Life Cycle Assessment

Comparison of a hardwood and
Medium Density Fiberboard (MDF) dining table

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February 2022

1. Abstract

Environmental impacts associated with the furniture industry have become of increasing importance. Generally, most of the impacts of a product are not created at a production facility, but along the supply chain. In order to control the impacts in each stage, it is necessary to measure them in the first place, i.e. by conducting a Life Cycle Assessment (LCA), a tool that quantifies and evaluates a broad scope of environmental impacts from the selected life cycle of a given product. Life Cycle Assessments are one of the most profound ways for the furniture industry to promote environmentally friendly products and business models with scientific evidence.

This report shows the LCA results of two case studies of wooden furniture. The compared products are an oak hardwood lumber and a Medium Density Fiberboard (MDF) dining table. The wooden tables selected are representative standard pieces taken from the Swiss market. In both cases, the raw material is taken from Poland. The MDF table was produced in Switzerland whereas the hardwood table was produced in Poland. CIVAG refers to this study as a “Traditional Case Study” because it does not include the company’s business model, but instead it aims to understand the typical life cycle of a dining table. The environmental impacts were measured in Europe, including countries such as Switzerland, Germany and Poland using the life-cycle inventory method through the Software OpenLCA.

Primary data was collected on a per-unit basis of 1 piece of furniture to find material flows and energy use. On the other hand, the environmental impact is measured with three variables: The energy consumption in MJ, the water consumption in L and the impact categories, which groups emissions into different effects on the environment, which then are put together in one variable called Environmental Cost Indicator ECI.

The cumulative allocated energy consumption during the cradle to grave life cycle assessment of 1.0 piece of furniture made of hardwood lumber corresponds to -3,80 GJ/m^3, while the energy for 1.0 piece of furniture made of MDF corresponds to -1,50 MJ/m^3. The negative value obtained is due to the energy recovery process through incineration during the waste disposal stage at the furniture’s end of life. This is the typical practice in Switzerland, from which 4% of the energy of the country is obtained [1]. Now, ignoring the waste disposal stage of the cycle and thereby its energy recovery, the cumulative allocated energy consumption is 9,66 GJ/m^3 and 8,93 GJ/m^3 for the hardwood lumber and the MDF table, respectively. The materials used and energy consumed during the manufacturing of the wood furniture materials - lumber and Medium Density

Fiberboard (MDF) - affect the furniture's environmental performance significantly. However, this report shows that other processes such as the transport and the manufacturing of the final wood product have a higher impact on the furniture's environmental performance.

Finally, the emission data obtained through the modeling estimated a total carbon dioxide production of 2410,9 and 2782,3 kg CO_2/m^3, respectively, considering all impacts in the cradle to grave life cycle assessment. The amount of carbon emitted in MDF case exceeds hardwood lumber emissions. In terms of other emissions, the MDF case has greater impact in all the categories than hardwood lumber. The exact values can be seen later on in the report. As another example total water consumption during the life cycle corresponds to 6,38 and 25,08 L respectively.

The impact specific to the CIVAG circular rental model is not assessed in this report, but in a subsequent one.

Key words: Furniture, Life Cycle Assessment LCA, cradle to grave, hardwood, Medium Density Fiberboard (MDF), energy, impact categories.

2. Method and resources

This study was developed in compliance with the ISO 14040 and the LCA practices from the United Nations Environmental Programme [2]. The LCA was conducted in OpenLCA using the impact method database "CML-IA baseline".

Concept definitions

- Raw material: Also known as a feedstock, unprocessed material, or primary commodity, is the basic material that is used to produce finished products. The raw materials in this report are: In the wood category is the tree from which its processed to sawlogs for the hardwood case and wood chips for the MDF case, in the metal category is steel, and in the chemical category are all the compounds from the liquid substances used e.g. Toluene as part of the lacquer and thinner, or Aluminium Chloride as part of the glue.
- Material: It is defined as a substance that is intended to be used for certain applications.
- Material category: It is a classification of the three types of materials found in wooden furniture: Wood, metals and chemicals.
- Product: It is a material or a union of materials that are manufactured or refined for sale.
- Product manufacture: It is the transformation process of the raw material into an intermediate product, that can be a wood product, a metal product or a chemical product.
- Wood product: It is a wood material that is manufactured or refined for creating an intermediate product e.g. oak timber, MDF plate. It will be again manufactured in the future to produce the final product.
- Metal product: It is a metal material that is manufactured or refined for creating an intermediate product e.g. fasteners.
- Chemical product: It is a union of chemical substances that are transformed or refined for creating the chemical inputs e.g. glue, thinner, paint.

- Final product manufacture: It is the transformation process of the intermediate product into the final product, which in this case is the wood table.
- Furniture piece (dining table): It is the finished product after the production phase.

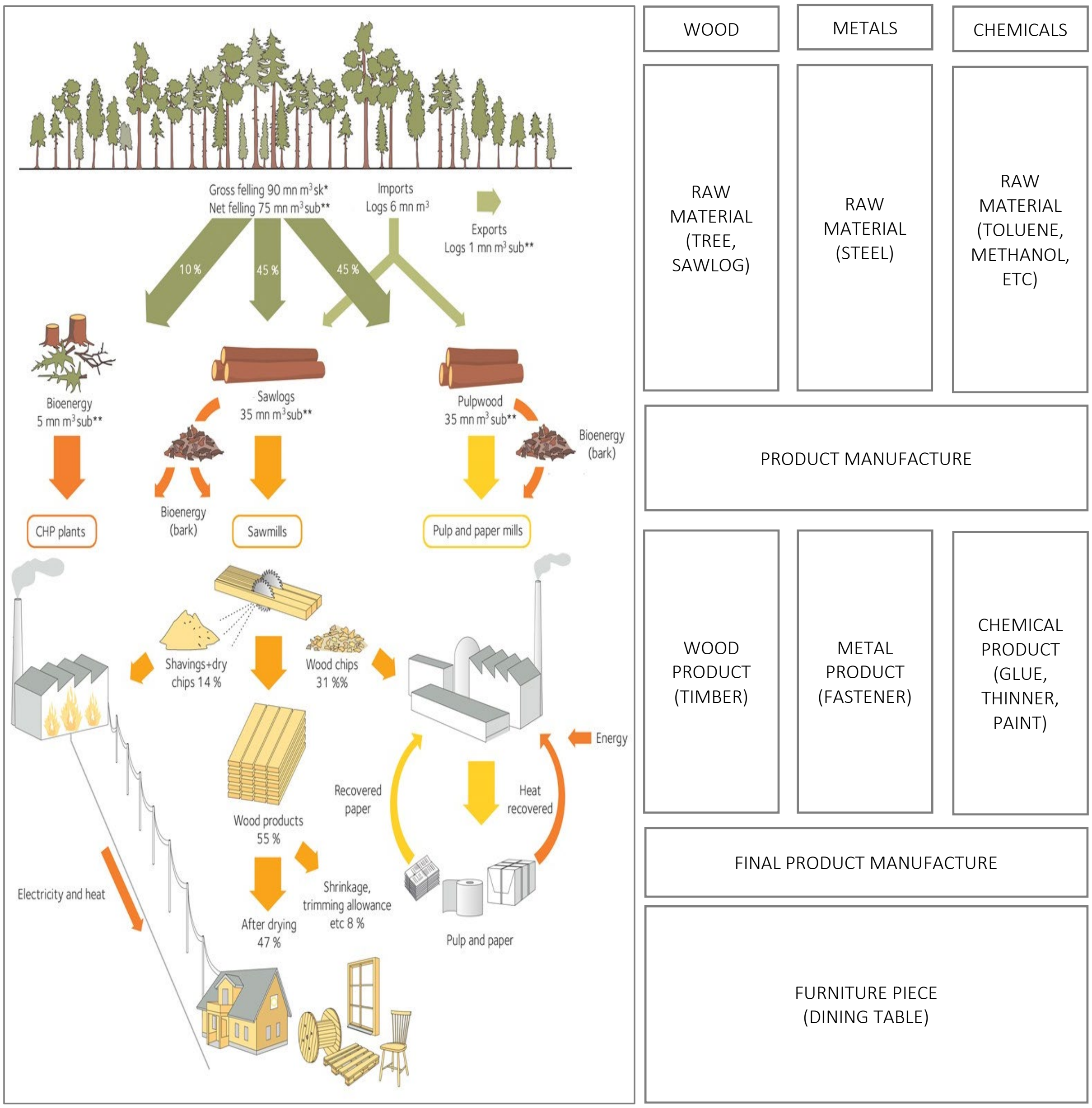

Figure 1. Concept definition and general flow diagram for wooden products. [3]

3. Goal and scope

The goals of this report are to:

1. Identify and measure the environmental impact during the cradle to grave life cycle for a Traditional study case of wood furniture.
2. Compare the environmental impact of two different wood materials in a piece of furniture.
3. Outline improvement opportunities by identifying the source of major footprint contributions on the LCA in terms of material inputs and processes.

In Table 1 are stablished the calculation parameters for conducting the LCAs.

Table 1. LCA calculation parameters

LCA calculation parameter	**LCA calculation parameters defined for the Traditional case study**
Product	1. Dining table made of hardwood Oak. 2. Dining table made of Medium Density Fiberboard (MDF) Ad 1: Bought at a high-end retailer that has more than one shop in Switzerland Ad 2: Available at one of the most relevant online shops for furniture in Switzerland and Europe
Measurement system	Use of Cradle to Grave analysis
Functional Unit	1.0 piece of furniture: dining table
Reference Service Life (RSL)	For indoor tables, it is declared by producer and related to intended use, being in this case residential. Necessary measures for the maintenance and repair of the table include the repaint every 4 years, change of parts (replacement) every 15 years and repair every 4 years. Not considered for this Traditional case
Estimated Service Life (ESL).	For indoor tables, 20 years for the hardwood table and 15 years for the MDF table.
System boundaries	See Figure 1
Impact category	The impact categories evaluated are: • Global warming in kg CO_2 eq • Abiotic depletion in kg Sb eq • Abiotic depletion by fossil fuels in MJ • Acidification in kg SO_2 eq • Eutrophication in kg PO_4 eq • Fresh water aquatic ecotoxicity in kg 1,4-DB eq • Human toxicity in kg 1,4-DB eq • Marine aquatic ecotoxicity in kg 1,4-DB eq • Ozone layer depletion (ODP) in kg CFC-11 eq • Photochemical oxidation in kg C_2H_4 eq • Terrestrial ecotoxicity in kg 1,4-DB eq
Exclusion *Criteria for the exclusion of inputs and outputs (cut-off)*	Processes excluded from the assessment include: - The production process of the input materials (except for the wood products) such as chemicals and fasteners. - The machinery production for manufacturing for both the wood product and the final product.

Functional Unit

The functional unit is a piece of furniture, a dining table made out of wood materials. The characteristics for each case study are shown in Table 2.

Table 2. Functional unit characteristics: dimensions and materials.

	Hardwood case		MDF case	
Part	**Dimension (cm)**	**Material**	**Dimension (cm)**	**Material**
Tabletop	220 x 95 x 3	White oak timber	220 x 95 x 2,5	MDF
Apron (long) (x2)	220 x 9 x 3	White oak timber	220 x 7 x 3	White oak timber
Apron (width) (x2)	95 x 9 x 3	White oak timber	95 x 7 x 3	White oak timber
Legs (x4)	12 x 12 x 75	White oak timber	7 x 7 x 75	White oak timber

System boundaries

The LCA has a scope of cradle to grave. This means that the life cycle includes the following stages: raw material extraction (including forest management), materials production and manufacture, product manufacture, transportation, use phase and End-of-Life EOL waste disposal.

In terms of the products selected, the description in terms of dimensions and materials can be found in Table 2. It is important to mention that the table selected for the MDF case study is not only made out of MDF, but the structure is made out of hardwood.

Figure 1 is the diagram of production system boundary. It can be seen that modules B4 – B5 related with maintenance, repair, replacement and refurbishment are not included in the system boundary of this study. This since the Traditional case study aims to follow the typical life cycle of the table without extending it. The modules B6-B7: Operations during Usage are not considered in this case study, since it is an end-customer-product and its use is private.

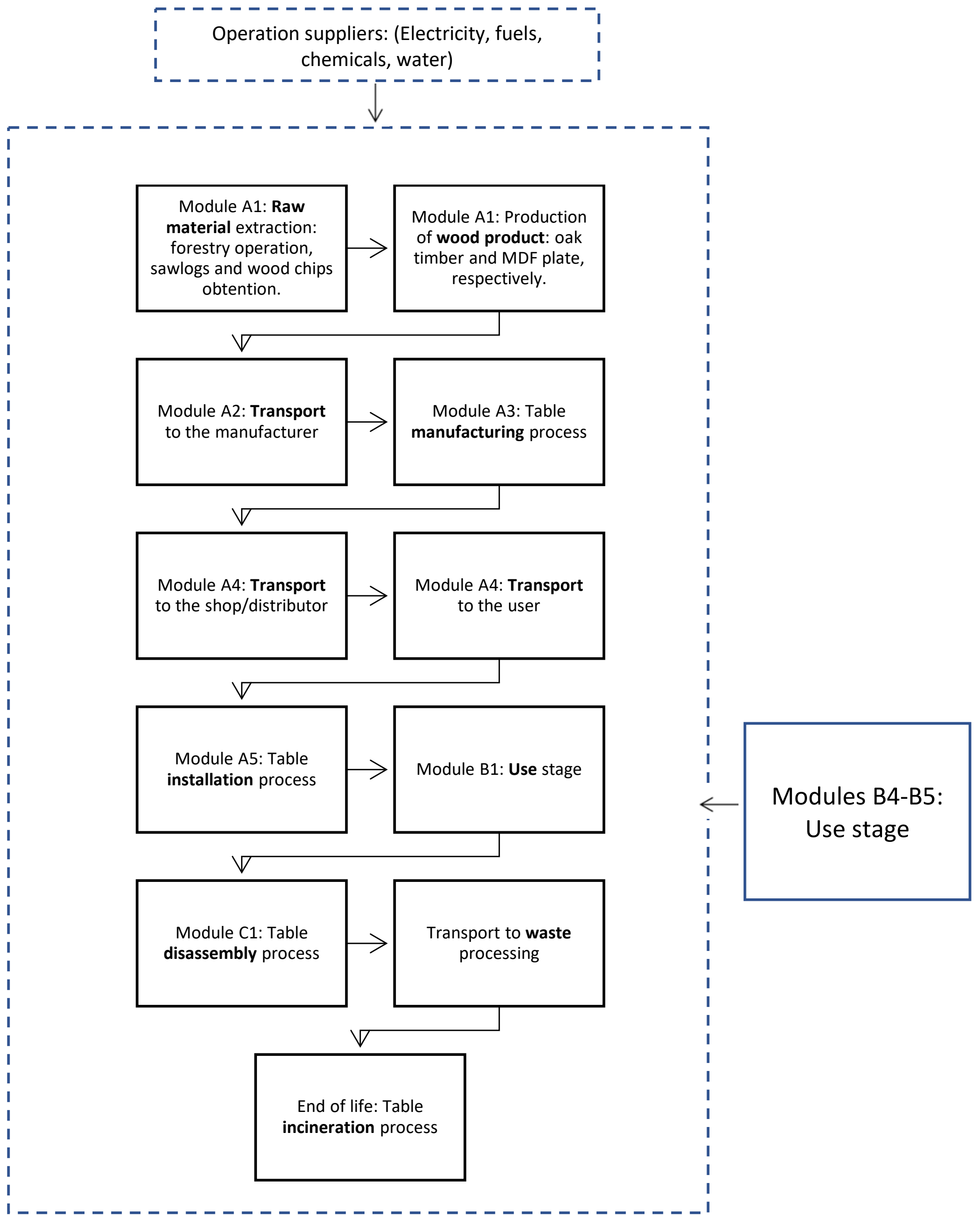

Figure 2. LCI system boundary. The dash line area represents the system boundary.

4. Life Cycle Inventory LCI

4.1. Material consumption or inputs

The raw material inputs involved in the table production process are shown in Table 2 for each case study. Only two stages involve input materials: module A1, related with the production of the wood products, corresponding to oak timber and MDF plate respectively; and the module A3 for the table manufacturing process. The rest of the stages have energy fluxes, reason why the fuels or other power sources are considered in Section 4.2.

It is important to mention that the waste wood from the wood product manufacture is considered. For the case of hardwood, it corresponds to 45% of the sawlog raw material that entered the process for producing the oak timber, while for the case of MDF 15% of wood chips are waste.

Table 3. Material inputs for each wood table case study.

Hardwood table				MDF table		
Material	**Functionality**	**Quantity**		**Material**	**Functionality**	**Quantity**
<u>Module A1:</u> Production of wood product: oak timber and MDF plate, respectively.						
Sawlog hardwood	Tabletop	0,063 m^3		Wood chips	Tabletop	0,052 m^3
	Apron (long) (x2)	0,006 m^3			**Total (incl. excess material e.g cut off)**	**0,097 m^3**
	Apron (width) (x2)	0,003 m^3		Sawlog hardwood	Apron (long) (x2)	0,005 m^3
	Legs (x4)	0,043 m^3			Apron (width) (x2)	0,002 m^3
	Total (incl. excess material e.g cut off)	**0,177 m^3**			Legs (x4)	0,019 m^3
					Total (incl. excess material e.g cut off)	**0,032 m^3**
				Urea-formaldehyd resin		2,09 kg
				Wax		0,11 kg
				Urea scavenger		0,15 kg
				Ammonium Sulfate		0,003 kg
				Urea		0,03 kg
<u>Module A3:</u> Table manufacturing process						
Oak lumber trimmed	Table	0,114 m^3		MDF	Tabletop	0,063 m^3
Stainless steel wire	Fasteners	0,06 kg		Oak lumber trimmed	Table structure	0,028 m^3
Dichloromethane	Remover lack	89,37 ml		Stainless steel wire	Fasteners	0,06 kg
Iso-propyl alcohol	Remover lack	26,87 ml		Dichloromethane	Remover lack	89,37 ml
Monoethanolamine	Remover lack	2,5 ml		Iso-propyl alcohol	Remover lack	26,87 ml
Hydroxyacetic acid	Remover lack	6,25 ml		Monoethanolamine	Remover lack	2,5 ml
polyvinyl alcohol	Glue	0,010 kg		Hydroxyacetic acid	Remover lack	6,25 ml
Aluminum chloride	Glue	0,055 kg		polyvinyl alcohol	Glue	0,008 kg
Calcium chloride	Glue	0,007 kg		Aluminum chloride	Glue	0,042 kg
oxalic acid	Glue	0,013 kg		Calcium chloride	Glue	0,005 kg
Toluene	Thinner	126 ml		oxalic acid	Glue	0,010 kg
Hexane	Thinner	17,22 ml		Toluene	Thinner	126 ml
Acetone	Thinner	17,22 ml		Hexane	Thinner	17,22 ml
Methanol	Thinner	10,08 ml		Acetone	Thinner	17,22 ml
Xylene	Thinner	8,61 ml		Methanol	Thinner	10,08 ml
Aromatics	Thinner	6,3 ml		Xylene	Thinner	8,61 ml
Propyl acetate	Thinner	5,88 ml		Aromatics	Thinner	6,3 ml
Cellosolve (Ethoxyethanol)	Thinner	4,2 ml		Propyl acetate	Thinner	5,88 ml
Methyl isobutyl ketone	Thinner	3,78 ml		Cellosolve (Ethoxyethanol)	Thinner	4,2 ml
2-propanol	Thinner	3,57 ml		Methyl isobutyl ketone	Thinner	3,78 ml
Butoxyethanol	Thinner	3,36 ml		2-propanol	Thinner	3,57 ml
Methyl butyl ketone (hexanone)	Thinner	3,36 ml		Butoxyethanol	Thinner	3,36 ml
Butyl acetate	Thinner	2,31 ml		Methyl butyl ketone (hexanone)	Thinner	3,36 ml
Benzene	Thinner	0,63 ml		Butyl acetate	Thinner	2,31 ml
Polymethylsiloxane	Sealant	30 ml		Benzene	Thinner	0,63 ml

Aluminum hydroxide	Sealant	96 ml		Polymethylsiloxane	Sealant	30 ml
Graphite (thermally expanded)	Sealant	14 ml		Aluminum hydroxide	Sealant	96 ml
Ethyl silicate-32	Sealant	60 ml		Graphite (thermally expanded)	Sealant	14 ml
Zinc phosphate	**Paint**	**8 ml**		Ethyl silicate-32	Sealant	60 ml
Zeolite	Paint	16 ml		**Zinc phosphate**	**Paint**	**8 ml**
Barium sulfate	Paint	23,04 ml		Zeolite	Paint	16 ml
Titanium dioxide	Paint	9,28 ml		Barium sulfate	Paint	23,04 ml
Talc	**Paint**	**23,04 ml**		Titanium dioxide	Paint	9,28 ml
Alkyd resin 52% sunflower seed oil)	Paint	119,36 ml		**Talc**	**Paint**	**23,04 ml**
Solvent (white spirit)	Paint	121,28 ml		Alkyd resin 52% sunflower seed oil)	Paint	119,36 ml
Nitrocellulose RS 5/6	Lacquer	47,25 ml		Solvent (white spirit)	Paint	121,28 ml
Toluenesulfonamide formaldehyde resin	Lacquer	20,25 ml		Nitrocellulose RS 5/6	Lacquer	47,25 ml
Dibutyl phthalate	Lacquer	13,5 ml		Toluenesulfonamide formaldehyde resin	Lacquer	20,25 ml
Acrylates copolymer	Lacquer	5,4 ml		Dibutyl phthalate	Lacquer	13,5 ml
Butyl acetate	Lacquer	47,25 ml		Acrylates copolymer	Lacquer	5,4 ml
Ethyl acetate	Lacquer	20,25 ml		Butyl acetate	Lacquer	47,25 ml
Isopropanol	Lacquer	13,5 ml		Ethyl acetate	Lacquer	20,25 ml
Toluene	Lacquer	103,27 ml		Isopropanol	Lacquer	13,5 ml
				Toluene	Lacquer	103,27 ml

Where the inputs could not be measured, they were taken from several references (See reference list for Input Materials References in Chapter 11). Crucial elements are highlighted for sections below related.

4.2. Energy consumption

Table 4 shows the energy consumption per life cycle stage, given per energy source. In the end this represents the total value of energy consumption.

Energy for the production of hardwood oak timber and MDF comes from electricity, wood sources, natural gas, and oil, whereas other fuels such as diesel and liquid gas are used to operate transport and other equipment. Electricity is used throughout the process to operate equipment within the plant such as conveyors, refiners, fan motors, hydraulic press motors, sanders, and emission control systems. The fuels for equipment are used for loaders and forklifts, and the natural gas and wood fuels are used to provide process heat for flash-tube dryers and presses.

During the manufacture of the wood table stage, the machinery uses electricity, diesel oil and natural gas typically, while propane was used in the hardwood case only. It is important to mention that the energy mix is defined per region, including Poland, Germany and Switzerland data depending on the stipulated route for each case study (see section Modules A2, A4 shop/distributor, A4 user, C2: Transport).

Table 4. Energy consumption during the cradle to grave life cycle of a hardwood and MDF diner table

Energy source	**Hardwood table energy amount (MJ)**		**MDF wood table energy amount (MJ)**
Module A1: Production of wood product: oak timber and MDF plate, respectively.			
Electricity	55,55		130,295
Natural gas	12,75		80,172
Diesel oil	25,97		0,726
Propane	5,90		
Total energy consumption	**97,21**		**211,19**
Module A2: Transport to the manufacturer			
Diesel oil	70,33		16,44
Module A3: Table manufacturing process			
Electricity	77,01		132,11
Natural gas	17,94		19,48
Diesel oil	12,54		2,41
Propane	17,94		
Total energy consumption	**125,42**		**153,98**
Module A4: Transport to the shop/distributor			
Diesel oil	2,42		174,84
Module A4: Transport to the user			
Diesel oil	5,95		5,36
Module A5: Table installation process			
Electricity	1,62		1,62
Module C1: Table disassembly process			
Electricity	1,62		1,62
Module C2: Transport to waste processing			
Diesel oil	44,94		44,94
Module C4: Table disposal process			
Electricity	-1188,81		-942,34
Total energy before module C4	**753,98**		**829,92**
Total energy after module C4	**-434,83**		**-112,43**

In terms of the raw material obtention (or wood product), it is assumed for both case studies that the production occurs in an industrial level. However, for the table manufacturing process, a small-scale manufacture company is assumed.

According to the results, the energy consumption during the A1 Raw Material Extraction shows that the MDF production requires more than the double of energy (211,2 MJ) compared to the hardwood (97,2 MJ). This because of the complexity during the MDF production process compared to the oak lumber process.

For the A2 Transport to the Manufacture, the energy consumed by the truck for transporting one hardwood table is 4 times higher than the energy for transporting one MDF table. This occurs because of the distance that was assumed: 1064 Km in the hardwood case from Poland to Switzerland, compared to only 341 within Poland in the MDF case. Furthermore, the capacity plays a roll since more MDF tables can be transported in one truck, which represents less energy consumption and therefore emissions per unit compared with the hardwood case (see section Modules A2, A4 shop/distributor, A4 user, C2: Transport).

During the A3 Table Manufacturing Process, the energy consumption is very similar, the MDF case (153 MJ) is about twenty percent higher than the hardwood case (125 MJ). The difference is not primarily due to the table structure, which is basically the same in terms of material usage and the dimensions for both case studies, but due to the extra energy consumed for the MDF tabletop compared to the hardwood tabletop production.

The energy consumed for the A4 Transport to the Shop Distributor is slightly lower for the hardwood case (2,4 MJ) than for the MDF case (6,1 MJ). On the first glance, it seems to be counterintuitive taking into account the explanation given above for the module A2. However, in this case the manufacturer for hardwood is located already in Switzerland, at a distance of 11 km from the shop distributor. On the contrary, the MDF manufacturer is located in Poland, reason why the distance is 1088 km.

Similarly than the previous module, the energy consumption for the A4 Transport to the User is almost the same (5,9 and 5,4 MJ, respectively). This considering that the distance from the distributor to the user (assumed to be in Zurich, Switzerland) is 9 km and 316 km respectively.

The modules A5 and C1 related with the table installation and disassembly processes consume the same energy (1,6 MJ) e.g. for powering tools like a screwdriver for fixing the joints with fasteners.

The energy consumed for the C2 Transport to the Waste Processing is the same for both case studies. This due to the fact that the user will transport individually the piece of furniture to the closest waste collection point, assuming a distance of 20 Km, corresponding to 10 km to and back from the recycling point. Hence, the energy required for powering the car is dramatically higher (45 MJ) compared to the rest of transport modules, which are done in larger quantities.

Finally, during the C4 Table Disposal Process there is net negative energy consumption but instead energy generation. This explains the negative sign shown in Table 4. This occurs during a waste incineration process, where the biomass is converted into electrical energy or heating. The amount of energy produced in each case scenario depends on the combustion heat value of each material, corresponding to 13,7 MJ/kg for hardwood and 14,9 MJ/kg for MDF. Taking into account the weight difference between the two case studies, the energy produced is higher for the hardwood case (1188 MJ and 942 MJ respectively).

The total energy *consumed* during the entire cradle-to-grave life cycle of the table is lower for the hardwood case than the MDF case (756 MJ and 830 MJ respectively). Now, considering that the energy *produced* in the module C4 is higher than the total consumption, there is an “energy offsetting” process, which in other words means that the energy used in the life cycle is completely recovered and even more is generated. Hence, the final energy *recovered* during the entire cradle-to-grave life cycle of the table corresponds to 435 MJ and 112 MJ, respectively. These values are also display as negative in Table 4. The reader must keep in mind that this does not necessarily mean that producing a table and then incinerate it is sustainable. In the Impact Categories Section, it will be shown the environmental impact in terms of emissions during incineration process.

Users of dining tables might ask themselves “how big is this energy consumption?”. Well, Table 4 shows an energy equivalence to a daily activity that every user knows; using a computer screen. With the purpose of dimensioning the energy consumption in both case studies, the equivalent number of hours, which a 24-inch LD computer screen would run with the same energy required for each case study is indicated.

Table 5. Energy consumption equivalence for the case studies: Number of hours that a 24-inch LD computer screen would run with that energy.

Energy source	Hardwood energy equivalence (h)		MDF energy equivalence (h)
Module A1: Production of wood product: oak timber and MDF plate, respectively.			
Total energy consumption	**1080**		**2346**
Module A2: Transport to the manufacturer			
Diesel oil	781		6
Module A3: Table manufacturing process			
Total energy consumption	**1393**		**1710**
Module A4: Transport to the shop/distributor			
Diesel oil	27		68
Module A4: Transport to the user			
Diesel oil	66		59
Module A5: Table installation process			
Electricity	18		18
Module C1: Table disassembly process			
Electricity	18		18
Module C2: Transport to waste processing			
Diesel oil	4993		4993
Module C4: Table disposal process			
Electricity	-13209		-10470
Total hours before module C4	**8377**		**9221**
Total hours after module C4	**-4831**		**-1249**

Taking into account that 1765 h per Year corresponds to a working year [3], this means that the energy consumption before module C4 is more than 4,75 and 5,25 years non-stop screen time at the office, respectively. Hence, the net energy recovery would correspond to 2,75 years and 0,7 years of powering a screen, respectively.

4.3. Water consumption

The water consumption is shown in Table 5. Water used during transportation was not considered. The water usage is not problematic in Switzerland, which is not affected by water scarcity. Yet Poland faces water scarcity, making water consumption relevant [4] [5].

Table 6. Water consumption for each case study.

Stage of the life cycle	Hardwood water consumption (L)		MDF water consumption (L)
Module A1: Production of wood product: oak timber and MDF plate, respectively	4,5		5,0
Module A3: Table manufacturing process	3,2		16,1
Module A5: Table installation process	0,8		0,8
Module C1: Table disassembly process	0,8		0,8
TOTAL WATER CONSUMPTION	**9,3**		**22,4**

5. Life Cycle Impact Assessment LCIA

Based on the OpenLCA LCIA simulation, the results are shown in Table 8. It can be seen that for all the categories, the MDF case study had a worse impact on the environment compared to the hardwood case.

The analysis in detail for each impact category includes a short description and a discussion by comparing the results with a case study from the Oregon State University: cradle-to-gate LCI of residential wood building materials [6] [7]. It is important to mention that the materials selected for the comparison are not the same for this case study, these are lumber KD and plywood. However, the properties are very similar and, taking into account that the purpose is to have an idea on the order of magnitude, it is accurate enough.

Global warming, or Global Warming Potential GWP is basically the amount of CO_2 that is emitted. According to the reference found, the value is 92 kg CO_2 eq, while the result obtained for the hardwood table it is 34,3 kg CO_2 eq. This shows that the order of magnitude of the three values are comparable. However, the reference generates higher emissions than the case study. For the second case, the value corresponds to 146 kg CO_2 eq in the reference case, while results obtained for the MDF case correspond to 157 kg CO_2 eq.

- **Abiotic depletion** refers to the reduction of nonliving resources such as minerals, clay, and peat. It is measured in kilograms of antimony (Sb) equivalents.
- **Abiotic depletion by fossil fuels** corresponds to the reduction of resources, in this case fossil fuels, which is why it is measured in MJ.
- **Acidification** refers to the deposition of acids in the ecosystem, which leads to a decreasing pH value and an increase of potentially toxic elements. It is measured in terms of SO_2 equivalents.
- **Eutrophication** is the addition of nutrients to a soil or water system which leads to an harmful addition in biomass, damaging other life forms. In the case of water, it acquires a high concentration of nutrients, especially phosphates and nitrates promoting excessive growth of algae. Eutrophication is measured in terms of phosphate PO_4 equivalents.
- **Freshwater ecotoxicity** is dominated by heavy metal emissions to the freshwater from the comminution-beneficiation process and phosphorus associated with the water treatment processes resulting from the comminution-beneficiation process. It is measured in dichlorobenzene DB.
- **Marine ecotoxicity** is mainly caused by emissions of heavy metals and eco-toxic substances released into the water. The impact is measured in DB (dichlorobenzene), which is an important water pollutant. Analysing the drivers to this result, it was identified that the transport stage, the hardwood forestry operation & production, and the woodchips production make the highest contribution to the category. In all this processes, the diesel fuel consumption is the responsible of the huge damage in the marine ecosystems. Other stages have a significant impact, such as the polydimethylsiloxane production, an upstream process from the manufacture stage.
- **Terrestrial ecotoxicity** is dominated by pesticide emissions to agriculture soil as well as the use of both sulphuric acid and steam during the conversion process. It is measured in dichlorobenzene DB.

- **Human toxicity** refers to the chemicals which describes fate, exposure and effects of toxic substances for human health.
- **Ozone layer depletion** refers to the reduction in the concentration of ozone in the ozone layer. It is measured CFC-11 eq.
- **Photochemical oxidation** refers to is secondary air pollution, also known as summer smog. It is the formed in the troposphere caused mainly by the reaction of sunlight with emissions from fossil fuel combustion creating other chemicals. It is measured in C_2H_4 eq.

Table 7. Impact categories results during the cradle to grave life cycle of a hardwood and MDF diner table.

Impact categories	Hardwood table impact		MDF table impact
Global warming (GWP100a) in kg CO_2 eq	34,34		157,31
Abiotic depletion in kg Sb eq	1,2 E-04		0,001
Abiotic depletion by fossil fuels in MJ	471,84		1559,41
Acidification in kg SO_2 eq	0,14		0,701
Eutrophication in kg PO_4 eq	0,042		0,253
Freshwater aquatic ecotoxicity in kg 1,4-DB eq	7,85		47,140
Human toxicity in kg 1,4-DB eq	15,93		61,998
Marine aquatic ecotoxicity in kg 1,4-DB eq	18439,85		142804,12
Ozone layer depletion (ODP) in kg CFC-11 eq	5,2 E-05		6,E-05
Photochemical oxidation in kg C_2H_4 eq	0,014		0,132
Terrestrial ecotoxicity in kg 1,4-DB eq	0,060		0,972

After analyzing the main drivers of the impact categories, the ten processes from the entire life cycle that create the highest negative environmental impact were identified. They are shown in Table 9. Each process has a two-column value, where the left one corresponds to the hardwood case study and the right one to the MDF case study.

Table 8. Processes that negatively affect the impact categories the most on each case scenario.

Process	Antifoaming agent, silicone emulsion production		Dichloromethane production		Hardwood forestry, oak, sustainable forest management		Polydimethylsiloxane production		Toluene production		Transport, freight, light commercial vehicle		White spirit production		Urea-formaldehyde resin production		Wax production		Wood chips production, softwood, at sawmill	
Hardwood (HW) / MDF	HW	MDF	HW	MDF	HW	MDF	HW	MDF	HW	MDF	HW	MDF	HW	MDF	HW	MDF	HW	MDF	HW	MDF
Abiotic depletion	5,8,E-08	-	6,3,E-08	-	1,1 E-06	8,6 E-05	1,2 E-06	1,2 E-06	3,1,E-09	-	1,2 E-04	1,2 E-04	1,9 E-08	1,9 E-08	-	8,0 E-04	-	1,4 E-05	-	1,1 E-04
Abiotic depletion (fossil fuels)	-	-	-	-	6,2,E+00	4,6,E+02	3,2,E+00	3,2,E+00	-	-	4,6E+02	4,7,E+02	-		-		-		-	6,2 E+02
Acidification	-	-	-	-	2,0 E-03	1,6 E-01	2,0 E-03	2,4 E-03	-	-	1,4 E-01	1,4 E-01	-		-		-		-	4,0 E-01
Eutrophication	1,4,E-10	-	7,3,E-11	-	6,0 E-04	4,7 E-02	6,0 E-04	6,4 E-04	1,1,E-11	-	4,0 E-02	4,2 E-02	1,7,E-11	1,7,E-11	-	1,9 E-07	-	2,4 E-09	-	1,6 E-01
Fresh water aquatic ecotox.	7,4,E-11	-	3,3,E-11	-	1,1 E-01	8,6E+00	1,1 E-01	1,2 E-01	2,8,E-10	-	7,6,E+00	7,8,E+00	1,9,E-10	1,9,E-10	-	6,2 E-07	-	7,6 E-09	-	3,1 E+01
Global warming (GWP100a)	-	-	-	-	4,9 E-01	3,7,E+01	4,7 E-01	4,7 E-01	-	-	3,3,E+01	3,4,E+01	-		-		-		-	8,6 E+01
Human toxicity	2,8,E-05	-	2,0,E-05	-	1,5 E-01	1,1E+01	1,8 E-01	1,9 E-01	6,7,E-05	-	1,6,E+01	1,6,E+01	4,7,E-05	4,7,E-05	-	2,0 E-01	-	2,1 E-03	-	3,4 E+01
Marine aquatic ecotoxicity	8,0,E-02	-	5,0,E-02	-	2,0E+02	1,5,E+04	6,6,E+02	6,6,E+02	6,0,E-01	-	1,8E+04	1,8,E+04	4,2,E-01	4,2,E-01	-	1,1E+03	-	1,7E+01	-	1,1 E+05
Ozone layer depletion (ODP)	-	-	-	-	7,8 E-08	5,9 E-06	4,6 E-05	4,6 E-05	-	-	5,9 E-06	6,0 E-06	-		-		-		-	6,7 E-06
Photochemical oxidation	1,2,E-08	-	5,3,E-09	-	1,0 E-03	9,2 E-02	1,2 E-04	1,3 E-04	1,5,E-07	-	2,0 E-02	1,9 E-02	9,1,E-08	9,1,E-08	-	1,8 E-04	-	2,2 E-06	-	2,6 E-02
Terrestrial ecotoxicity	8,1,E-08	-	3,5,E-08	-	8,0 E-03	6,4 E-01	1,2 E-03	1,2 E-03	4,7,E-08	-	5,0 E-02	5,0 E-02	2,4,E-08	2,4,E-08	-	4,0 E-04	-	5,2 E-06	-	2,8 E-01

From the results, it can be seen that there are four impact categories affected by mainly three processes: Hardwood forestry, polydimethylsiloxane production (this is an upstream process involved during the module A3 Table Manufacturing Process, specifically a component of the sealant), and transport. They are described below as follows:

1. Abiotic depletion of fossil fuels: Here, the highest impact comes from transport in both cases, which is where the highest amount of fossil fuels are depleted.
2. Acidification: The highest impact comes from transport and hardwood forestry for both case studies.
3. Global warming: Same as the previous category, the highest impact comes from transport for the hardwood case and from hardwood forestry for the MDF case.
4. Ozone layer depletion: Here, the highest impact comes from polydimethylsiloxane production in both cases. The production of this chemical is an upstream process involved during the module A3 Table Manufacturing Process, specifically a component of the sealant.

Apart from the three processes mentioned previously, there are processes that only affect the impact categories of the hardwood case, these are:

A. Antifoaming agent, silicone emulsion production: This is an upstream process involved during the module A3 Table Manufacturing Process, specifically a component of the lacquer.
B. Dichloromethane production: This is an upstream process involved during the module A3 Table Manufacturing Process, specifically a component of the remover lack.
C. Toluene production: This is an upstream process involved during the module A3 Table Manufacturing Process, specifically a component of two input materials: thinner and lacquer.
D. White spirit: This is an upstream process involved during the module A3 Table Manufacturing Process, specifically a component of the paint.

As well, there are processes that only affect the impact categories of the MDF case, these are:

A. Urea-formaldehyde resin production: This is an upstream process involved during the module A1 Raw Material Extraction and Wood Product Production, specifically a component of three input materials: Urea-formaldehyde resin, Urea scavenger and Urea.
B. Wax production: This is an upstream process involved during the module A1 Raw Material Extraction and Wood Product Production, since wax is one of the input materials for processing the MDF.
C. Wood chips production, softwood, at sawmill: This is a process that makes part of the module A1 Raw Material Extraction and Wood Product Production.
D. White spirit: This is an upstream process involved during the module A3 Table Manufacturing Process, specifically a component of the paint.

Now that the processes are clear, their influence on the rest of the impact categories will be explained:

1. Abiotic depletion: For the hardwood case, the highest impact comes from transport, while for MDF comes from the urea-formaldehyde resin production.
2. Eutrophication: For the hardwood case, the highest impact comes from transport, while for MDF comes from the wood chips production, softwood, at sawmill.

3. Fresh water aquatic ecotoxicity: For the hardwood case, the highest impact comes from transport, while for MDF comes from the wood chips production, softwood, at sawmill.
4. Human toxicity: For the hardwood case, the highest impact comes from transport, while for MDF comes from the wood chips production, softwood, at sawmill.
5. Marine aquatic ecotoxicity: For the hardwood case, the highest impact comes from transport, while for MDF comes from the wood chips production, softwood, at sawmill.
6. Photochemical oxidation: For the hardwood case, the highest impact comes from transport, while for MDF comes from the hardwood forestry.
7. Terrestrial ecotoxicity: For the hardwood case, the highest impact comes from transport, while for MDF comes from the hardwood forestry.

In conclusion, for the hardwood case, the processes that affect the impact categories the most are the transport and the hardwood forestry. This is because the materials used are quite regenerative and the production processes are rather low impact. In comparison, the MDF case has a similar negative influence from transport and the hardwood forestry on the impact categories. Additionally, a higher negative impact from wood product production. This involves the input materials such as resin and wax, and the wood chips production and hardwood forestry.

To check the results obtained in the impact category related with CO2 emissions (Global warming), a second analysis was conducted. This confirms that transport and production in the MDF case. As well that is less in hardwood than in MDF. It depends heavily on what kind of electricity is coming from (energy mix). The traditional LCA tool did not highlight the importance of waste management, from which the higher CO2 emissions are coming from. Furtheremore, the manufacturing process has still a considerable impact. The following results per module could be obtained in Table 10.

Table 9. CO_2 emissions per energy source during the cradle-to-grave life cycle of a hardwood and MDF diner table.

Energy source	**Hardwood table CO_2 emissions (Kg)**		**MDF wood table CO2 emissions (Kg))**
Module A1: Production of wood product: oak timber and MDF plate, respectively.			
Electricity	6,71		15,74
Natural gas	0,69		4,34
Diesel oil	1,96		0,05
Propane	0,35		
Total CO_2 emissions	**9,71**		**20,138**
Module A2: Transport to the manufacturer			
Diesel oil	5,30		0,04
Module A3: Table manufacturing process			
Electricity	4,96		15,96
Natural gas	0,97		1,05
Diesel oil	0,94		0,18
Propane	1,07		
Total CO_2 emissions	**7,95**		**17,20**

Module A4: Transport to the shop/distributor			
Diesel oil	0,18		**0,46**
Module A4: Transport to the user			
Diesel oil	0,45		0,40
Module A5: Table installation process			
Electricity	0,11		0,11
Module C1: Table disassembly process			
Electricity	0,11		1,62
Module C2: Transport to waste processing			
Diesel oil	33,87		33,87
Module C4: Table disposal process			
Incineration	141,86		112,662
TOTAL CO_2 EMISSIONS	**217,20**		**222,29**

6. Environmental Cost Indicator (ECI).

After the impact analysis conducted in the chapter before, the next section assesses the cost associated to those negative impacts by unifying all environmental impact categories into a single score of environmental costs. The Environmental Cost Indicator (ECI) is a single-score indicator expressed in Euro. It is representing the environmental "shadow price" of a product or project. As a result, this indicator can be compared across industries and products.

In order to calculate the ECI, the environmental impacts are weighted based on the shadow price method. The shadow price is the highest cost level acceptable for governments per unit of emission control (prevention costs). The score on the basic environmental effects is multiplied by a conversion factor. The total of these results is added together and yields the ECI value/shadow price. These are the prevention costs that should be incurred to remedy the environmental damage.

The shadow price factors for each impact category are shown in Table 7 https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_7N54_Environmental_Prices_Handbook_2017_FINAL.pdf [8]. According to Trading Economics EU Carbon Permits [9], European carbon prices rose to around 87 EUR a tone. Another source from Routers [10] shows that the price for one ton of CO_2 reached the value of 90,75 EUR in December of 2021 and will reach 100 EUR in 2022. However, taking into account that this analysis is done in Switzerland specifically, Switzerland currently has one of the most expensive rates per ton of CO_2 in the world. The rate today in Switzerland is 96 CHF (90,91 EUR) per ton of CO_2. This is set to increase to 120 CHF (113,63 EUR) in 2022, the maximum foreseen by current legislation, as emissions have not yet dropped sufficiently [11].

Table 10. Shadow price factor for each impact category.

Impact category	Shadow price factor (EUR/unit)
Global warming in kg CO_2 eq	0,909
Abiotic depletion in kg Sb eq	0,16
Abiotic depletion by fossil fuels in MJ	5
Acidification in kg SO_2 eq	11
Eutrophication in kg PO_4 eq	11
Fresh water aquatic ecotoxicity in kg 1,4-DB eq	0,025
Human toxicity in kg 1,4-DB eq	50
Marine aquatic ecotoxicity in kg 1,4-DB eq	7
Ozone layer depletion (ODP) in kg CFC-11 eq	30
Photochemical oxidation in kg C_2H_4 eq	5
Terrestrial ecotoxicity in kg 1,4-DB eq	0,612

To the theme of abiotic resource depletion, including fossil fuels, some sources assume a shadow price of zero. The explanation given mentions that, in properly functioning markets, future scarcity will be reflected in prices and there will be no externalities.

Table 11. Environmental Cost Indicator ECI and the impact category result for each case study.

	Hardwood table case study			MDF table case study	
Impact category	Impact	ECI (EUR)		Impact	ECI (EUR)
Global warming in kg CO_2 eq	34,34	3,61		157,31	16,52
Abiotic depletion in kg Sb eq	1,2 E-04	2,0 E-05		0,001	2,0 E-04
Abiotic depletion by fossil fuels in MJ	Tbd[1]	Tbd[1]		Tbd[1]	Tbd[1]
Acidification in kg SO_2 eq	0,141	1,55		0,701	7,72
Eutrophication in kg PO_4 eq	0,042	0,46		0,253	2,78
Freshwater aquatic ecotoxicity in kg 1,4-DB eq	7,85	0,20		47,140	1,18
Human toxicity in kg 1,4-DB eq	15,93	796,72		61,998	3099,91
Marine aquatic ecotoxicity in kg 1,4-DB eq	Tbd[1]	Tbd[1]		Tbd[1]	Tbd[1]
Ozone layer depletion (ODP) in kg CFC-11 eq	5,2 E-05	2,0 E-03		6,E-05	2,0 E-03
Photochemical oxidation in kg C_2H_4 eq	0,014	0,07		0,132	0,66
Terrestrial ecotoxicity in kg 1,4-DB eq	0,060	0,04		0,972	0,59

- [1] Tbd: To be defined. Comparing the result with other studies, https://www.sciencedirect.com/science/article/pii/S2405844019357305 the result obtained by the software were not valid. However, the studies indicate that the output for MDF is worse than for hardwood due to the additional chemicals used.

7. Module description

7.1. Module A1, raw material extraction and processing

For this stage, the resources found include the forestry operation and the processing of the wood products for each case study: oak hardwood timber and MDF plates.

Hardwood case study

The raw material extraction and processing for this case study is the production of oak hardwood lumber. The study from the University of Wisconsin and the USDA Forest Products Laboratory was used as the key reference [12] [9].

Figure 2 shows a flow diagram of the hardwood lumber production process. It can be seen that the logs are an input, which in other words means that the forestry operation is not included in their analysis. However, a different resource is used to consider this part of the process [13]. It is important to mention that forestry operations vary regionally [14] but typically include some combination of growing seedlings, natural regeneration, site preparation, planting, thinning, fertilization (where applicable), and final harvest. Harvesting included felling, skidding, processing, and loading for both commercial thinning and final harvest operations.

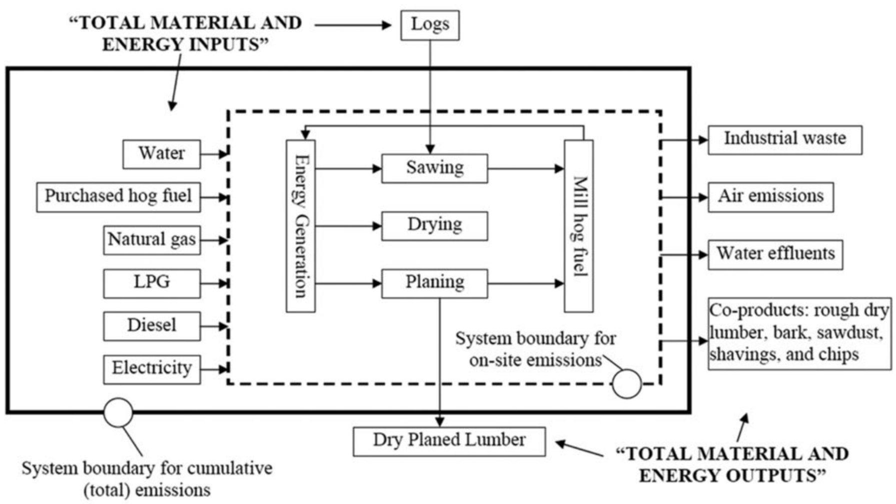

Figure 3. System boundaries and flow diagram for hardwood lumber production. Taken from [12]

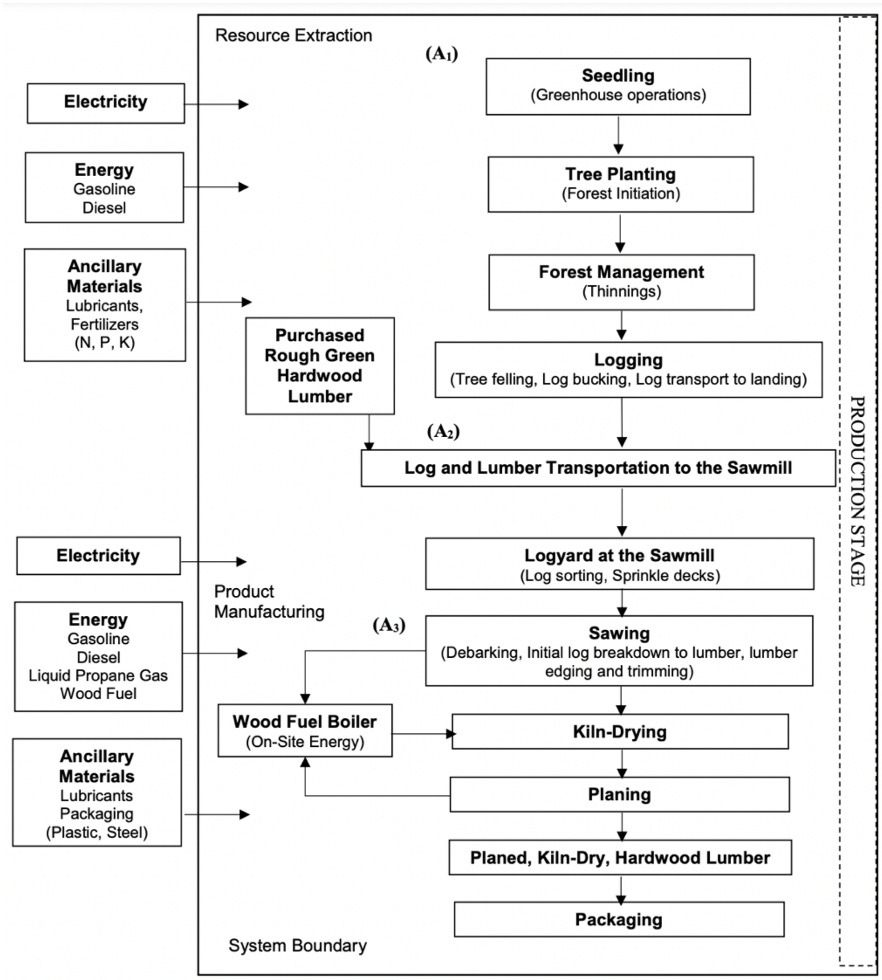

Figure 4. System boundaries and flow diagram for hardwood lumber production including forest operation. Taken from [13].

MDF Case study

The study from CERNE [15] was used as the core reference for the MDF case study. The main MDF raw material is wood chips [15]. In Europe, the wood used to produce MDF panels is mostly from waste wood (preconsumer, e.g., from forest operations and sawmills, and postconsumer). However, this study makes the assumption, that additional trees will be grown, managed and felled in order to take into account the necessary forestry operations and reflecting the vast amounts of woodchips produced in total.

Figure 2 shows a flow diagram of the MDF production process. For forestry operations (regeneration, thinning, and harvest), an additional source [16] was reviewed.

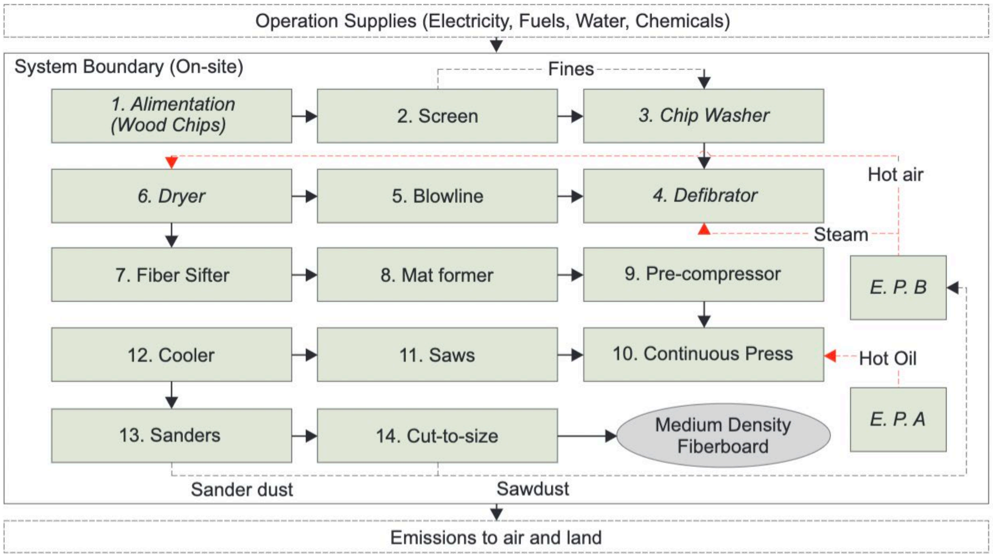

Figure 5. Flow diagram of MDF Manufacturing System. Taken from [15].

After forest management, the sawlog is debarked and chipped, that is, turned into small pieces (chips) of wood. The chips are washed and steamed, coated in paraffin wax, dried and ground to make the fibers. Resin is added, then the dried fibers are put onto a mat and pressed under a roller. The mats are cut to the right size, cooled and sanded. Then a top coating is added. Throughout the process, substandard materials are removed from the production line, though chips that are too large are re-chipped and used in a future MDF board. The red lines in the figure represent the flows of energy coming back to the process. It consists of two Thermal Plants. The first (E.P.A) is responsible for heating the hot oil used in the continuous press, where its fuel is natural gas. The E.P.A produces around 0.187 MWh of hot oil per m³ of MDF produced. The second (E.P.B) provides steam and hot air to the processor, where its main fuel is biomass (sawdust from the process and purchased from other plants) and occasionally it also uses natural gas as fuel. The E.P.B generates about 15 Gcal h^{-1} to hot air in dryer process and 10Gcal h^{-1} in steam to defibrator process.

7.2. Modules A2, A4 shop/distributor, A4 user, C2: Transport

Regarding material consumption, the input materials involved for these process are out of scope. In terms of energy consumption, the only energy source considered is diesel oil due to the fact that 96% of the float in Europe is powered with this fuel. The CO_2 emissions associated to the transport are calculated per unit. Hence, the pressed wood table emissions per unit are lower due to the fact that in one trip more tables are transported.

7.2.1. Assumptions

There are four different vehicle types regarding capacities, with the correspondent stage of the process and the number of table units, mentioned as follows:

Table 12. Transport assumptions per case study.

Process stage	Transport method capacity	Diesel per 100 km	Hardwood table units transported	MDF table units
Transport to the manufacture	Truck: load 20 t	40	194	308
Transport to the shop or distributor	Truck: load 6 t	25	58	92
Transport to the user	Truck: load 2 t	15	19	31
Transport to the waste collection point	Car	7	1	1

- It is assumed that the truck will be fully loaded for both case studies. However, it is important to mention that in reality, especially for the hardwood table distribution, it could tend to have less efficient capacity usage due to organizational factors such as: 1. The size of logistics and ordering company and 2. the lacking "bulk ordering", which takes into account that the final product is commonly "made to order", which could lead to, at least on the last miles, shipments with much less order volume than truck capacities would allow.
- The route for each case scenario was selected taking into account the market situation in Switzerland. This is the reason why the raw material in both case studies was taken from Poland, while the manufacturing processes were done for hardwood in Poland and for MDF in Switzerland. The end user in both cases is located in Switzerland, which is why the end of life is assumed to be there.
- For the module C2: End of life stage, the distance is assumed to be 20 Km, which corresponds to the distance within a metropolitan area, where the wood will be collected for incineration, recycling or other usage.
-

7.2.2. Transport routes

Hardwood case study

1. Selection of the raw material (sawlogs) suppliers: This transport stage is not taken into account since the used OpenLCA software automatically does the upstream process for the lumber transport.
2. Selection of the wood suppliers: The oak lumber is imported, it is selected a company near Lodz in Poland, located as shown in the Figure 3.
3. Selection of the table manufacturer: The selected manufacturer is located in Switzerland. The distance from b to c corresponds to 1064 Km.
4. Selection of the store/stock: The selected store is located near Zurich, Switzerland. The distance from c to d corresponds to 11 Km.
5. Selection of the customer location: Zurich, Switzerland. The distance from d to e corresponds to 9 Km.

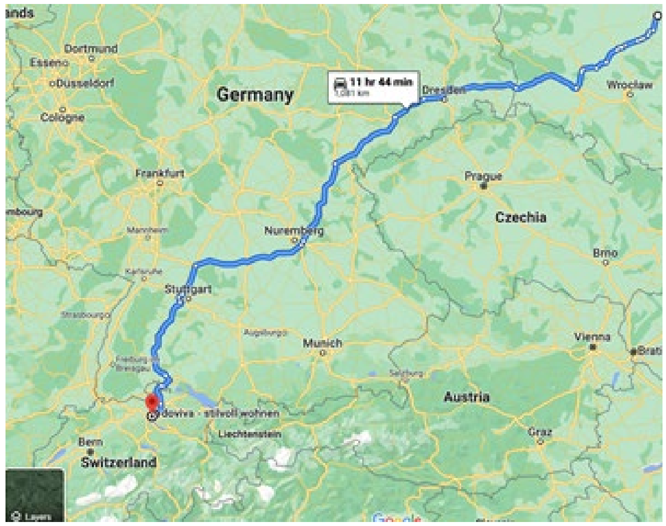

Figure 6. Route assumed for the hardwood case study

MDF case study

1. Selection of the raw material (wood chips) suppliers: This transport stage is not taken into account since the software automatically does the upstream process for the wood chips transport. However, in the case it must be given, the company selected is M*.
2. Selection of the wood product (MDF) suppliers: For the MDF, the company near Lodz in Poland, located as shown in Figure 4 was selected.
3. Selection of the table manufacturer: The company selected is a design and manufacture company near Warsaw. The distance from b to c corresponds to 341 Km.
4. Selection of the stock/logistics hub: It is located near Munich. The distance from c to d corresponds to 1088 Km.
5. Selection of the customer location: Locates in Zurich, Switzerland. The distance from d to e corresponds to 316 Km.

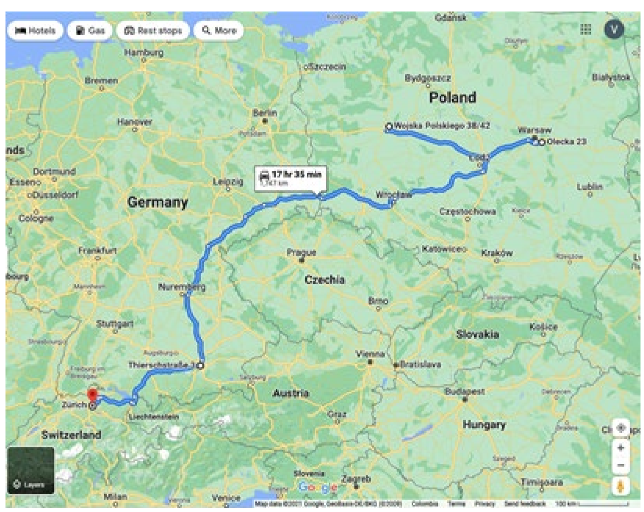

Figure 7. Route assumed for the MDF case study

7.2.3. Discussion

Based on the results shown in Table 3, if the wood is taken from Poland, the user will have a 80-120 MJ energy consumption for transport. On the other hand, if the wood is from Switzerland or the surroundings, it will represent between 40-60 MJ energy consumption for transport.

In an ideal case scenario (not considering stops etc., driving only most direct way and also assuming a full load), the fuel consumption would be about half a liter of diesel fuel per furniture piece.

The footprint depends on the production and supply chain management operations model. Having this in mind, the objective is to optimize both the load, stock management and shipment time.

7.2.4. Recommendations

- As a manufacturer, aim to create a bulk delivery system, which establishes periodic delivery dates based on the amount of furniture ordered.
- Implement a “collective route and load optimization for takebacks and waste management” for the users. This would reduce the emissions generated by traveling individually.
- Reorganize the supply chain locally by selecting the raw material and manufacturing in Switzerland.

7.3. Module A3: Table manufacturing process

In both case studies, it is assumed that the material for the structure is the same. For the dimensions, the apron is the same in both cases and the legs have different dimensions. Nevertheless, the main difference between the hardwood and the MDF manufacturing process is the tabletop.

7.4. Modules A5 and C1: table installation and disassembly process

For these stages it was assumed that the only process involving energy consumption to be done is the usage of power tools. Specifically, the use of a screwdriver in order to fix the fasteners or disassembly them, as it corresponds. There are other processes involved, such as the surface cleaning with a few drops of water, which have been excluded to the analysis due to their neglectable magnitude or user individual behavior..

7.5. Module B1: Usage stage

Both MDF and hardwood table’s surfaces generate emissions of Volatile Compounds VOCs during its lifetime. These emissions are coming from talc and zinc dust, components of the paint. There are different factors that influence the rate in which VOCs are emitted, such as the temperature, the humidity and the atmospheric pressure at the location.

The input material that produces the most emissions is the paint. According to a study done by the University of Texas [17], from the 10 chemicals with the maximum ratios of emissions to short-term (1-hour) effect screening levels (ESLs), two of them are compounds found in wood paint. These chemicals and its environmental impact are shown in Table 5. In health impacts terms, these chemicals are likely to be of most concern.

Table 13. Emissions of VOCs generated during the usage stage of the wood dining tables

Component	Maximum Emission VOCs Rate E (lb/hr)	Short- Term ESL (μg/m^3)
Talc	37,19	20
Zinc dust	91,88	50

If the hardwood was not painted as it was assumed in the case study, the VOCs associated to the talc and zinc dust would not apply. In that case, the hardwood tabletop should be oiled in order to maintain and keep the wood's moisture. Otherwise, it might get damaged.

If the tabletops were painted, they can be cleaned with water and soap. This means either there are more VOCs due to the paint or footprint due to the oil.

7.6. Module C4: Table disposal process

This stage contemplates the energy generation process typically accounted for the CO2 offset. In essence, furniture is transported from the residential buildings to the waste incineration plants, which can usually be found per urban area. There, electricity or energy for heating is generated through incinerating waste like furniture.

The authors want to mention that burning of (waste) materials for energy production does replace other inputs (e.g. fossil fuels) but should still be considered critically. After all, our planetary boundaries will not allow to simply burn things (like wood) in order to satisfy a potentially unlimited energy demand. There is no "magical energy production", which is not consuming any resources and would be free of any footprint.

8. Conclusions

There are mainly three elements identified that contribute to the footprint of wooden furniture: The production processes (including forest management and the table manufacturing), the transport and the disposal process.

- The production processes represent only 10-20% of the total emissions, which confirms that wooden furniture can be called sustainable in terms of materials compared to other type of furniture pieces made of metals or plastics.
- The manufacturing process impacts acidification, marine depletion and human toxicity due to the chemicals involved. However, the contribution in terms of CO_2 emissions is very low. Hence, the manufacturing processes of wooden furniture do not have a significant negative environmental impact.
- Transport is the second largest contributor of CO_2 emissions in the lifecycle of wooden furniture. It corresponds to 15-20% of total CO_2 emissions and strongly depends on the source of raw materials and the supply chain setup.
- The furniture offsets all of its CO2 emissions, especially its energy for production and waste management (50-65% of CO_2) by the energy recovery of waste incineration processes. So the remaining footprint comes largely from transport. Transport cannot offset itself. Its energy consumed for traveling distances is lost, has no direct utility and is not bound within the materials for later energy recovery. To make an example: If a piece of furniture travelled around the world, or stayed local during its creation and usage phase, does naturally not change the amount of energy recovered at incineration and usually does not significantly increase its utilization.
- On top of this, transport is the largest net contributor to the other negative impact categories harming ecosystems and human health. That's why transport, in the case of wood products, is an important factor and localization value chains makes a difference.

9. Future steps and recommendations

- Create specific use case and LCA that reflects the additional impacts of CIVAG's rental model. For this, the already established Life Cycle Inventory LCI for the Traditional study case be used and reassessed by the application of the circular business model of CIVAG. This means that the scope will broaden to a Cradle-to-Cradle analysis. This can be conducted by exchanging the waste stage with the refurbishment process for "closing the loop", or in other words, including the rental model.
- Create new case scenarios to optimize the process stages. For example, define at least two different locations for the raw material extraction and develop the LCA for each case scenario to define which option has the lowest impact.
- Taking into account the volatile and increasing fuel and electricity prices, and the interest in reducing fossil fuels consumption and other efficiency gains, it is recommended for the forest management and manufacturing companies to use alternative renewable energy

sources or production methods to reduce the CO_2 emissions from fossil fuels and get more sustainable.

- For the forest management and manufacturing processes, it is recommended to install emissions control systems, to meet PCWP MACT regulations.
- Apply Sustainable Forestry Management practices during the raw material extraction phase. Since this is an outsourced stage, aim to contract companies that treat the trees in a way that is “socially just, ecologically sound and economically viable” according to PEFC [18]. This includes practices such as making sure the forest has enough seedlings to regenerate, choosing which trees to harvest and which to leave to keep the forest healthy, monitoring the flow of water, respecting the rights of local people to access the forest according to their traditions and economic needs, as well as protecting the forest as an ecosystem, including animals and other plants.
- Use a sealant without polydimethylsiloxane since it has a high impact on Abiotic depletion of fossil fuels, Acidification, Global warming and Ozone layer depletion for both hardwood and MDF case studies.
- Focus on locally produced wood products and on local manufacture companies. This reduces the impact generated by transport significantly.
- Choose hardwood furniture instead of MDF. Wood furniture is not only more sustainable but also more durable than MDF.
- Prolong and intensify the usage of furniture and later find the most valuable re-usage in order to reach the incineration grave as late as possible. Hence alternative measures or functional units need to be in the center of analysis. E.g., Footprint per usage unit. If that is not changed, nothing changes to the LCA result as time or usage are not considered.
- In addition to closing the technical cycle, opt for materials that are biologically degradable and by design physically separable from the non-degredable parts.
- Further analyze willingness to pay and decision making processes regarding more regenerative and pre-used products. Both, of privately and professionally marketed business models.

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11. References materials for LCA

Material	Reference source
Hardwood wood product content	https://jssae.journals.ekb.eg/article_57711_95675cea3d67abb59643a500f3fadb80.pdf
MDF wood product content	https://www.researchgate.net/publication/305693872_ecoPROSYS_An_Eco-efficiency_Framework_Applied_to_a_Medium_Density_Fiberboard_Finishing_Line/figures?lo=1 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.422.4345&rep=rep1&type=pdf
MDF chemical content	https://www.researchgate.net/publication/272880166_Effect_of_Refining_Parameters_on_Medium_Density_Fibreboard_MDF_Properties_from_Oil_Palm_Trunk
Fasteners (screws)	https://woodworkingformeremortals.com/types-screws-use-woodworking-basics/ https://www.amazon.com/GRK-772691020697-Number-8-4-Inch-100-Piece/dp/B001PCZ7GO
Benzyl alcohol	https://calculator-converter.com/milliliters-to-kilograms.htm
Thinner composition	https://www.woodworkingnetwork.com/best-practices-guide/sanding-and-finishing/what-chemicals-are-your-lacquer-thinner
Sealant	https://www.google.com/search?q=sealant+composition&tbm=isch&ved=2ahUKEwj49I_wmujzAhUqSN8KHZ1oBzUQ2-cCegQIABAA&oq=sealant+composition&gs_lcp=CgNpbWcQAzIGCAAQBRAeMgQIABAYOgUIABCABDoGCAAQBxAeOgYIABAIEB46BAgAEEM6CAgAEAgQBxAeUOWcHliDpx5gsKkeaABwAHgAgAFyiA H9B5IBAzMuN5gBAKABAaoBC2d3cy13aXotaW1nwAEB&sclient=img&ei=SgZ4YfinNaqQ_Qad0Z2oAw#imgrc=jbWos4nyUr7_SM
Aluminum oxide	https://www.google.com/search?q=aluminum+hydroxide+percent+composition&source=lnms&tbm=isch&sa=X&ved=2ahUKEwjcvL75soH0AhXiVTABHb1jBFYQ_AUoAXoECAEQAw&biw=1440&bih=789&dpr=2#imgrc=fjn5msUgdY02DM
Ethyl silicate:	https://www.chemicalbook.com/ChemicalProductProperty_EN_CB9924316.htm
Anhydrous ethanol	https://www.sciencedirect.com/science/article/abs/pii/S1364032110000705
Paint remover or stripper composition	https://patents.google.com/patent/US4269724A/en
Glue composition	https://patents.google.com/patent/US5091458A/en
Paint composition	https://www.researchgate.net/publication/322766291_Zeolites_as_reservoirs_for_CeIII_as_passivating_ions_in_anticorrosion_paints/figures?lo=1
Lacquer composition	https://patents.google.com/patent/EP0061348A1/en