cracking, may be challenging to repair if damaged (Furniture, n.d.). Consequently, the assumption is that only solid wood tables can feasibly have their lifespans extended. Consumer perceptions of product care are closely linked to quality considerations, particularly aesthetics, functionality, and material quality, highlighting a greater inclination towards repairing solid wood tables over those made from engineered wood (Iraldo et al., 2017). To reflect the previously mentioned "fast furniture" mentality it is assumed that only 20% of all solid wood tables are repaired by consumers while 80% are replaced by new tables. For analytical clarity, this study furthermore simplifies the repair scenario to only encompass physical damages like gouges, or dents on solid wood tables. Drawing on relevant literature, the necessary materials for addressing such specific flaws are then attributed to the created repair activity within the Ecoinvent database.

In this thesis, it is assumed that a dent measuring 2 centimeters in length and 1 centimeter and 0.2 centimeters in width and depth on the table surface is repaired using the wood filler method. The repair process involves filling the dent with wood filler, allowing the paste to dry, sanding the repaired area until it is level with the surrounding surface, and then applying a wood finish to blend the repaired area with the rest of the wood (Kubrick, 2023). Since wood filler is not included in the EcoInvent inventory, it's composition had to be approximated for this thesis. Based on literature it was determined that the wood filler consists of the inert substance calcium carbonate, the colorant titanium dioxide, the raw material cellulose fiber, and the binding agent epoxy resin (Cao et al., 2020; Hubbe and Gill, 2016; Petrie, n.d.). The weight of filler used for the repair was calculated by first computing the volume of the dent which needs filling by multiplying the length with the width and the depth resulting in 0.4cm^3. This result was then multiplied with the density of an average calcium carbonate wood filler of 2.6 g/cm^3 (Cao et al., 2020) to obtain the weight of filler used of 1.3g. The percentage composition as shown in Table 6 of wood filler was then used to compute the weight of each filler component required for the repair in order to be added to the life-cycle inventory.

Table 6: Average wood filler composition (Cao et al., 2020)

Wood filler component	**Composition [%]**
Calcium carbonate	50
Titanium dioxide	3
Cellulose fiber	17
Epoxy resin	30

The same procedure is applied to sand paper which is used for the sanding process step. It is on average composed of the abrasive material aluminum oxide, the backing material coated paper and the adhesive phenolic resin (Anwar and Li, 2024; Jasonxue, 2024; Uneeda, n.d.). For a sand paper with the dimensions of 114 mm length and 140 mm width the percentage composition as shown in Table 7 were used to compute the weight of each sand paper component.

Table 7: Average sand paper composition (Jasonxue, 2024)

Sand paper component	**Composition [%]**
Aluminum oxide	45
Paper	40
Phenolic resin	15

Lastly it is assumed that the wood finish applied to blend the repaired area with the rest of the wood is acrylic varnish which is included in EcoInvent. In order to find out how much varnish is required for the dent in question, the surface area to be covered by the varnish is calculated by multiplying the length of the dent by its width resulting in 2cm^2. Then the average coverage of 375 square feet per gallon as indicated in the product data sheet of a varnish producer is converted to grams per square centimeter and multiplied with the calculated surface area, resulting in 0.022 grams (Minwax, n.d. The amount of human labor is not quantified in the life-cycle inventory of the wood repair as well as auxiliary tools used to apply the wood filler or varnish which are assumed to be in stock in an average household such as kitchen paper and spatula. The complete life-cycle inventory of the repair of the solid wood table is depicted in Table 8

Table 8: Repair life-cycle inventory

Repair component	Component compound	Quantity [kg]
Wood filler	Calcium carbonate	6.50E-04
	Titanium dioxide	3.90E-05
	Cellulose fiber	2.21E-04
	Epoxy resin	3.90E-04
Sand paper	Aluminum oxide	3.50E-04
	Paper	7.06E-05
	Phenolic resin	3.70E-05
Wood finish	Acrylic varnish	2.20E-05

To ensure comparability between solid wood and engineered wood tables in this case, the principle of substitution is employed. Following repair, the lifespan of the solid wood table is assumed to double. In contrast, the engineered wood tables must be replaced with new ones to achieve an equivalent extended lifespan, thereby necessitating an assessment of the impacts associated with the production of these replacement tables.

Transport to the to end-of-life treatment facility

In order to estimate the distance from the consumer household where the furniture is collected for disposal by the municipal waste collection service to the waste treatment facility the three biggest cities in Norway, Oslo, Bergen and Trondheim are used as a reference. These cities were chosen because their high population density ensures that a large percentage of the population is covered, making them representative of the Norwegian context for this study. The distances between the city centers and the waste treatment facilities of the three cities are used to calculate the average distance which serves as a base for the ton kilometer calculation. The average weight of all assessed tables is 0.054 tons. In a similar manner to the section on "Transport to furniture wholesale store" the ton kilometers presented in Table 9 were obtained by multiplying the average table weight per surface area (converted to tons) with the distance between the city centers and the waste treatment facilities.

Table 9: Ton kilometers per material and end-of-life (EOL) treatment facility location

City	Distance to EOL treatment facility [km]	Ton kilometers [tkm]
Oslo	6.9	0.37
Bergen	2.4	0.13
Trondheim	12.2	0.66
Average	7.2	0.38

End-of-life-treatment

In order to incorporate an end-of-life unit process in this LCA, it is essential to establish the treatment methods for discarded tables in Norway. The Norwegian statistics on wood waste management for the year 2022 illustrate the fate of generated wood waste. Of the total wood waste in 2022, 11.6% was directed towards recycling, while a significant portion of 86.7% underwent incineration. The remaining 1.7% underwent diverse treatment methods such as landfill disposal, composting, biogas production, and other disposal methods which lacked specific categorization (SSB, n.d.).
Given the negligible proportion of 1.7% relative to the larger fractions and its diverse treatment methods, this fraction was excluded from further consideration. To maintain consistency in the analysis, adjustments were made to the reported percentages. Consequently, the re-calibrated figures indicated that recycling accounted for 12% of the total wood waste, with incineration representing 88%. This adjustment ensured that all material flows within the LCA were accurately accounted for, avoiding discrepancies or undefined outcomes.

The wood waste recycling process in Norway involves converting eligible furniture waste into particleboard at one of two specific particleboard manufacturing facilities (Kristina Bringedal Gedde, Norwegian Institute of Bioeconomy Research, personal communication, April 18, 2024). However, this recycling is restricted to eligible furniture waste because physical and chemical contaminants present in some waste wood resources hinder recycling processes and degrade the quality of the recycled particleboard (Nguyen et al., 2023). The use of waste wood for particleboard production also raises the risk of formaldehyde emissions in the recycled product (Nguyen et al., 2023). Consequently, it was necessary to identify which tables assessed in this master thesis are suitable for recycling.

Studies indicate that solid wood and particleboard can be recycled into particleboard, whereas fiberboard, particularly MDF, poses significant challenges and is generally rejected by particleboard manufacturers. The high levels of heavy metals and organic compounds in fiberboard can cause stability and processing issues during recycling (Faraca et al., 2019; Mark Irle, 2023; Russell et al., 2022).

Therefore, in this LCA, it is assumed that 12% of the tables made of particleboard and solid wood are recycled into particleboard, while 88% of these tables, along with 100% of the tables made of MDF, are incinerated.

To account for the emission offset, the avoided particleboard production emissions are added to the MDF table. This substitution approach ensures the comparability of the tables.

It is assumed that the incineration process within the EcoInvent database accurately represents waste incineration in Norway, given that it references a norwegian municipal waste incineration plant in 2010. However, a potential discrepancy between the EcoInvent database incineration process and the actual incineration process of the tables lies in the waste composition, which consequently affects the heating value of the waste.

The EcoInvent process assumes a lower heating value 11.7 MJ/kg for the municipal solid waste treated. The heating values for the three representative tables made of MDF, PB, and solid wood have been calculated in order to compare them with the EcoInvent process for adjustment purposes. The table compositions shown in Table 2 was summarized into broader material categories for which generic heating values were found in literature sources. The heating values were then multiplied with the percentage share of the respective material resulting in the table heating values shown in Table 10

The wood lower heating value for three out of the five wood types used in the tables have been found in literature. The average lower heating value for wood was attributed to the other wood types.

Table 10: Lower heating value calculation for representative tables

Table materials [%]	Metal	Carton	Plastics	MDF	PB	Oak wood	Beech wood	Birch wood	Average wood	**Lower heating value [MJ/kg]**
Average MDF table composition [%]	8%	2%	0.003%	75%	1%	8%	0.2%	4%	1%	16.00
Average PB table composition [%]	14%	2%	0.01%	-	79%	1%	0.02%	3%	1%	14.03
Average solid wood table composition [%]	7%	2%	0.04%	-	-	79%	0.02%	-	11%	18.40
Lower heating value [MJ/kg]	-0.15[1]	17.00[2]	45.86[3]	17.00[4]	16.00[5]	19.9[6]	19.65[6]	19.3[6]	19.93[6]	

[1]Christensen, 2010
[2]Zetacarton, 2021
[3]Vlasopoulos et al., 2023
[4]Günther et al., 2012
[5]Arauco, 2016
[6]Porankiewicz et al., 2016[7]

To accurately reflect the differences in heating values between the EcoInvent database and the specific wood waste types examined in this thesis, the amount of waste considered was adjusted. The EcoInvent process for 1 kg of municipal waste assumes a lower heating value than what is applicable for the wood waste in this study. Therefore, the amount of waste was adjusted to be the table weight per square meter table surface reduced by the percentage difference in heating values between the EcoInvent data and the specific wood materials used in this thesis.

As a result, the waste incineration process was adjusted as follows:

- For MDF (Medium Density Fiberboard) table waste, the weight of 30 kilograms was decreased by 37%.
- For particleboard table waste, the weight of 35 kilograms was decreased by 20%.
- For solid wood table waste, the weight of 35 kilograms was decreased by 57%.

These adjustments ensure that the incineration process more accurately represents the actual heating values of the different wood waste types.

3.3.3 Table Lifetime determination

For the third case examined in this LCA, the entire product life cycle of engineered and solid wood tables, including product lifespan, will be considered. Therefore, the environmental impacts of the tables will be normalized over their lifespan, defined as the duration from acquisition until replacement, when another product assumes the original application (Iraldo et al., 2017). The determination of the lifespans of the assessed tables presented challenges in this LCA due to the limited availability of durability product declarations. Consequently, three distinct approaches were explored to attribute specific lifespans to tables made of MDF, PB, and solid wood.

1. The first method for determining table lifespans relied on a **literature review**. While the sources provide specific lifespan estimates, these figures should be interpreted with caution as they originate from non-academic sources.

   Medium-density fiberboard The durability of MDF largely depends on its quality. Low-quality MDF boards may only last around a year before they begin to deteriorate. In contrast, high-quality MDF can remain in good condition for up to ten years with proper care and maintenance (Quiz, 2022; Risedesk, 2022).

   Particleboard While one source indicates that PB furniture typically lasts between 2 to 3 years and can extend up to 5 years with light use (Frank, 2021), other sources suggest a typical lifespan of 3 to 5 years (India, n.d.; Siloy, 2022). Additionally, one source asserts that the furniture would not show significant signs of wear before the end of this period (Siloy, 2022).

Oak wood Since different solid wood types have varying attributes and lifespans, this analysis focuses on oak wood as it is the primary component of the average solid wood table shown in Table 2. According to various sources, oak and other solid wood furniture are renowned for their durability and longevity which vary with the quality of the wood, construction techniques, and maintenance (Block, 2020; O.O.F., 2021; Teoh, 2023). One source even goes as far as suggesting that with proper care, oak furniture can last indefinitely (O.O.F., 2021). Other studies indicate that well-made oak furniture can last for generations, with high-quality, handcrafted pieces potentially becoming family heirlooms that endure for 20-30 years per generation and over 100 years with proper care (Block, 2020; Rahaman, 2023; Teoh, 2023). Heirloom-quality handmade wood furniture, including oak, can last more than a lifetime, often reaching the antique milestone of 100 years or more with proper maintenance (Block, 2020).

Overall, these sources agree that oak furniture, when well-crafted and properly maintained, can endure for several generations, often exceeding a century.

Table 11: Approach 1 - table lifetimes

Table material	**Table lifetime [years]**
MDF	1 - 10
PB	2 - 5
Solid wood	20 - 100+

2. The second approach involved evaluating the tensile strength perpendicular to the grain of each material in order to derive the table lifetime. This measure was chosen for its ability to indicate a board's resistance to delamination or splitting (**european_panel_european_nodate**). The tensile strength, expressed in N/mm², is the force required to split a test piece. In the EU, tensile strength is a key **mechanical property** for classifying particleboard and fiberboard (**european_panel_european_nodate**). According to the standard BS EN 319, this property ensures consistency and reliability in assessing the quality and structural integrity of these wood-based panels (BSI, 1993). Subsequently, a literature-informed baseline lifespan is adjusted proportionally for each material based on its tensile strength.

Baseline lifespan First, the baseline lifespan must be defined by averaging the lifespans identified in the literature review. For MDF, a lifespan of 1 to 10 years is reported, resulting in an average lifespan of 5.5 years. Particleboard is stated to have a lifespan of 2 to 5 years, yielding an average of 3.5 years. Although multiple sources claim that oak furniture can last over 100 years, this typically applies to handcrafted heirloom pieces. Since most tables in this study are flat-packed for consumer assembly without glue, it is unrealistic to assume they are heirloom quality. Therefore, it is assumed that these tables last from one to two generations, or 20 to 60 years, resulting in an average lifespan of 40 years.

The baseline lifespan, which shall be adjusted for each material based on their mechanical properties, is approximately 16 years, representing the average of the three lifespans found in the non-academic literature.

Calculation of lifespan based on tensile strength The tensile strength values for MDF, particleboard, and oak wood were identified from literature and material environmental production declarations. These values are 0.1 - 0.5 N/mm² for MDF, 0.14 - 0.75 N/mm² for particleboard, and 5.5 N/mm² for oak wood (Green et al., 2010; Peters, 2020a, 2020b). The average tensile strength of all three materials is 2.1 N/mm². In the next step the difference between the average tensile strength and the tensile strength of each wood type is calculated. This percentage difference is then used to in- or decrease the baseline lifetime. In case of MDF and PB the tensile strength is smaller than the average tensile strength by 86% and 79%, which means that the baseline lifetime of 16 years needs to be reduced by this percentage difference. The tensile strength of solid wood is 264% larger than the average tensile strength, which means that the baseline lifetime of 16 years needs to be increased by that amount.

Table 12: Approach 2 - table lifetimes

Table material	**Table lifetime [years]**
MDF	2
PB	3
Solid wood	58

3. The third approach for determining table lifespans involved reviewing **resale prices** of tables made from the three materials on second-hand platforms and calculating an average. The percentage variances between the material types were then intended to be used to adjust a foundational lifespan from the literature, analogous to the adjustments made in the first approach.

Calculation of lifespan based on resale price The resale prices of five tables of each wood type, listed in System Boundary 1 and detailed in Table 1, were researched on the Norwegian resale platform "Finn.no". These prices were then compared to the original sales prices of the tables from the respective wholesale outlets as shown in Table 13. The number of five tables was chosen because the solid wood tables assessed in the LCA amount to that number. However, not every solid wood table model was available on "Finn.no", so other table models from the same wholesale companies were selected to compensate. Notably, the "Mörbylånga" table from Ikea and the "Skovby SM24" table from Bohus were used for this purpose.

The in Table 13 observed price reductions for tables vary by material: MDF tables show a decrease ranging from 34% to 70%, PB tables from 21% to 75%, and solid wood tables from 24% to 78%. Unfortunately, limited data on the duration of table use was available in the resale ads, preventing the calculation of representative correlations between price reduction and usage time. From the available data, it can be inferred that these tables are typically resold after being used for a few months to approximately two and a half years. Often, a short usage period is due to people moving to a new apartment or house. However, this information cannot directly be used to determine table lifetimes since the tables on the resale platform have not reached the end of their lifespans and the data is not comprehensive enough to be representative. Additionally, the variability in usage duration due to factors such as relocation or changes in personal preference further complicates the assessment of true table lifetimes based on resale data alone.

The average price reductions for the different materials are quite similar: 47% for PB, 48% for solid wood, and 50% for MDF. The similarity in price reductions across all materials makes it challenging to derive differences in table lifetimes. If price reduction were directly translated to table lifetimes, it would imply that tables made from different materials have similar lifetimes. This contradicts existing literature, suggesting that resale prices are not a reliable method for determining furniture lifetimes. Consequently, the information gathered from this approach will not be used further.

Table 13: Table resales price overview

Table material	Wholesale company	Table name	Sales price [NOK]	Resale price [NOK]	Price difference [%]	Use time [years]	Average price reduction [%]
	Jysk	AABENRAA	1,599 [8]	1,000 [9]	37%	1.9	
	Bohus	FRIBURG	8,499 [10]	5,000 [11]	41%	0.7	
MDF	Ikea	EKEDALEN	2,995 [12]	1,000 [13]	67%	/	50%
	Jysk	TERSLEV	1,999 [14]	600 [15]	70%	/	
	Bohus	GOTLAND	11,425 [16]	7,500 [17]	34%	2.0	
	Bohus	TRONDHEIM	4,999 [18]	3,000 [19]	40%	2.7	
	Ikea	VANGSTA	1,995 [20]	500 [21]	75%	/	
PB	Ikea	LISABO	2,795 [22]	2,200 [23]	21%	0.2	47%
	Ikea	YPPERLIG	3,659 [24]	1,250 [25]	66%	1.5	
	Ikea	VOXLÖV	3,895 [26]	2,600 [27]	33%	/	
	Jysk	ROSKILDE	8,999 [28]	4,500 [29]	50%	0.5	
	Bohus	SKOVBY SM27	29,999 [30]	15,999 [31]	47%	/	
Solid wood	Ikea	SKOGSTA	6,795 [32]	1,500 [33]	78%	/	48%
	Ikea	MÖRBYLÅNGA	8,495 [34]	4,900 [35]	42%	/	
	Bohus	SKOVBY SM24	33,599 [36]	25,500 [37]	24%	/	

3.4 Limitations

The conclusions drawn from this study are subject to several constraints that must be considered for a thorough evaluation of the research results. Firstly, the study focuses on the ten most popular tables from the three most frequented furniture wholesale stores in Norway: Ikea, Bohus, and Jysk. However, the distribution of materials among these tables is not equal, with a predominant use of MDF over PB and solid wood. This imbalance in the sample sizes for PB and solid wood compared to MDF affects the generalizability of the findings and introduces a bias towards conclusions related to MDF.

Additionally, a significant limitation arises from the assumptions made regarding component equivalents to create the life cycle inventory for each table. The lack of cooperation from wholesale stores leading to the absence of primary data from the industry necessitated the sourcing of component equivalents from the existing online market, which was particularly challenging for custom parts that are not standardized. The varying levels of detail provided by the wholesale stores in their table setup manuals and online presence further complicated this task. For instance, Ikea's unique standards and nomenclature required approximations for many component dimensions, which could lead to inaccuracies in the life cycle inventory. In contrast, Jysk's detailed standard names for their components helped reduce uncertainty in the inventory for those tables, as it was easier to find precise matches for the components. Furthermore, the assumption that components are made from uniform materials due to the absence of detailed information introduces an additional layer of uncertainty to the environmental impacts. This assumption, while simplifying the model-

[8] Jysk, n.d.-a
[9] FINN.no, n.d.-e
[10] Bohus, n.d.-a
[11] FINN.no, n.d.-b
[12] Ikea, n.d.-a
[13] FINN.no, n.d.-a
[14] Jysk, n.d.-c
[15] FINN.no, n.d.-f
[16] Bohus, n.d.-b
[17] FINN.no, n.d.-j
[18] Bohus, n.d.-e
[19] FINN.no, n.d.-n
[20] Ikea, n.d.-f
[21] FINN.no, n.d.-h
[22] Ikea, n.d.-c
[23] FINN.no, n.d.-c
[24] Ikea, n.d.-h
[25] Ikea, n.d.-b
[26] Ikea, n.d.-g
[27] FINN.no, n.d.-d
[28] Jysk, n.d.-b
[29] FINN.no, n.d.-m
[30] Bohus, n.d.-d
[31] FINN.no, n.d.-l
[32] Ikea, n.d.-e
[33] FINN.no, n.d.-k
[34] Ikea, n.d.-d
[35] FINN.no, n.d.-i
[36] Bohus, n.d.-c
[37] FINN.no, n.d.-g

ing process, fails to account for potential variations in material composition that could significantly influence the environmental impact calculations. For instance, a table crossbar, typically perceived as being made entirely of wood, may actually consist of both wood and metal parts, thereby affecting its overall environmental footprint. Similarly, different batches of MDF or PB can have varying resin contents or additives. In this master's thesis, it was assumed that the MDF and PB composition was consistent across all components due to the lack of specific information. These necessary simplifications and approximations, driven by data constraints, contribute to uncertainties that must be considered when interpreting the results of this study.

Another limitation is the exclusion of the furniture package assembly unit process in the LCA due to a lack of available data. This omission implies that the environmental performance of the wholesale stores cannot be comprehensively derived from the LCA, as the impacts associated with packaging and assembly are not accounted for. The exclusion of these processes potentially overlooks significant environmental burdens, such as the energy consumption, material use, and waste generation associated with packaging and assembly activities. Incorporating primary data from the industry regarding these processes would enhance the precision and completeness of this analysis, providing a more accurate reflection of the true environmental impacts associated with the furniture lifecycle.

Supply chain assumptions, particularly regarding transport and distance, introduce significant uncertainties into the study. The analysis assumed that all solid wood is sourced from Poland, MDF from Germany, and PB from Norway. However, it remains unclear whether all wholesale stores source their raw materials from these same suppliers and locations. This lack of specificity can significantly affect the accuracy of the environmental impact calculation. For instance, the assumption that particleboard is sourced from Norway, with its relatively shorter transport distance, could lead to lower estimated transportation emissions compared to those for MDF and solid wood. If, in reality, some particleboard is sourced from more distant locations, the actual emissions would be higher than those calculated. Conversely, if MDF or solid wood were sourced from closer locations than assumed, their transportation emissions would be overestimated. These variations in transport distances and associated emissions underscore the need for precise supply chain data to ensure accurate environmental impact assessments

For system boundary 2 end-of-life treatment assumptions significantly contribute to the limitations of this study. Although primary sources confirm the recyclability of wood types, the LCA model does not adequately reflect the easier recyclability of solid wood compared to PB. Solid wood, with its homogeneous composition and lower contaminant levels, facilitates more efficient recycling and produces higher-quality recycled materials (Mark Irle, 2023). In contrast, particleboard's adhesives and resins complicate recycling, introducing impurities and reducing the quality of the recycled output. This omission leads to an overestimation of the environmental benefits associated with recycling, as it assumes uniform efficiency and quality across different wood types. As a result, the environmental advantages of recycling particleboard may be overstated, while the true benefits of recycling solid wood might not be fully captured.

Lastly, for system boundary 3, the lifetime of each table type had to be determined without access to definitive data. The absence of comprehensive literature on the lifespans of different table types and the lack of established standards necessitated the conversion of qualitative information into quantitative assumptions. This process introduced significant uncertainties into the analysis. The reliance on these assumptions could result in either overestimating or underestimating the environmental footprint of the tables over their entire lifecycle, thereby affecting the overall accuracy and credibility of the study's findings. Incorporating more precise and standardized data on product lifetimes would greatly enhance the robustness of the environmental impact assessments.

In summary, while this study provides valuable insights into the lifecycle analysis of tables from major Norwegian wholesale stores, these limitations underscore the need for caution in interpreting the results.

4 Results and discussion

4.1 System boundary 1

In system boundary 1 environmental impacts of producing engineered wood tables were contrasted with those of tables made from solid wood. The exact results of the LCA can be found in Table A.1 in the Appendix.

4.1.1 Observations

In Figure 9, the environmental impacts of tables made from medium-density fiberboard (MDF), particleboard, and solid wood are illustrated across the selected impact indicators. Each dot in the scatterplot has a unique color and represents the environmental impact results associated with one table, categorized by the predominant wood material used in its construction. This color-coding allows for an effective comparison of each table's performance across the impact indicators. To facilitate meaningful conclusions from this diverse set of results, the geometric mean was calculated for each wood type and displayed as a red dot. The geometric mean was selected over the arithmetic mean to mitigate the influence of extreme values, thereby reducing the impact of outliers on the analysis.

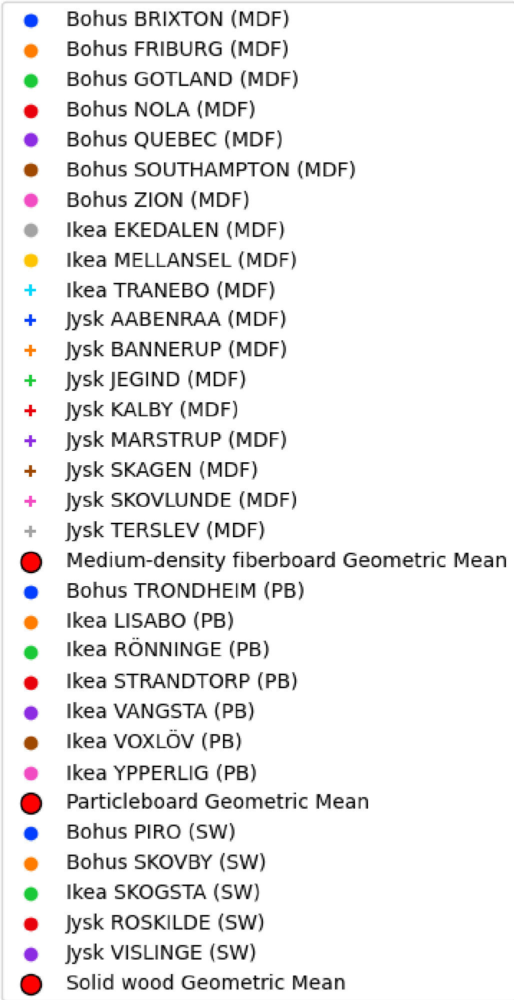

Figure 8: Environmental indicators legend - System boundary 1

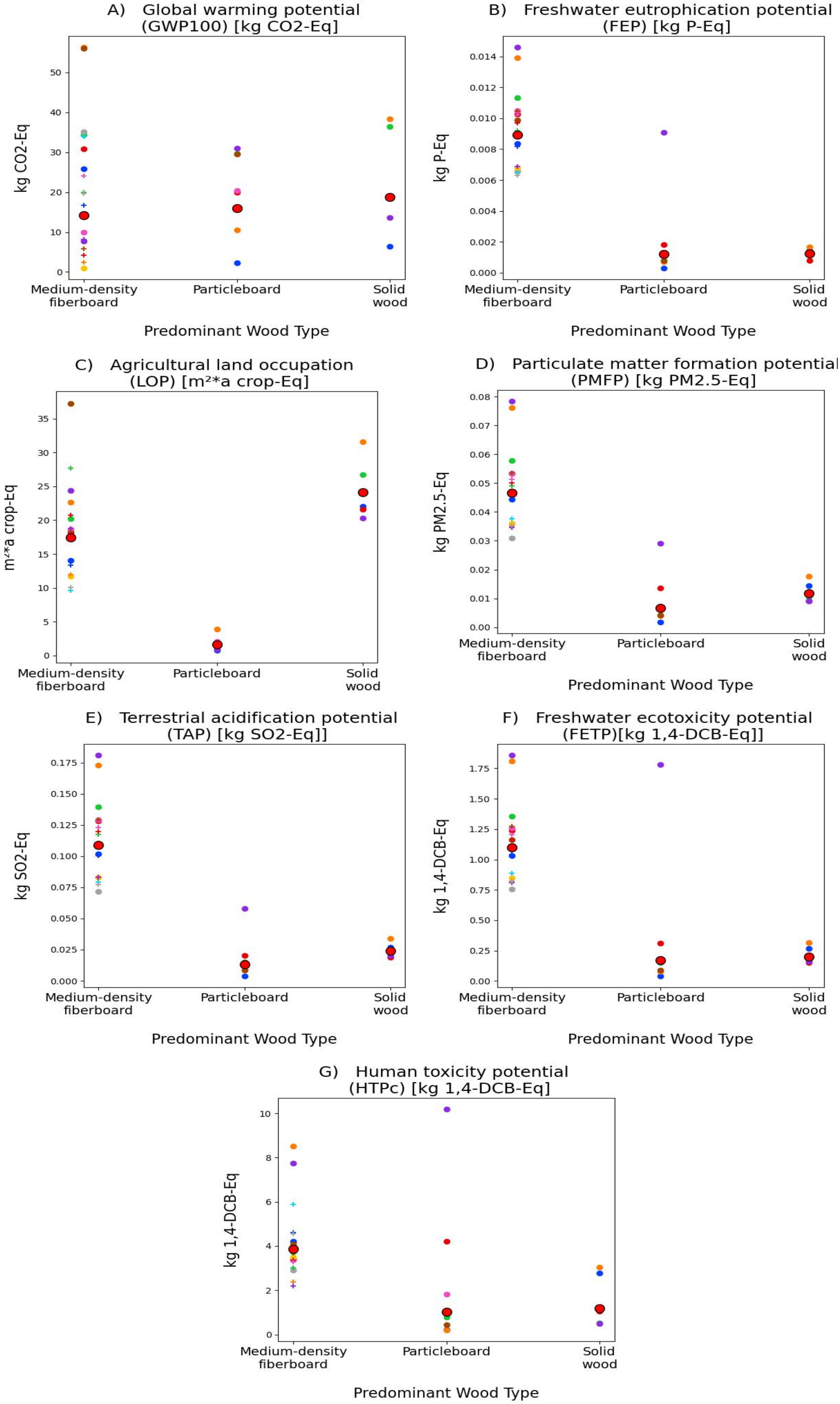

Figure 9: Environmental indicators with calculated geometric mean

[System boundary 1: Cradle-to-gate]

MDF tables exhibit a greater spread along the y-axis of every impact indicator compared to PB and solid wood tables, indicating significant variability in their environmental impacts. This variation can be attributed to the diverse designs of the MDF tables and the larger sample size of 18 MDF tables versus 7 PB and 5 solid wood tables. Diverse table designs can lead to differences in material use, manufacturing processes, and the amount of energy and resources required for production while a larger sample size inherently has a higher potential for variability.

Across the various impact indicators of **Freshwater Eutrophication Potential, Particulate Matter Formation Potential, Terrestrial Acidification Potential, Freshwater Ecotoxicity Potential, and Human Toxicity Potential** the MDF tables generally show higher environmental impacts than particleboard and solid wood tables. The primary contributor to these impacts is the MDF production process, largely due to its high energy intensity and the presence of melamine formaldehyde resin. Melamine formaldehyde resin production itself requires significant amounts of energy and raw materials, leading to elevated emissions of pollutants and toxins (Krupadam and Rayalu, 2021). Sulfur dioxide, produced in substantial quantities during the synthesis of ammonia—a key feedstock for urea, the precursor to melamine—is a major pollutant affecting these impact indicators (Ghavam et al., 2021; Khan et al., 2024). Additionally, the chemical processes involved in melamine production generate hazardous by-products, further exacerbating the environmental footprint of MDF tables in these categories. For most of the impact indicators, MDF production is the primary contributor to the environmental impacts associated with MDF tables. Even for Human Toxicity Potential, where MDF production has the lowest contribution, it still accounts for the majority of the impact at just under 60%. For this impact indicator the steel production required for auxiliary table components, such as screws, contributes 43% of the impact, which is due to the emissions of chromium VI associated with stainless steel production (Ecfia, 2023).

In the impact indicators of **Agricultural Land Occupation and Global Warming Potential**, solid wood tables exhibit the highest negative environmental impact among the three wood types. Specifically, solid wood tables require, on average, 12 times more agricultural land during production compared to particleboard tables and 1.4 times more than MDF tables. This disparity arises because engineered wood tables, such as MDF and PB, incorporate significant amounts of resins and additives, which reduce the reliance on solid wood. In contrast, solid wood production necessitates substantial agricultural land for the cultivation and growth of the trees, accounting for their higher land occupation. Regarding Global Warming Potential, the values for all three table types do not differ by more than 24%. For each table type, the contributions to global warming potential are relatively evenly distributed among transportation, carton production, and the production processes of the respective wood types. This can be attributed to the carbon-intensive nature of these activities, whether through the use of fossil fuels or other energy carriers in their production cycles. Consequently, despite the differences in material composition, the overall global warming impacts remain relatively comparable across the three table types.

4.1.2 Contribution analysis

When examining specific tables across different subplots depicted in Figure 9, it can be observed that tables with large imapcts in one impact indicator often exhibit similarly large impacts in other indicators. To gain a deeper understanding of how various supply chain steps contribute to the environmental impacts, a contribution analysis was conducted on the tables with the highest impact indicators for each wood type, using a cutoff percentage of 1%. Figure 10 illustrates the contribution of different supply chain steps to the Freshwater Ecotoxicity Potential (FETP) indicator for each of the three tables. The FETP indicator was chosen as a representative example because the contribution percentages for this indicator are similar to those of the other impact indicators. This consistency suggests that the FETP indicator is well-suited for drawing broader conclusions about the environmental impact contributions of different supply chain steps. Common supply chain steps across the tables are highlighted with consistent colors: "Transport" in pink, "Steel" in yellow, and "Energy" in red.

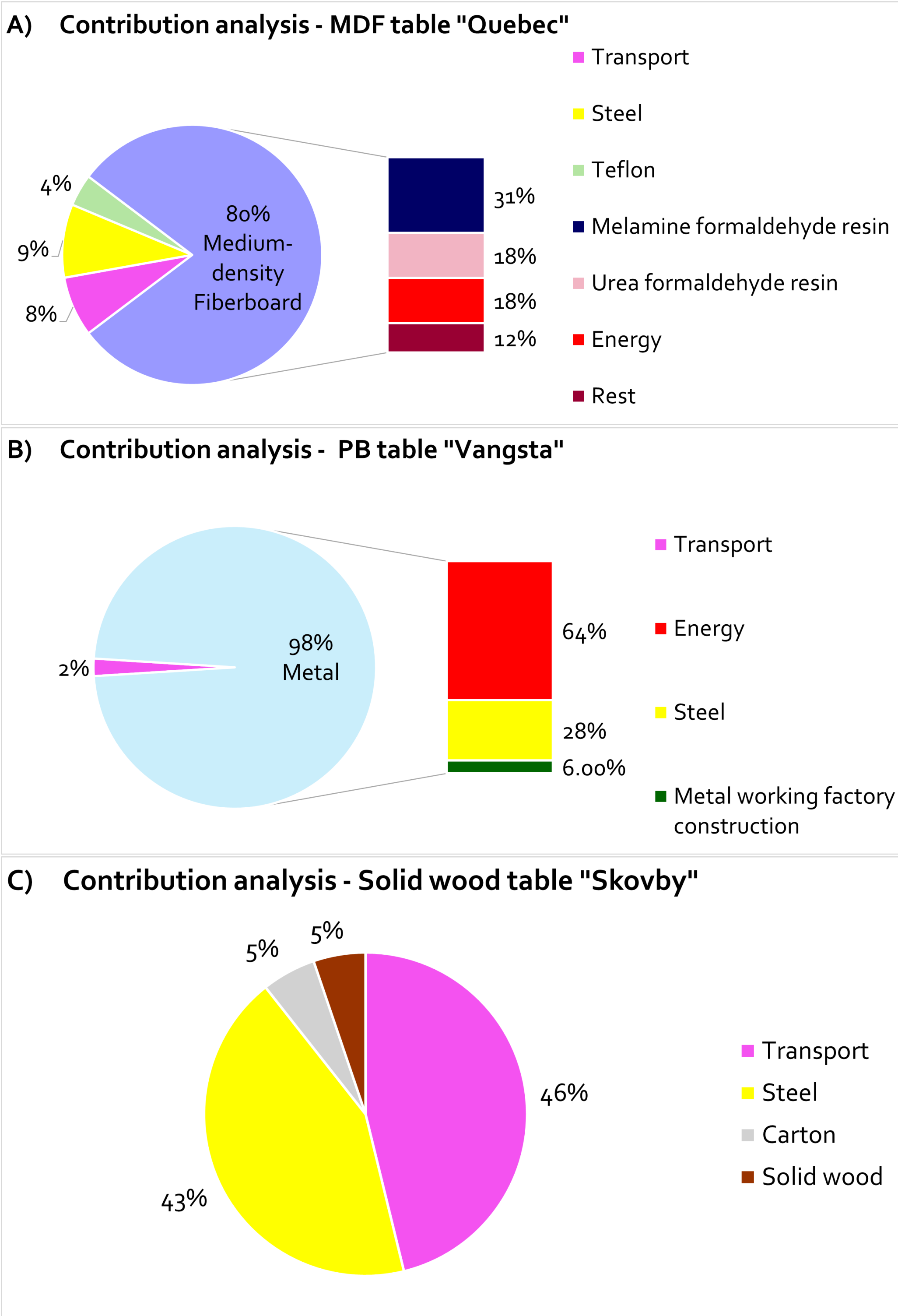

Figure 10: Contribution Analysis: Freshwater Ecotoxicity Potential for highest impact table per wood type

Amongst the **MDF tables**, the "Quebec" table exhibits the highest impacts in the categories of Global Warming Potential, Freshwater Eutrophication Potential, Particulate Matter Formation Potential, Terrestrial Acidification Potential, Freshwater Ecotoxicity Potential, and Human Toxicity Potential, closely followed by the "Friburg" table. This is attributed to their high MDF content relative to other MDF tables. In the impact category of Agricultural Land Occupation, the "Southampton" table has the highest impacts associated to it. This is primarily because it has the highest solid wood content among the MDF tables. Specifically, 55% of the Agricultural Land Occupation impact of the "Southampton" table is attributed to the oak wood used in its legs and veneer, whereas MDF only contributes 44%.

Subplot A) in Figure 10 illustrates the contribution of each supply chain step to the environmental impacts associated with the "Quebec" table. It is evident that supply chain steps associated with MDF production are responsible for approximately 80% of the overall environmental impacts of this table. The production of melamine formaldehyde and urea formaldehyde resin and the energy consumed during the MDF production process are the primary contributors to these impacts as mentioned previously in the subsection 4.1.1. In addition to MDF, steel contributes 9% to the overall impacts, while transportation accounts for 8%. The notable impact of steel is striking, especially since it only makes up 14% of the table's weight. In contrast, MDF, which constitutes 84% of the table's weight, accounts for 80% of the environmental impacts. This comparison reveals that increasing the steel content would disproportionately amplify the overall environmental impacts more than increasing the MDF content.

Amongst the **PB tables**, the "Vangsta" table exhibits the highest impacts in the categories of Global Warming Potential, Freshwater Eutrophication Potential, Particulate Matter Formation Potential, Terrestrial Acidification Potential, Freshwater Ecotoxicity Potential, and Human Toxicity Potential, closely followed by the "Strandtorp" table. This is because both tables have the highest metal content among the PB tables, which is due to their intricate metal table extension system which weighs more than the particleboard components of the table. As noted in the MDF table contribution analysis, increased steel content disproportionately elevates the environmental impacts of the tables. In the case of the "Vangsta" table, steel components contribute an average of 98% to the environmental impact indicators (Subplot B) of Figure 10). The high contribution of metal components is due to the significant energy required to shape the metal parts and the environmental burden of steel production.

Additionally, the "Ypperlig" table has the second highest Global Warming Potential after the "Vangsta" table, primarily due to its Teflon table gliders, which are attached to the legs to prevent floor scratching. Despite Teflon comprising only 0.2% of the table's weight, its production has substantial environmental impacts, contributing 74% to the table's Global Warming Potential.

It is surprising that particleboard contributes less than 1% to the environmental impacts and is therefore below the cutoff percentage. This highlights the relatively low environmental impact of particleboard production. These findings regarding the particleboard tables suggest that auxiliary items, such as screws, brackets, table extension runners, and Teflon components like table gliders, significantly impact the overall environmental footprint of the tables. The disproportionate influence of these materials highlights the importance of considering auxiliary items in the environmental assessment of furniture.

Amongst the **solid wood tables**, "Skovby" and "Piro" exhibit the highest impacts in Freshwater Eutrophication Potential, Particulate Matter Formation Potential, Terrestrial Acidification Potential, Freshwater Ecotoxicity Potential, and Human Toxicity Potential. The "Skovby" table, being the heaviest of the solid wood tables, has the highest ton-kilometer value for transport from the wood production location to the logistics center. This weight significantly influences its environmental performance, as transport contributes on average 46% to the "Skovby" table's environmental impacts visible in Subplot C) of Figure 10. Transport plays a relatively more crucial role for solid wood tables compared to other wood types because the source locations for solid wood are the furthest from the wholesale logistics centers in the Oslo area, indicating that the LCA results for solid wood tables are particularly sensitive to changes in transport distances.

Additionally, the steel content in solid wood tables significantly impacts their environmental performance, contributing approximately 43% to the overall impacts. For instance, the "Skogsta" table follows "Skovby" in terms of the highest Agricultural Land Occupation due to its high solid wood content, consistent with trends observed in other wood types.

Furthermore, the "Vislinge" table has the highest impact in Global Warming Potential, primarily due to its large Teflon gliders. The Teflon components of this table contribute 61.4% to the Global Warming Potential, followed by transport at 24%. This mirrors the Global warming potential finding of the particleboard table "Ypperlig"

Compared to the MDF and PB tables with the highest environmental impacts, the environmental impact contributions for solid wood tables are more evenly distributed among various sources. This balanced impact profile indicates that mitigating the environmental footprint of solid wood tables requires addressing a range of contributing factors.

In the following, it shall be tested whether the results from the LCA for system boundary 1, which focus on cradle-to-gate impacts support or contradict findings from the literature review.

While assessing the results, it becomes clear that auxiliary items significantly influence the overall environmental performance of particleboard and solid wood tables. This observation aligns with the literature review, which states that metals and plastics exert greater environmental burdens compared to wood in furniture manufacturing. For particleboard tables, this statement is strongly supported by the finding that metal contributes to the majority of the environmental impacts, whereas particleboard, the main constituent, contributes less than 1%. Another interesting finding is that table components such as Teflon gliders have a very large impact on the Global Warming Potential despite their small weight percentage of the table.

However, the assertion from one source that wood composite materials have higher environmental impacts than solid wood counterparts, primarily due to chemical additives, is confirmed only for MDF in this study. Another source of conflicting literature suggests that durable solid wood furniture may either amplify environmental impacts or mitigate climate change by increasing wood usage. This study cannot definitively confirm or deny this latter claim. The results indicate that while solid wood appears to be a more environmentally friendly option for dining tables compared to MDF, it is not more environmentally friendly than particleboard. It is important to note that transport significantly contributes to the environmental impacts of solid wood. Since the transport distance for solid wood supply in this LCA is based on assumptions, it raises the hypothesis that if solid wood were sourced locally from Norway, similar to particleboard, it could potentially exhibit the lowest environmental impacts among the three wood types. This would align with the statements found in the literature.

Finally, the findings from the LCA support the consensus in literature that the primary environmental impacts associated with furniture occur during the life cycle stages of raw material and auxiliary material production, regardless of the material type, be it MDF, PB, or solid wood. This was indeed the case for all tables studied, as most environmental impacts originated from background processes related to resource extraction and material production.

The comparison of 30 tables made from the three wood types across various impact indicators yields consistent and interpretable results. These results align with the majority of findings in the existing literature, lending credibility and significance to the conclusions drawn. This agreement with established research supports the robustness of the LCA methodology used and underscores the reliability of the findings. Consequently, these results are considered significant in addressing the research question, as they provide a clear and evidence-based comparison of the environmental impacts of engineered wood tables versus solid wood tables.

The LCA results for system boundary 1, which focus on cradle-to-gate impacts, provide valuable insights into the first part of the first research question: ***How do the environmental impacts of engineered wood tables compare to those of solid wood tables, specifically considering production processes?***. This question will be addressed in the following discussion.

While solid wood tables generally exhibit lower environmental impacts compared to engineered wood tables made from MDF, they do not perform better than PB tables. This conclusion is, however, context-dependent, based on the assumptions made within this LCA and specific to the Norwegian context. If all wood types were sourced from the same location, the results might indicate a better performance for solid wood tables. Solid wood tables have the highest environmental impacts concerning agricultural land occupation, which is expected due to the extensive use of land required for the cultivation and growth of the trees.

The global warming potential results do not allow for a clear ranking of wood types, as impacts are relatively evenly distributed among transportation, carton production, and the production processes of the respective wood types. This distribution holds true unless Teflon gliders with a significant surface area are used for scratch prevention, which notably increases the environmental impact of such tables.

PB tables generally have the lowest environmental footprint among the three types examined. It is evident that PB production itself is rarely the main contributor to the environmental impacts associated with PB tables. Instead, the environmental performance of these tables is significantly influenced by the steel content used in their construction. The amount and type of steel components, such as screws, frames, or supports, seem to play a critical role in determining the overall environmental impact of PB tables. The superior environmental performance of PB compared to MDF may be attributed to the differences in their production processes. MDF production involves additional steps, such as the defibration process where wood fibers are separated, and the incorporation of greater amounts of resins and additives to bond the fibers (Lao and Chang, 2023). These additional steps result in higher energy consumption and greater use of chemicals, leading to increased emissions and environmental impacts. Conversely, PB production generally requires fewer steps, mainly involving the chipping of wood and the subsequent pressing and bonding of the wood particles with resins, which contributes to its relatively lower environmental footprint (Lao and Chang, 2023).

Another reason why MDF tables have significantly higher environmental impacts than the other wood types is the large amount of melamine formaldehyde resin required during production. This resin has been identified as a major contributor to the emissions associated with MDF tables. The extensive use of this resin, combined with the energy-intensive processes involved in MDF production, leads to the higher environmental impacts observed for MDF tables compared to particleboard and solid wood tables.

In summary, while solid wood tables tend to have lower environmental impacts than MDF tables, they do not outperform particleboard tables in this study.

4.2 System boundary 2

In System Boundary 2, the environmental impacts of producing engineered wood tables were compared to those of solid wood tables, taking into account recyclability factors. This assessment included the use-phase and end-of-life treatment to evaluate table recyclability. The exact results of the LCA can be found in Table A.2 in the Appendix.

4.2.1 Observations

In Figure 11 the environmental impacts of the average tables made from MDF, PB and solid wood are illustrated across the selected impact indicators. The results from the system boundary expansion are compared with those from the previous system boundary below.

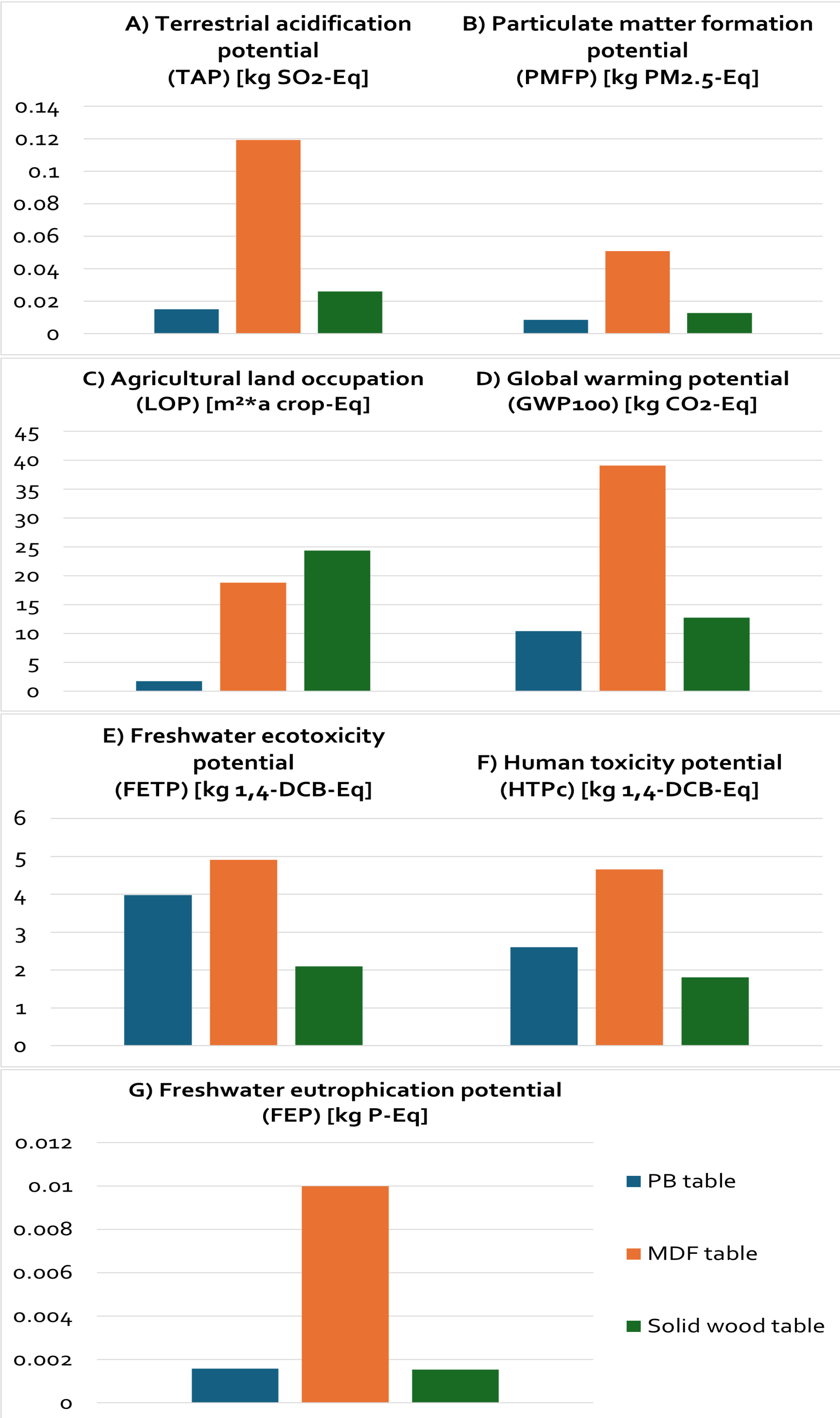

Figure 11: Environmental indicators

[System boundary 2: Cradle-to-grave]

The MDF table continues to have the highest environmental impacts for all impact indicators except agricultural land occupation, where the solid wood table has the highest impacts. This is plausible because the average solid wood table contains the most solid wood, which has the highest impact on this indicator as seen in Section 4.1. Generally, it can be observed that after adding the end-of-life treatment to the LCA evaluation, the indicator values of the average PB and the solid wood table are less different from each other than before. This indicates that the higher heating value of solid wood tables had a visible impact on its impacts, given that it is one of the few differentiating factors that changed between PB and solid wood tables from system boundary 1 to system boundary 2. The average PB table continues to have the lowest impacts in four out of the seven impact indicators (Particulate Matter Formation Potential, Terrestrial Acidification Potential, Agricultural Land Occupation, and Global Warming Potential). On the other hand, the solid wood table performs better after the system boundary adjustment, showing the lowest impacts in three out of the seven impact indicators (Freshwater Ecotoxicity Potential, Freshwater Eutrophication Potential, and Human Toxicity Potential).

It can be said that compared to the geometric mean of production-related emissions alone, the end-of-life treatment emissions do not significantly impact the indicator values of Agricultural Land Occupation and Terrestrial Acidification Potential, Particulate matter formation potential and Freshwater Eutrophication Potential. This lack of change for **Agricultural Land Occupation** can be explained by the fact that incineration does not impact land occupation since most of these impacts stem from cultivated resources rather than industrial plants.

Similarly, the minimal change in **Terrestrial Acidification Potential** can be attributed to the fact that incineration processes are designed to minimize the release of acidifying substances, and the majority of acidification impacts originate from earlier production stages rather than the end-of-life treatment (Mattison, 2000).

Since **Freshwater Eutrophication Potential** is largely influenced by nutrient runoff and leaching into water bodies, the agricultural and forestry activities typically involved in the production of raw materials for the tables are more significant contributors to eutrophication (Stacy, 2024). In the case of MDF production the ammonia synthesis necessary for the urea and therefore melamine production contributes significantly to freshwater eutrophication (Krupadam and Rayalu, 2021). In contrast, the incineration process generates emissions primarily in the form of gases and ash (Mattison, 2000), which are less likely to contain high levels of nutrients such as nitrogen and phosphorus that contribute to eutrophication. Additionally, the management of incineration residues ensures that these substances do not easily enter freshwater systems (Kubota et al., 2020). Therefore, the increase in eutrophication potential due to incineration emissions is negligible compared to the contributions from the initial production phases.

The **Particulate Matter Formation** seems to primarily occur during the initial production phases of both solid wood and engineered wood tables. This makes sense since processes such as wood harvesting, transportation, and manufacturing, are significant sources of particulate emissions (Salthammer et al., 2023).

In contrast, the incineration process at the end of life, while contributing some particulate emissions, is relatively controlled and optimized to minimize the release of particulates (Mattison, 2000). Modern incineration plants are equipped with technologies such as filters and scrubbers that effectively capture and reduce particulate emissions (Mattison, 2000).

When regarding the **Global Warming Potential**, the impacts associated to the average MDF table increase from an average of 14 kg CO2-equivalents to almost 40 kg CO2-equivalents, which is linked to the substitution of PB production which was added to the MDF table inventory to compensate for the fact that MDF cannot currently be recycled in Norway.

A curious finding is that with the addition of the end-of-life stage, the Global Warming Potential values of particleboard and solid wood tables decrease as opposed to increasing. This is the only impact indicator with such a development, which can be explained by the fact that during the incineration process, gases classified as near-term climate forcers are emitted, having a global cooling rather than warming potential (Bernt Johnke et al., n.d.; Szopa and Naik, n.d.). The Global Warming Potential value of the PB table, which has the lowest heating value and therefore more incineration emissions assigned to it, reduces the most by 35%, followed by the solid wood table, which reduces by 32%. Given that the transport distance from the consumer to the waste treatment facility is very short, even the carbon dioxide emissions of the lorry during waste transport do not outweigh the influence of the incineration on the global warming potential. This permits the hypothesis that if MDF did not have the emissions of the substituted particleboard production added to it, it would have the most drastic reduction in Global Warming Potential due to its lack of recycling and therefore use of incineration, which would cause more near-term climate forcer emissions than for particleboard and solid wood.

The two impact indicator values which increase the most for all tables when including the end-of-life treatment are **Human Toxicity Potential and Freshwater Ecotoxicity Potential**. In the case of Human Toxicity Potential, the value for the PB table increases the most, followed by those for the MDF and solid wood tables. This discrepancy is most likely due to differences in the composition of the average PB and solid wood tables, which may not align with the geometric mean composition. The Freshwater Ecotoxicity Potential changes the most for MDF and PB, indicating that the amount of kilograms incinerated has a large impact on this indicator. This is true because for PB and the MDF tables, the incineration amounts are 14 kg and 13 kg respectively, resulting in very similar freshwater ecotoxicity potential values of 5 and 4 kg 1,4-DCB-equivalents. Both tables lead to a similar incineration weight due to different average weight, table surface, recycling percentage, and average heating value. The solid wood table, on the other hand, is only incinerated in a quantity of 7 kilograms due to its larger surface area, recyclability, and higher heating value.

4.2.2 Contribution analysis

When examining the three average tables across different subplots depicted in Figure 11 and comparing the results to those from system boundary 1, it can be observed that the Freshwater Ecotoxicity Potential indicator changes the most, making this indicator particularly interesting to analyze. Another reason for selecting Freshwater Ecotoxicity Potential as an indicator is to maintain consistency within the thesis and ensure that the conclusions drawn are comparable with the contribution analysis for system boundary 1. This contribution analysis shown in Figure 12 was conducted using a cutoff percentage of 1%.

In contrast to the contribution analysis results of system boundary 1, the contribution percentages for Freshwater Ecotoxicity Potential differ significantly from those of the other impact indicators. This disparity can be attributed to the strong influence of the end-of-life treatment on this particular indicator. Conversely it is expected that the contribution of the end-of-life treatment on the results of the impact indicators which changed the least (such as Agricultural Land Occupation and Terrestrial Acidification Potential, Particulate matter formation potential and Freshwater Eutrophication Potential) is minimal. This expectation is confirmed by the data: for each of these impact indicators, the incineration process contributes less than 33%, while table production accounts for more than 67% of the total impact. This minimal contribution of incineration on the table emissions also holds for the Human Toxicity Potential indicator independent of the wood type. It stands out that for all three tables, the Agricultural Land Occupation emissions are not impacted by the incineration process confirming the statement in Section 4.2.1.

Common supply chain steps across the tables remain highlighted in Figure 12 with consistent colors: "Transport" in pink, "Steel" in yellow, "Incineration" in blue, "Table production" in orange and "MDF production" in lilac.

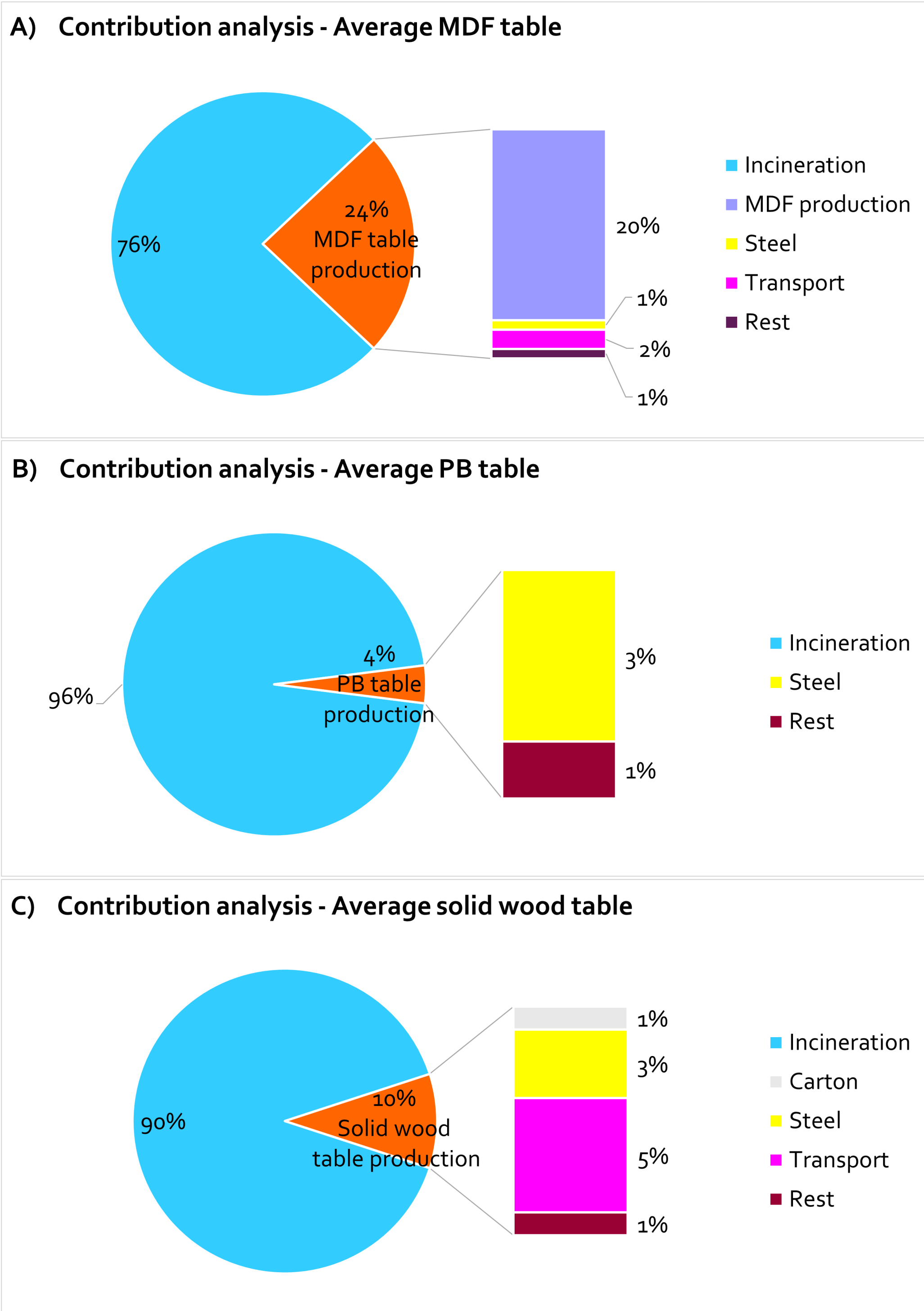

Figure 12: Contribution Analysis: Freshwater Ecotoxicity Potential for average table per wood type

Subplot A) in Figure 12 depicting the contributions of the **average MDF table** shows that the incineration process contributes 76% to the Freshwater Ecotoxicity Potential, whereas the MDF table production accounts for the remaining 24%. Within the MDF table production, the contribution distribution remains consistent with the "Quebec" table, where MDF production is the largest contributor, followed by transport and steel. This consistency indicates that the composition of the "Quebec" table is representative of the MDF table group.

Given that the contribution of transport has not significantly changed compared to the previous contribution analysis, it can be concluded that transport from the consumer to the waste treatment facility does not have a significant environmental impact compared to other supply chain steps.

Although PB production is substituted due to the lack of MDF recycling, it does not appear prominently in the contribution analysis. This suggests that the hypothetical future possibility of recycling MDF tables would not significantly offset the emissions associated with them.

Subplot B) in Figure 12 depicting the contributions of the **average PB table** shows that the incineration process contributes 96% to the Freshwater Ecotoxicity Potential, whereas the PB table production accounts for the remaining 4%. Steel remains the major contributor to the emissions associated with PB table production. Similarly to the findings from system boundary 1, does the PB production not show up in the contribution analysis, confirming that the PB production process leads to relatively low emissions.

It needs to however be mentioned that PB as well as carton and transport do show up as main contributor associated to the PB table production for all indicators except for Freshwater Ecotoxicity Potential, which relativates the previous statement.

Compared to the "Vangsta" table, the contribution chart for the PB table is not as heavily dominated by the impact of metal. This difference could be attributed to the higher emissions from the incineration process, which are particularly relevant to the Freshwater Ecotoxicity Potential indicator, as opposed to those from metal production. It is crucial to consider that incineration emissions are scaled to the overall weight and lower heating value of the table, whereas metal components constitute only a fraction of the table's total weight. This scaling results in the incineration process having a proportionally larger impact on the ecotoxicity indicator compared to the metal components.

The contribution analysis of the PB table demonstrates that its production-related emissions are significantly lower than those of the MDF table. Despite the incinerated masses of the two tables being nearly the same, resulting in similar volumes of emissions from incineration, the percentage contribution of PB table production is only a fraction of that of MDF table production. This indicates that the environmental impact from producing PB tables is considerably less than that from producing MDF tables.

Subplot C) in Figure 12, depicting the contributions of the **average solid wood table**, indicates that the incineration process contributes 90% to the Freshwater Ecotoxicity Potential, while the production of the solid wood table accounts for the remaining 10%.

The findings from the contribution analysis of the solid wood table are consistent with those for MDF, showing that the Freshwater Ecotoxicity Potential is the sole indicator for which incineration has a higher contribution than the table production.

Within the solid wood table production process, transport emerges as a major contributor, accounting for 5% of the total, alongside steel and carton. This supports the hypothesis that changes in model assumptions regarding supply chain distances and, consequently, transport emissions, would significantly impact the LCA results for this type of wood.

In comparison to the "Skovby" table, solid wood is no longer a significant contributor to the emissions from solid wood table production for the Freshwater Ecotoxicity Potential indicator. However, this is specific to the Freshwater Ecotoxicity Potential; for all other indicators, solid wood contributes between 2% and 96% of the emissions associated with solid wood table production. The lack of significant contribution from solid wood to the Freshwater Ecotoxicity Potential might be attributed to differences in table composition between the geometric mean "Skovby" table and the average table, potentially due to a lower solid wood content.

Due to the higher lower heating value of wood, the emissions from producing solid wood tables have a higher impact percentage-wise compared to PB tables, despite a lesser amount being incinerated. In contrast, PB tables have higher emissions associated with incineration, which makes the overall contribution of particleboard table production appear lower in comparison.

Given that few LCAs on furniture include the end-of-life phase, the results of this contribution analysis cannot be extensively compared with existing literature. However, a literature review by Cordella and Hidalgo (2016) indicates that the end-of-life phase can significantly influence the environmental performance of furniture. They mention that impact categories such as Eutrophication and Ozone Depletion are particularly affected by this phase.

The findings of this LCA partially confirm Cordella et al.'s statement. While the inclusion of the end-of-life phase does alter the overall contributions of various process steps, this impact is generally below 33% for most assessed indicators. Specifically, the Freshwater Eutrophication Potential does not change significantly with the addition of the end-of-life phase. However, the Freshwater Ecotoxicity indicator does show a substantial change, which does not fully align with the literature's claims.

The Ozone Depletion potential was not included in the scope of this thesis, so no conclusions can be drawn regarding its impact.

These findings offer valuable insights into the second part of the first research question: ***How do the environmental impacts of engineered wood tables compare to those of solid wood tables, specifically considering end-of-life treatment?*** Globally, it is evident that considering recyclability and heating value during the end-of-life treatment phase alters the overall environmental performance of each table and influences their ranking across various impact indicators. Due to the adjustment of the incineration volume in favor of wood types with higher heating values, the environmental impacts associated with the solid wood table approach those of the PB table. This leads to more balanced results between solid wood and PB tables. Whereas in system boundary 1 PB clearly was the wood type with the least emissions for all tables, in system boundary 2 the solid wood table now exhibits the lowest emissions for three of the seven impact indicators. In contrast, the environmental performance of MDF tables deteriorates further when adding the end-of-life phase to the analysis. Therefore, the question of whether engineered wood tables or solid wood tables have superior environmental performance cannot be answered categorically.

4.3 System boundary 3

In system boundary 3, the entire product life cycle of engineered and solid wood tables is analyzed, taking into account their lifespan and repairability. To achieve this, the lifespan of tables was estimated as detailed in Section 3.3.3. This estimation, coupled with a thorough literature review, addresses the second research question of this thesis: ***What methodologies can accurately estimate the lifespan of various table variants, and what distinguishing factors influence their expected lifetimes?*** Three different approaches were explored to estimate table lifetimes, which will be evaluated subsequently.

4.3.1 Lifetime determination methodology selection

In approach 1, a literature review provided broad ranges of product lifetimes, serving as a baseline for the lifespan of wooden tables. However, these ranges lacked specificity due to the absence of rigorous academic analysis in the referenced literature.

Approach 2 adjusted a baseline lifetime using the mechanical properties of the furniture material, resulting in estimates that fell within the range provided by approach 1. This outcome suggests a degree of realism in the estimates. Nevertheless, the reliance on the average baseline lifetime from approach 1 introduces a dependency between the two approaches. The tensile strength of the materials aligned with the durability described in the literature, validating it as a suitable property for estimating product lifetimes. Other mechanical properties, such as screw-holding ability, bending strength, modulus of elasticity, and dimensional stability, could also be effective for estimating furniture lifetimes if they are standard measurements for wooden panels (**european_panel_european_nodate**).

Conversely, approach 3 proved to be an ineffective methodology for estimating table lifespan. The anticipated correlation between resale price and material type did not yield differentiated table lifetimes for various wooden materials. While the idea of correlating use time with resale price appeared promising, the lack of detailed use time data rendered the results inconclusive. Additionally, factors such as the personal circumstances of resellers further complicated accurate estimations.

These three approaches underscore that factors such as the mechanical properties of materials used in furniture construction are viable for estimating their lifespan. The literature review, however, also indicates that several other common factors significantly influence the product lifetime of furniture.

Key determinants include the quality of the wooden material used, with higher-quality panels generally leading to greater durability and longevity (Block, 2020). The construction techniques and craftsmanship also play a critical role, with well-constructed pieces, such as those using dovetailed joints or mortise and tenon joinery, being more resilient compared to hastily assembled furniture (Scherrer, n.d.). Regular maintenance and care, such as dusting, polishing, and using gentle cleaning agents, also help preserve the furniture's finish and structural integrity (Block, 2020; Teoh, 2023). Additionally, environmental factors, including exposure to sunlight, temperature fluctuations, and humidity levels, significantly affect the wood's condition over time, potentially leading to warping, cracking, or fading if not properly managed (Scherrer, n.d.).

Overall, these factors collectively determine the durability and expected lifespan of wood furniture. Understanding and integrating these determinants into lifespan estimation methodologies can provide more accurate predictions for the longevity of various table variants.

4.3.2 Observations

In Figure 13 the environmental impacts of the average tables made from MDF, PB and solid wood are illustrated across the selected impact indicators. The results from this system boundary are compared with those from system boundary 2. The exact results of the LCA can be found in Table A.3 in the 5.

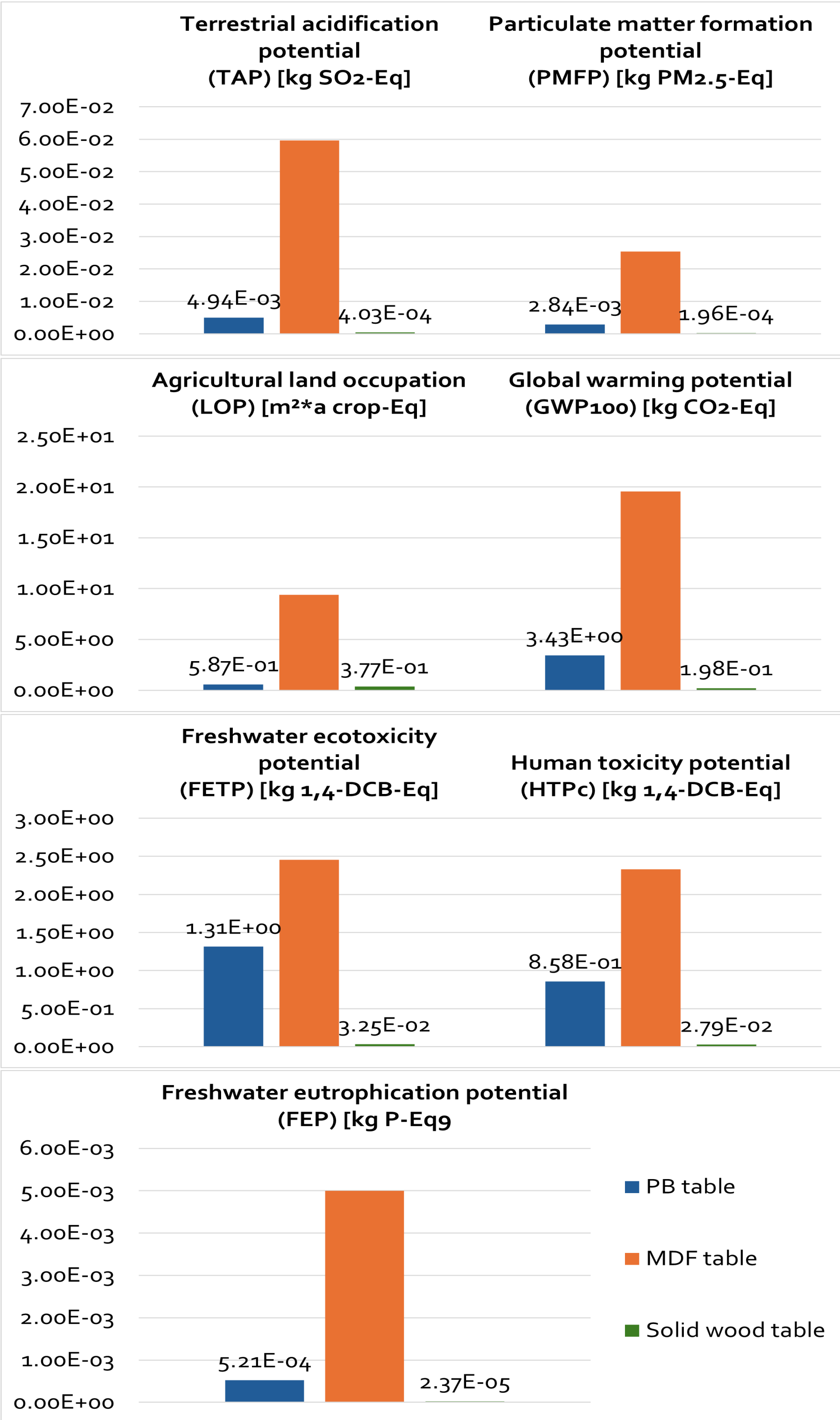

Figure 13: Environmental indicators

[System boundary 3: Cradle-to-grave including lifetime considerations]

It can be observed that the average solid wood table now exhibits the lowest environmental impacts across all categories, followed by the PB table and the MDF table.

This development highlights the substantial influence of product lifetime on environmental emissions when included in LCA.

While the MDF and PB tables have similar lifetimes, the solid wood table's lifetime is more than 19 times longer. Based on the functional unit definition, emissions were scaled to represent the impacts per year of table use, resulting in a significantly larger reduction in emissions for the solid wood table compared to MDF and PB. Additionally, it was assumed that 20% of consumers repair their solid wood tables, further prolonging their lifetime and reducing emissions. The graph and factorial changes between system boundaries 2 and 3 suggest that the environmental impacts associated with table repair over its lifetime are negligible. This conclusion is supported by a contribution analysis for the solid wood table, which shows that the repair process does not significantly affect the contributions of different processes or components. Since the contributions for the other tables do not change drastically either, these graphs have been excluded for system boundary 3.

The potential for consumer repairs to prolong table lifetimes and thus reduce annual emissions, combined with the negligible impact of repairs on overall emissions, suggests that increasing the proportion of people who repair their tables could substantially reduce table-related emissions per year of use.

The same principle applies when deciding whether to purchase a table with a long or short lifetime. The LCA results with this system boundary indicate that choosing a table with the longest lifetime tends to be the best option for emission reduction per year of table use, provided the table is made from particle board or solid wood. This holds true even for the Agricultural Land Occupation impact indicator, where the solid wood table had the highest environmental impacts in system boundaries 1 and 2. To determine if this statement also applies to MDF tables, a specific LCA scenario would need to be developed to test at which lifetime the emissions associated with MDF tables would become lower than those of PB and solid wood tables.

However, it should be noted that furniture lifetimes are not currently advertised by wholesalers and are difficult to derive from literature, making this information challenging for consumers to access. Additionally, literature suggests that consumers may not keep tables until the end of their lifetime due to trends like "fast furniture," which leads to discarding functional furniture for reasons other than the end of the product's life (Cooper et al., 2021. As discussed in Section 4.4, the lifetime values for the tables are rather uncertain due to the unavailability of this information, which tempers the conclusion that the table with the longest lifetime has the lowest environmental impact.

The results from this final system boundary align with statements found in during the literature review. Studies suggest that increasing wood usage in furniture could significantly contribute to mitigating climate change (Russell et al., 2022). This is confirmed when comparing solid wood to metal, plastics, or MDF, as the LCA showed higher emissions for these materials per volume than for solid wood. For PB, this statement holds true only when lifetime aspects are included in the LCA system boundary.

Another source suggests that extending product lifespan through reuse, repair, and refurbishment, along with designing for increased durability, is feasible, with wooden furniture reuse demonstrating the lowest environmental impact, though the impacts of repair and refurbishment vary based on design complexity (Russell et al., 2022). While this LCA does not evaluate reuse or refurbishment, it can be inferred that since repair-related emissions have a negligible impact on long-lived furniture, refurbishment, which involves more comprehensive modifications, is likely to have benefits that outweigh the emissions. However, no definitive statement can be made based on this LCA.

The results of system boundary 3 specifically answer the third research question: ***To what extent do environmental impacts differ between average engineered and solid wood tables when lifetime considerations are integrated into LCA, and what are the implications of these findings?*** The findings indicate that when lifetime is considered, solid wood tables exhibit the lowest environmental impacts across all categories compared to MDF and PB tables. This highlights the importance of promoting longer-lasting furniture and repair practices to reduce emissions. Thus, choosing tables with longer lifespans, particularly those made from solid wood, can significantly mitigate environmental impacts, underscoring the need for sustainable consumer practices and policies that encourage the use of durable materials.

4.4 Uncertainty

As discussed in the section on Limitations, the results obtained from this LCA are subject to uncertainties stemming from various assumptions and data quality issues. This chapter aims to evaluate the uncertainties associated with the processes involved in system boundary 3, encompassing the entire cradle-to-grave lifecycle, including lifetime aspects.

4.4.1 Table production

Firstly, it is essential to discuss the uncertainties related to the data quality of the LCI, as these directly impact the overall uncertainty in table production. As can be seen in Figure 6, the approaches used to identify the weight of the table components or the volume of wooden parts were classified into "Low, Medium and High" uncertainty.

Approaches estimated to introduce low levels of uncertainty into the table production emissions include finding the exact part dimensions in the table setup manual or on the webpage of the wholesale store. Based on these dimensions, the part weight or volume could be calculated or scaled by quantity, length, surface area, or volume. While weights and volumes cannot always be scaled linearly, this approach was applied to standardized components that are often part of component families available in varying sizes. This standardization ensures a more consistent and reliable estimation, thereby reducing overall uncertainty. An example of a part identified using one of these approaches is the 4-millimeter hexagonal Allen key, which is used in various tables to assemble and secure different parts, ensuring proper alignment and stability during setup. While the weight of the Allen key with a 4-millimeter cross-sectional width was not indicated on the webpages of online suppliers, the weight of an Allen key with a 5-millimeter cross-sectional width was available. Consequently, the weight of the larger Allen key was scaled down based on the difference in cross-sectional area between the two keys. This method does not introduce substantial amounts of uncertainty because the scaling process is straightforward and the components are geometrically similar, maintaining proportional relationships in their dimensions.

Another approach identified as introducing low amounts of uncertainty within the LCI is approximation based on component complementation. This means that when the exact dimensions of a part were not indicated in the setup manual, but it was specified that this part would be used with another well-documented part, it could be inferred that the parts had to share common dimensions. For example, consider a flat washer without exact thread size information. However, the setup manual indicated that the Socket Button Head Captive Screws with thread M6 would fit into the washer. Therefore, the thread size of the washer could be deduced. This approximation does not introduce significant uncertainties because the part dimensions were indirectly provided by the wholesale store, ensuring a reliable estimation. Overall approaches classified to introduce low uncertainties in the LCI were applied to 52% of all table components.

Approaches classified as introducing medium amounts of uncertainty involve incomplete or unavailable part dimension information in the setup manual, requiring supplementation based on literature sources or visual cues from the setup manual. For example, the thickness of the wood veneer was supplemented using average values from literature. The wholesale webpage specified that the table's top material was veneer and provided its length and width, but the setup manual did not indicate the veneer thickness. To calculate the veneer volume required for the LCI, the thickness from literature was used. This introduces a medium amount of uncertainty because, on one hand, the literature-based thickness may not precisely match the actual product specification. On the other hand, this method provides a reasonable estimate when direct information is unavailable.

In some cases, no dimensions of parts were indicated, but they could be derived based on their proportions in relation to a part with available dimensions depicted next to them in the setup manual. This introduced some uncertainty because it relies on the assumption that the setup manual accurately displays the proportions of the components, an assumption that was not verified. However, it does not introduce large amounts of uncertainty because setup manuals are generally precise in their depictions, providing a reliable basis for estimation and ensuring that the derived dimensions are likely close to the actual values. The approaches classified to introduce medium uncertainties in the LCI were applied to 32% of all table components.

Finally, the approaches introducing high levels of uncertainty into the LCI are those applied when neither dimensional nor standard information of the component was made available by the wholesale store. Their approximate physical properties were identified using one of two general approaches. If the part was not standardized and parts with the exact same design could not be found online, parts with a different design but serving the same purpose were used directly or scaled to match the table dimensions. Alternatively, if the part with unknown dimensions did not have an intricate design, such as wooden beams, their dimensions were derived based on their proportions in relation to other parts that also lacked provided dimensions in the setup manual. Both cases introduce a significant amount of uncertainty. The first approach relies on the assumption that parts fulfilling the same function have similar weights or volumes, even if their designs vary. This is a bold assumption because the lack of information about the actual scale of the part can lead to significant discrepancies. In the second approach, dimensions of parts are derived from their proportions to each other. If the dimensions of the base part used for comparison are inaccurate, this error will propagate to all other parts, compounding the overall uncertainty. The approaches classified to introduce high uncertainties in the LCI were applied to 16% of all table components.

In summary, the uncertainty of the LCI based on the data quality of the components varies: low uncertainty approaches, applied to 52% of table components, involve using exact dimensions from setup manuals or wholesale webpages, ensuring reliable estimations. Medium uncertainty approaches, applied to 32% of components, rely on supplementation from literature or proportional estimations, introducing some but manageable uncertainty. High uncertainty approaches, applied to 16% of components, involve significant assumptions due to the lack of dimensional data, leading to considerable uncertainty due to potential inaccuracies in scaling or proportion-based estimations.

Another significant factor introducing large amounts of uncertainty associated with production emissions is the transport based on the estimated supply chain distances. The transport of the purchased table to the consumer and the discarded table from the consumer to the waste treatment facility remains consistent for all wood types. Therefore, it does not significantly impact the comparison. However, the transport distances from the production sites of the wooden panels to the wholesale store logistics centers, where the tables were sold, vary for each wood type. This adaptation was necessary due to the varying availability of solid wood and engineered wood panels in Europe and Norway's unique production capabilities. Yet, it introduced substantial uncertainty.

The estimated transport distances for solid wood ranged between 1,148 km and 1,172 km, while the distances for particleboard ranged between 128 km and 209 km. These differences have a substantial impact on the emissions associated with transport, significantly affecting the overall contribution of transport emissions to the production emissions of the tables respective to their wood type. As previously discussed in the interpretation of system boundaries 1 and 2, the ranking of wood types by environmental impacts may be highly sensitive to changes in transport distances. This sensitivity suggests that the uncertainty in transport distances could result in an inaccurate ranking between solid wood tables and particleboard tables.

To fully investigate this hypothesis, a Monte Carlo simulation could be performed in future work. Additionally, obtaining primary information from wholesale stores about the locations of their panel suppliers would greatly reduce this uncertainty. Another aspect which could be solved with primary data is the exclusion of specific assembly-related information from the LCA analysis. In the thesis it was assumed that the raw and auxiliary material as described in Ecoinvent already possesses the desired design and coating upon arrival at the wholesale logistics center, which introduces a significant degree of uncertainty.

4.4.2 Table replacement and repair

Another factor introducing uncertainty in the LCA is the assumption that 20% of people repair their solid wood table while 80% replace it. This estimation was made for the purpose of this study and was not based on literature, highlighting the need for more accurate data. Although this uncertainty might influence the LCA results, it does not significantly impact the comparative LCA outcome since the lifetime of the solid wood table is 19 times longer than that of engineered wood tables.

A more uncertain assumption is that repairing the table doubles its lifetime. Due to a lack of data on the impact of repair on furniture lifetimes, doubling was chosen.

The environmental emissions associated with the repair were calculated based on the assumption that the repair could be performed using wood filler. Different types of damage might require various repair actions, leading to different associated emissions. However, despite the variability in emissions associated with the repair, their overall impact on the comparative LCA outcome is low when spread across the entire table lifetime.

While each individual assumption about the repair process does not significantly affect the LCA result, their combined effect can. For example, if the repair percentage is much lower than estimated, the repairs are extensive and require many products, and the repair only extends the furniture's lifetime by two years instead of doubling it, the results of the LCA could be impacted, although the overall outcome would likely remain unchanged.

4.4.3 End-of-life treatment

In this LCA, the differing heating values of various wood types were incorporated into the calculation of incineration amounts. This approach was chosen to avoid more complex calculations of the heat output resulting from incineration, which would have jeopardized the time frame of this thesis. Additionally, adjusting the waste composition in the incineration process, as modeled in Brightway, to account for the hypothetical feedstock changes required for this analysis would have been necessary. These aspects should be addressed in future research.

A direct consequence of this decision is that the emissions from incineration, associated with different wood types, are scaled according to their heating values. This introduces uncertainty, as it does not fully reflect the reality of a change in incineration feedstock composition. Consequently, the assumptions made regarding the end-of-life treatment in this analysis should be revisited and refined in future studies to achieve more accurate results.

4.4.4 Lifetime

The lifetime estimates utilized in this study were derived from non-academic literature, which are generally considered less reliable sources. From this broad range of lifetimes, an average baseline lifetime for each material type was calculated. More precise baseline lifetimes might have been established with additional data, such as insights from expert interviews, potentially resulting in more accurate estimates than the averaging approach employed here.

However, using tensile strength as a reference point for evaluating materials is considered to introduce low uncertainty, as this mechanical property is a justified measure for assessing wooden panels according to European standards (**european_panel_european_nodate**). The tensile strengths employed in this LCA were sourced from reliable, peer-reviewed data.

While the assumed lifetime parameters contain large uncertainties, their impact on the LCA outcomes could be critical. If the lifetime of the solid wood table were found to be comparable to that of MDF and PB, the results from system boundary 3 would no longer reflect the same ranking of wood types based on their environmental impacts. Consequently, the parameter of lifetime estimation carries the highest uncertainty, highlighting the need for further academic attention to accurately assess product lifetimes in LCAs.

In summary, the uncertainties related to the assumptions about transport, end-of-life treatment and table lifetime critically affect the answers to the research questions. These uncertainties necessitate further academic attention and more precise data to enhance the reliability of LCA outcomes and to provide a more robust comparison of the environmental impacts associated to tables of different wood types.

4.5 Relevance

Despite its significance, durability remains relatively underexplored within the furniture sector (Iraldo et al., 2017). Current LCA studies often focus on environmental impacts from raw material extraction and production processes, neglecting end-of-life treatment and the product lifespan. This oversight can lead to misleading conclusions, as products with shorter lifespans might appear to have lower impacts despite frequent replacements. This thesis addresses this gap by evaluating how furniture lifespan influences environmental impacts through comparative LCA. The study demonstrates that tables with longer lifespans, particularly those made from solid wood, exhibit the lowest annual environmental impacts, underscoring the necessity of integrating durability and recyclability into comprehensive environmental assessments.

The implications of this study are significant for policymakers, manufacturers, and consumers.

Policymakers can leverage these findings to develop regulations and incentives that promote the production and use of durable furniture, thereby reducing environmental impacts. Manufacturers are encouraged to focus on creating longer-lasting, repairable furniture, aligning with sustainability goals and appealing to environmentally conscious consumers. For consumers, the study highlights the environmental advantages of selecting durable furniture and participating in repair practices, providing a clearer understanding of how these choices impact the environment. Recognizing product lifespans allows consumers to make informed decisions that balance practicality with sustainability. By being aware of the longevity and durability of various furniture options, consumers can choose items that fulfill their immediate needs while also offering long-term environmental benefits, thereby supporting sustainability efforts through waste reduction and resource conservation.

Encouraging the production and use of furniture that lasts longer can significantly decrease the frequency of replacements, reducing the overall demand for raw materials and associated environmental impacts. Repairing furniture rather than discarding it extends its lifespan and further minimizes environmental footprints, making it a key strategy in sustainable consumption.

For LCA methodologies, the study highlights the importance of incorporating product longevity to accurately capture environmental impacts. Current LCAs often neglect the significance of lifespan, which can result in incomplete or misleading conclusions. By integrating longevity into LCA models, a more comprehensive evaluation of a product's environmental impact throughout its entire life cycle can be achieved, leading to more accurate and meaningful outcomes.

Future research should prioritize the performance of LCAs that include durability and quality considerations, and focus on developing methodologies to precisely estimate product lifetimes. This will enhance the reliability and applicability of LCA in assessing environmental impacts across various product categories. Including durability and quality in LCA methodologies will improve the precision of environmental impact assessments. Additionally, developing robust methods for estimating product lifetimes will provide better data for LCAs, guiding more informed decision-making for sustainable product development and consumption. This advancement will strengthen LCA as a tool for promoting sustainability across a wider range of products.

5 Conclusion

This thesis assessed the environmental impacts of MDF, PB, and solid wood tables using a comprehensive LCA across three system boundaries, addressing significant research questions related to production processes, lifespan estimation, and lifetime considerations.

System Boundary 1 focused on cradle-to-gate impacts, addressing the research question: "How do the environmental impacts of engineered wood tables compare to those manufactured from solid wood, considering both production and end-of-life treatment?" The results indicate that solid wood tables generally have lower environmental impacts than MDF tables but do not outperform particleboard (PB) tables, which exhibit the lowest environmental footprint among the three types. This is largely context-dependent and specific to the Norwegian context, with solid wood tables having high impacts related to agricultural land occupation and PB tables benefiting from fewer production steps and lower energy consumption compared to MDF. The significant influence of auxiliary items like screws, metal frames, and Teflon gliders on the overall environmental performance of PB and solid wood tables was also highlighted, as well as the impact of transport on the overall emissions of solid wood tables, suggesting that locally sourcing solid wood could further reduce its environmental impacts. However, uncertainties in Life Cycle Inventory (LCI) data quality arise from varying approaches to estimating component weights and volumes, with 52% of components classified as low uncertainty, 32% as medium, and 16% as high. Additionally, significant uncertainties stem from estimated transport distances from production sites to logistics centers, which can substantially impact the ranking of wood types by environmental impacts.

System Boundary 2 incorporates cradle-to-grave impacts, including recyclability factors, further addressing the first research question. The findings reveal that MDF tables continue to exhibit the highest environmental impacts across most indicators, except for Agricultural Land Occupation, where solid wood tables have the highest impact due to their extensive wood content. The higher heating value of solid wood positively affects its environmental impacts compared to PB tables, making their impacts more comparable after accounting for end-of-life treatment. PB tables generally perform the best in several categories, while solid wood tables show improvements in others. The Global Warming Potential of PB and solid wood tables decreases due to the emission of gases with cooling effects during incineration, while it increases for MDF tables due to their non-recyclability and related substituion. These findings align partially with existing literature, confirming that end-of-life treatment significantly influences certain environmental indicators but has a lesser effect on others. However, scaling incineration emissions based on heating values introduces uncertainties, as it does not fully capture changes in incineration feedstock composition.

System Boundary 3 evaluates the entire life cycle of engineered and solid wood tables, incorporating lifespan and repairability. This directly addresses the second research question: "What methodologies can be employed to accurately estimate the lifespan of various table variants, and what are the distinguishing factors influencing their expected lifetimes?" To answer this, three approaches were explored: a literature review providing broad lifespan ranges, estimates adjusted using mechanical properties like tensile strength, and a correlation between resale price and material type, which proved ineffective. The study found that mechanical properties are viable for estimating lifespans, and factors such as material quality, construction techniques, maintenance, and environmental conditions significantly influence furniture longevity. However, estimating furniture lifespans is challenging due to a lack of advertised lifetimes and trends like "fast furniture," where consumers discard functional furniture early. Assumptions about the percentage of tables repaired (20%) and the doubling of table lifespans due to repair introduce further uncertainties due to the lack of robust data. Additionally, lifespan estimates based on non-academic literature carry large uncertainties, although using mechanical properties like tensile strength introduces less uncertainty.

The third research question, "To what extent do environmental impacts differ between average engineered and solid wood tables when lifetime considerations are integrated into the Life Cycle Assessment (LCA), and what are the implications of these findings?" is directly answered in System Boundary 3. The results indicate that when lifespan is considered, solid wood tables exhibit the lowest environmental impacts across all categories compared to MDF and PB tables. With lifespans more than 19 times longer, solid wood tables significantly reduce emissions per year of use. Repairing solid wood tables, assumed to be done by 20% of consumers, further prolongs their lifespan with negligible impact on overall emissions. Choosing tables with longer lifespans, especially solid wood, is the best option for reducing emissions per year of use, even for indicators like Agricultural Land Occupation.

Overall, the mentioned uncertainties in transport, end-of-life treatment, and table lifespan, as well as data quality constraints in the LCI of the tables, significantly affect the LCA outcomes, underscoring the need for more precise data and further academic attention.

The implications of this study are substantial for consumers amongst other stakeholders. Enhancing consumer awareness of furniture lifespans can enable more informed purchasing decisions that balance practicality and sustainability. By promoting the production and use of durable furniture, the frequency of replacements can be significantly reduced, lowering the demand for raw materials and associated environmental impacts. Encouraging the repair of furniture extends its lifespan, thus supporting sustainable consumption by minimizing environmental footprints.

In terms of LCA methodologies, this study underscores the importance of including product longevity to accurately reflect environmental impacts. Current LCAs often overlook lifespan, leading to incomplete or misleading conclusions. Integrating longevity into LCA models allows for a more comprehensive evaluation of a product's environmental impact over its entire life cycle, resulting in more accurate and meaningful assessments. Future research should prioritize LCAs that incorporate durability and quality aspects, and focus on developing precise methodologies for estimating product lifetimes. This approach will enhance the reliability and applicability of LCAs in evaluating environmental impacts across various product categories, ultimately guiding better decision-making for sustainable product development and consumption. By refining LCA methodologies to consider durability and quality, sustainability can be promoted across a broader range of products, providing more accurate and actionable insights.

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A Appendix

A.1 Methodology

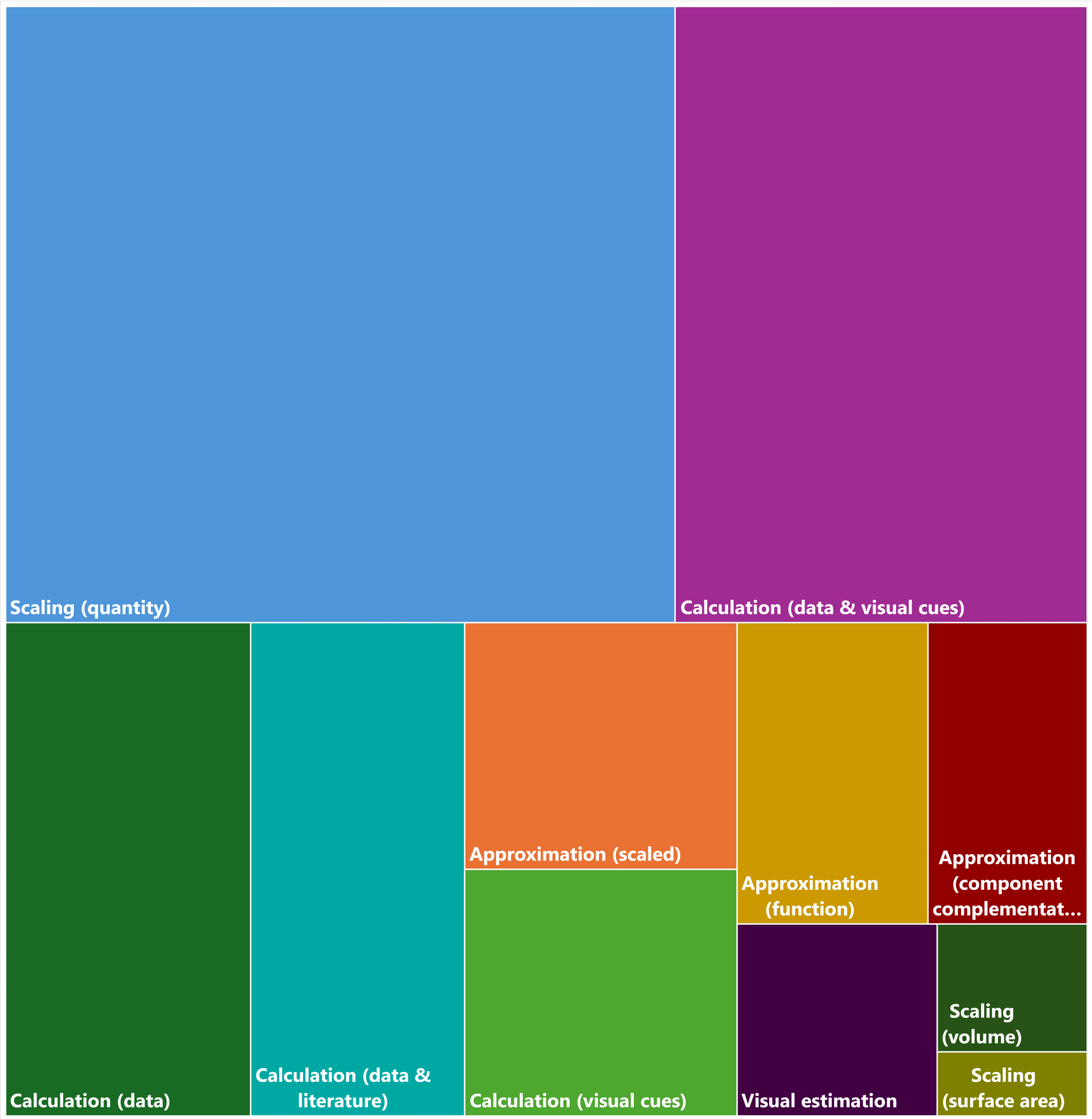

Figure A.1: Bohus: Applied estimation approaches for physical properties of table components

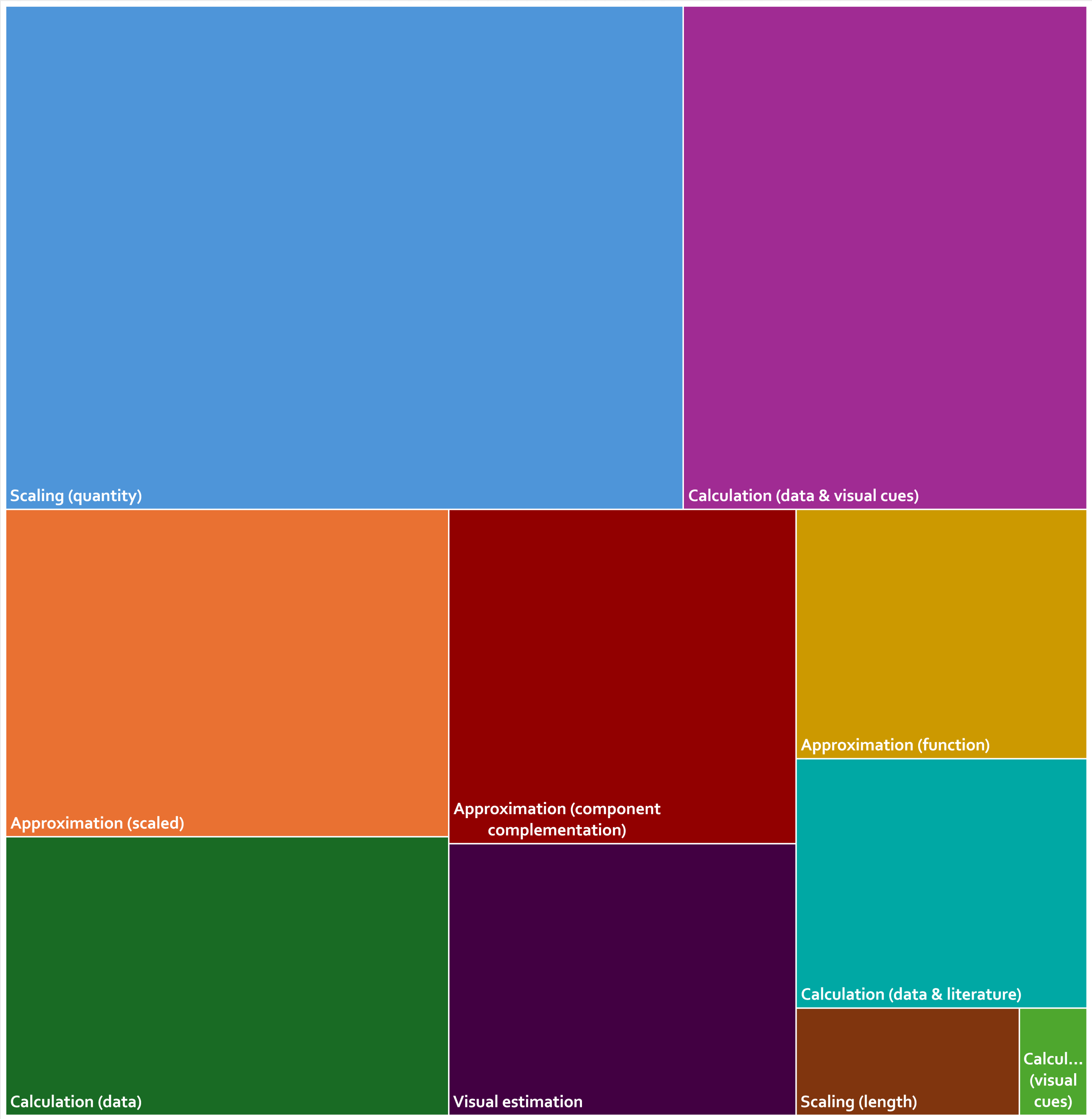

Figure A.2: Ikea: Applied estimation approaches for physical properties of table components

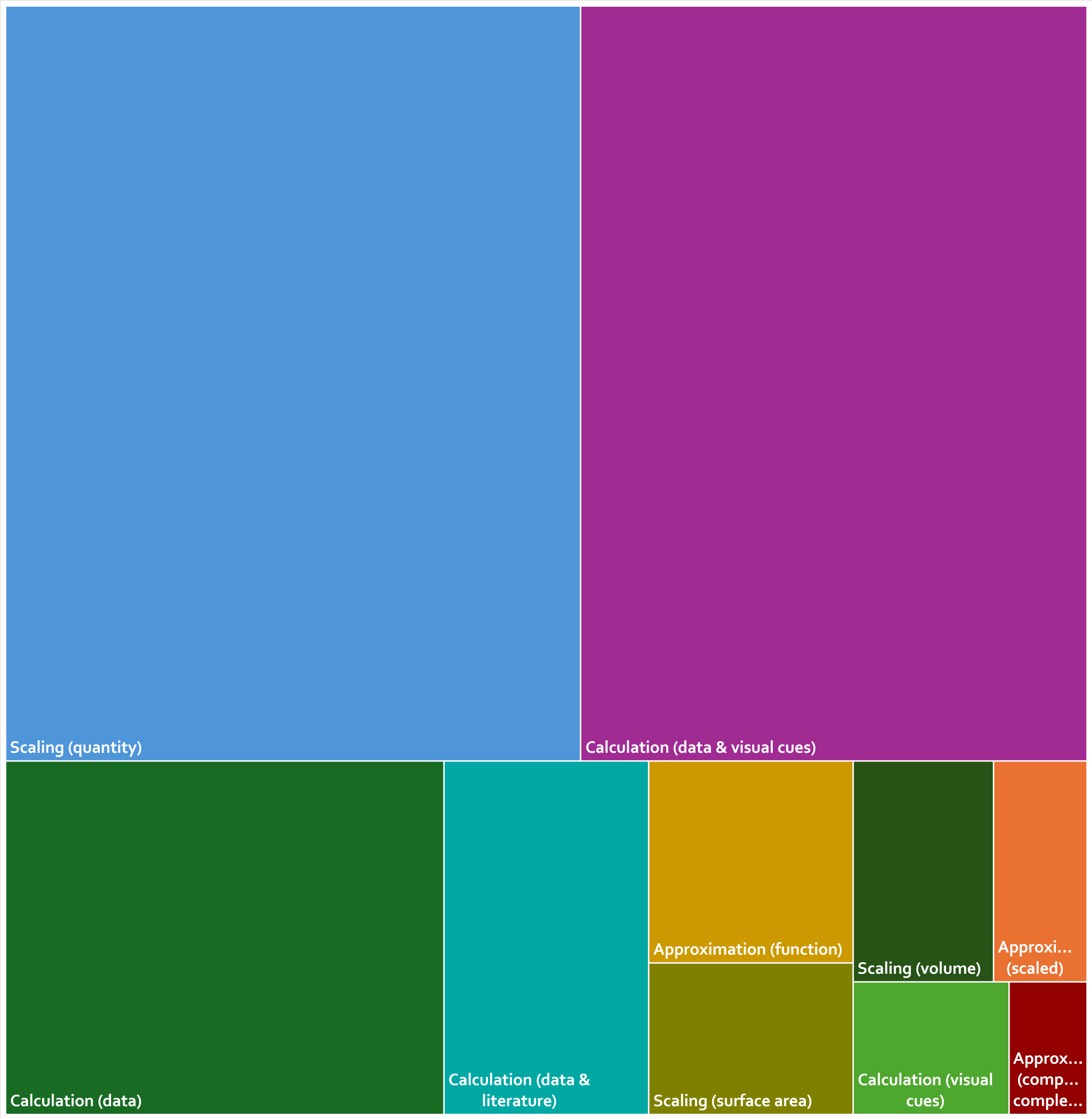

Figure A.3: Jysk: Applied estimation approaches for physical properties of table components

A.2 Results and discussion

Table A.1: LCA results - System boundary 1

Table name	Terrestrial acidification potential (TAP) [kg SO2-Eq]	Freshwater eutrophication potential (FEP) [kg P-Eq]	Particulate matter formation potential (PMFP) [kg PM2.5-Eq]	Human toxicity (HTPc) [kg 1,4-DCB-Eq]	Freshwater ecotoxicity potential (FETP) [kg 1,4-DCB-Eq]	Agricultural land occupation (LOP) [m²*a crop-Eq]	Global warming potential (GWP100) [kg CO2-Eq]
Bohus SOUT-HAMPTON (MDF)	0.110	0.010	0.046	4.086	1.161	37.225	35.117
Jysk JEGIND (MDF)	0.118	0.009	0.049	3.016	1.112	27.670	30.957
Bohus QUEBEC (MDF)	0.181	0.015	0.078	7.758	1.859	24.334	56.068
Bohus FRIBURG (MDF)	0.173	0.014	0.076	8.524	1.809	22.622	56.303
Bohus SKOVBY (SW)	0.034	0.002	0.018	3.055	0.315	31.546	9.897
Jysk KALBY (MDF)	0.120	0.010	0.050	3.354	1.161	20.704	29.435

Table A.1 continued from previous page

Table name	Terrestrial acidification potential (TAP) [kg SO2-Eq]	Freshwater eutrophication potential (FEP) [kg P-Eq]	Particulate matter formation potential (PMFP) [kg PM2.5-Eq]	Human toxicity (HTPc) [kg 1,4-DCB-Eq]	Freshwater ecotoxicity potential (FETP) [kg 1,4-DCB-Eq]	Agricultural land occupation (LOP) [m^2*a crop-Eq]	Global warming potential (GWP100) [kg CO2-Eq]
Bohus PIRO (SW)	0.027	0.001	0.014	2.780	0.265	22.028	7.717
Bohus GOTLAND (MDF)	0.139	0.011	0.058	3.721	1.358	20.182	34.328
Ikea VANGSTA (PB)	0.058	0.009	0.029	10.193	1.781	0.936	19.613
Jysk MARSTRUP (MDF)	0.083	0.007	0.035	2.186	0.807	18.770	20.310
Bohus ZION (MDF)	0.129	0.010	0.053	3.384	1.258	18.638	33.960
Ikea YPPERLIG (PB)	0.013	0.001	0.007	1.808	0.175	2.082	10.494
Jysk SKAGEN (MDF)	0.129	0.010	0.054	3.676	1.274	18.339	38.342

Table A.1 continued from previous page

Table name	Terrestrial acidification potential (TAP) [kg SO2-Eq]	Freshwater eutrophication potential (FEP) [kg P-Eq]	Particulate matter formation potential (PMFP) [kg PM2.5-Eq]	Human toxicity (HTPc) [kg 1,4-DCB-Eq]	Freshwater ecotoxicity potential (FETP) [kg 1,4-DCB-Eq]	Agricultural land occupation (LOP) [m²*a crop-Eq]	Global warming potential (GWP100) [kg CO2-Eq]
Ikea STRAND-TORP (PB)	0.020	0.002	0.013	4.214	0.309	1.825	5.784
Ikea SKOGSTA (SW)	0.024	0.001	0.011	0.511	0.165	26.697	8.093
Ikea RÖNNINGE (PB)	0.015	0.001	0.007	0.783	0.154	2.028	4.223
Bohus NOLA (MDF)	0.128	0.010	0.053	3.376	1.238	18.252	30.891
Ikea LISABO (PB)	0.009	0.001	0.004	0.208	0.080	3.847	2.369
Ikea VOXLÖV (PB)	0.009	0.001	0.004	0.449	0.089	1.345	2.276
Bohus TRONDHEIM (PB)	0.004	0.000	0.002	0.222	0.042	0.763	0.997

Table A.1 continued from previous page

Table name	Terrestrial acidification potential (TAP) [kg SO2-Eq]	Freshwater eutrophication potential (FEP) [kg P-Eq]	Particulate matter formation potential (PMFP) [kg PM2.5-Eq]	Human toxicity (HTPc) [kg 1,4-DCB-Eq]	Freshwater ecotoxicity potential (FETP) [kg 1,4-DCB-Eq]	Agricultural land occupation (LOP) [m²*a crop-Eq]	Global warming potential (GWP100) [kg CO2-Eq]
Jysk SKOVLUNDE (MDF)	0.123	0.010	0.051	3.288	1.205	17.637	36.466
Ikea EKEDALEN (MDF)	0.072	0.007	0.031	2.903	0.756	17.504	16.658
Bohus BRIXTON (MDF)	0.102	0.008	0.044	4.224	1.031	14.079	25.807
Jysk AABENRAA (MDF)	0.101	0.008	0.044	4.615	1.040	13.352	29.707
Jysk BANNERUP (MDF)	0.084	0.007	0.035	2.367	0.818	11.952	19.978
Jysk VISLINGE (SW)	0.020	0.001	0.009	0.484	0.159	20.277	13.560
Ikea MELLANSEL (MDF)	0.083	0.007	0.036	3.497	0.846	11.664	19.927

Table A.1 continued from previous page

Table name	Terrestrial acidification potential (TAP) [kg SO2-Eq]	Freshwater eutrophication potential (FEP) [kg P-Eq]	Particulate matter formation potential (PMFP) [kg PM2.5-Eq]	Human toxicity (HTPc) [kg 1,4-DCB-Eq]	Freshwater ecotoxicity potential (FETP) [kg 1,4-DCB-Eq]	Agricultural land occupation (LOP) [m^2*a crop-Eq]	Global warming potential (GWP100) [kg CO2-Eq]
Jysk TERSLEV (MDF)	0.077	0.006	0.035	4.569	0.824	10.013	18.750
Ikea TRANEBO (MDF)	0.079	0.006	0.038	5.874	0.885	9.582	23.996
Jysk ROSKILDE (SW)	0.019	0.001	0.009	1.059	0.151	21.620	6.435

Table A.2: LCA results - System boundary 2

Wood type	**Terrestrial acidification potential (TAP) [kg SO2-Eq]**	**Freshwater eutrophication potential (FEP) [kg P-Eq]**	**Particulate matter formation potential (PMFP) [kg PM2.5-Eq]**	**Human toxicity (HTPc) [kg 1,4-DCB-Eq]**	**Freshwater ecotoxicity potential (FETP) [kg 1,4-DCB-Eq]**	**Agricultural land occupation (LOP) [m^2*a crop-Eq]**	**Global warming potential (GWP100) [kg CO2-Eq]**
PB	0.015	0.002	0.009	2.599	3.983	1.778	10.408
MDF	0.119	0.010	0.051	4.657	4.913	18.780	39.076
Solid wood	0.026	0.002	0.013	1.804	2.097	24.350	12.770

Table A.3: LCA results - System boundary 3

Wood type	**Terrestrial acidification potential (TAP) [kg SO2-Eq]**	**Freshwater eutrophication potential (FEP) [kg P-Eq]**	**Particulate matter formation potential (PMFP) [kg PM2.5-Eq]**	**Human toxicity (HTPc) [kg 1,4-DCB-Eq]**	**Freshwater ecotoxicity potential (FETP) [kg 1,4-DCB-Eq]**	**Agricultural land occupation (LOP) [m^2*a crop-Eq]**	**Global warming potential (GWP100) [kg CO2-Eq]**
PB	4.9E-03	5.2E-04	2.8E-03	8.6E-01	1.3E+00	5.9E-01	3.4E+00
MDF	6.0E-02	5.0E-03	2.5E-02	2.3E+00	2.5E+00	9.4E+00	2.0E+01
Solid wood	4.0E-04	2.4E-05	2.0E-04	2.8E-02	3.2E-02	3.8E-01	2.0E-01

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