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Sustainability analysis of Martela's upcoming Sola chairs

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Abstract

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In this thesis, three approaches to quantify products’ sustainability are used and compared. The sustainability evaluation methods are limited to the ones that were available to the author at the time. Products compared are six variations of chairs from Martela’s Sola product family. Software used is The Footprinter for the carbon footprint study, Nativalab’s Ouro for the sustainability life cycle assessment, and GreenDelta’s openLCA for the life cycle impact assessment. Commercial licenses for The Footrpinter and Ouro were provided by The Natural Interest, and openLCA is an open-source application. ELCD database was used as the main source of life cycle inventory data, and impact methods used were CML baseline and ILCD 2011.

The carbon footprint study of the products revealed that the chair model with the least amount of steel had the lowest emission equivalent while the model with the most amount of steel had the highest. The SLCA study highlighted the weak areas sustainability-wise in the production chain, and the LCIA study concluded that the ELCD database is not sufficient for a thorough LCA study.

Keywords	LCIA, SLCA, carbon footprint, sustainability, impact

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Abbreviations

CFP	Carbon footprint
CO_2eq	Carbon dioxide equivalent
ELCD	European Reference Life Cycle Database
EOL	End of life
FSSD	Framework for Strategic Sustainable Development
GHG	Greenhouse gas
GWP	Global warming potential
ILCD	International Reference Life Cycle Data System
JRC	Joint Research Center
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
SLCA	Sustainability life cycle assessment
TNI	The Natural Interest
TNS	The Natural Step

1 Introduction

The Merriam-Webster dictionary defines the word "sustainable" as something "capable of being sustained" and "of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged". Sustainable development, in turn, is defined as development that meets present needs without undermining future generations' ability to reach their needs. In the recent years, sustainability development has been increasingly spreading around the globe. New legislation forces companies to implement sustainable solutions, which has given rise to firms that specialize in just that, sustainable solutions.

This thesis was done at The Natural Interest, which is a company that offers sustainability expertise and training to local enterprises. Originally, the project only involved the carbon footprinting portion of this study, however, due to availability of resources, it was decided to conduct two additional studies and evaluate different sustainability assessment methods. [1]

Martela is a Finnish office furniture company that specializes in creating solutions that inspire people. Employing over 700 professionals and boasting a turnover of 136 million euro in the year 2014, Martela is the largest furniture company in Finland, as well as one of the three largest companies in the sector within Nordic countries. With the vision of "Creating the best workplaces", Martela offers its customers a variety of services, most notable of which are ready-made solutions such as chairs, tables, space dividers, and storage units. Full list of existing services includes customized interior design and layout planning, furniture rental and recycling, delivery, assembly, and many more. Production facilities are located in Finland, Sweden, and Poland, while the main markets are situated in the Baltic Sea region, Norway, Hungary, Ukraine, the Netherlands, and even Japan. [2]

Sola is a family of universal chairs created by the designer Antti Kotilainen. Available in an assortment of configurations to perfectly suit each customer's taste, Sola chairs fit well in all sorts of environments. Some of the designs can be seen in Figure 1.

Figure 1: Sola chairs

This project concentrated on six configurations: 378AC, 377PC, 378DC, 377RGC, 377DEKMC, and 377PEKMC. Table 1 gives the descriptions and visuals for the products. [3]

Table 1: Sola chair configurations

Model	Description	Visual representation
378AC	four-leg chromed base, upholstered seat, armrests	

377PC	four-leg ash wood base, upholstered seat, no armrests	
378DC	chromed sled base, upholstered seat, armrests	
377RGC	four leg base with chromes castors, up-holstered seat, no armrests	

377DEKMC	high chromed sled base, upholstered seat, stackable	
377PEKMC	high ash base, uphol-stered seat, non-stackable	

2 Goals

The goal of this study was to evaluate and compare sustainability of six chair models using different approaches to sustainability assessment. Additional objective was to identify parts of the production process tree that are most damaging to the environment.

Two distinct research methods were used in this thesis – quantitative (CFP and LCIA) and qualitative (SLCA). Quantitative methods deal with numbers, while qualitative methods use qualities, descriptions and observations. Qualitative assessment methods are subject to the author's expertise and awareness, as well as subjective opinions. Quantitative methods, on the other hand, are repeatable and will produce identical results if input values are unchanged. Due to this, quantitative methods are generally more reliable for progress tracking, whereas qualitative methods should be used to assess current state of the system.

Limitations as well as assumptions for each study are discussed in further detail in their respective chapters. General assumption was that the products would have 30 years of useful lifespan, after which they would be disposed of locally.

3 System boundaries

Boundaries set out in this chapter are applicable to the CFP and LCIA studies, and boundaries for the SLCA study are specified in Chapter 5: SLCA.

Inventory analysis was performed to obtain knowledge about the products' life cycles, and then the process diagram sketched (Figure 2).

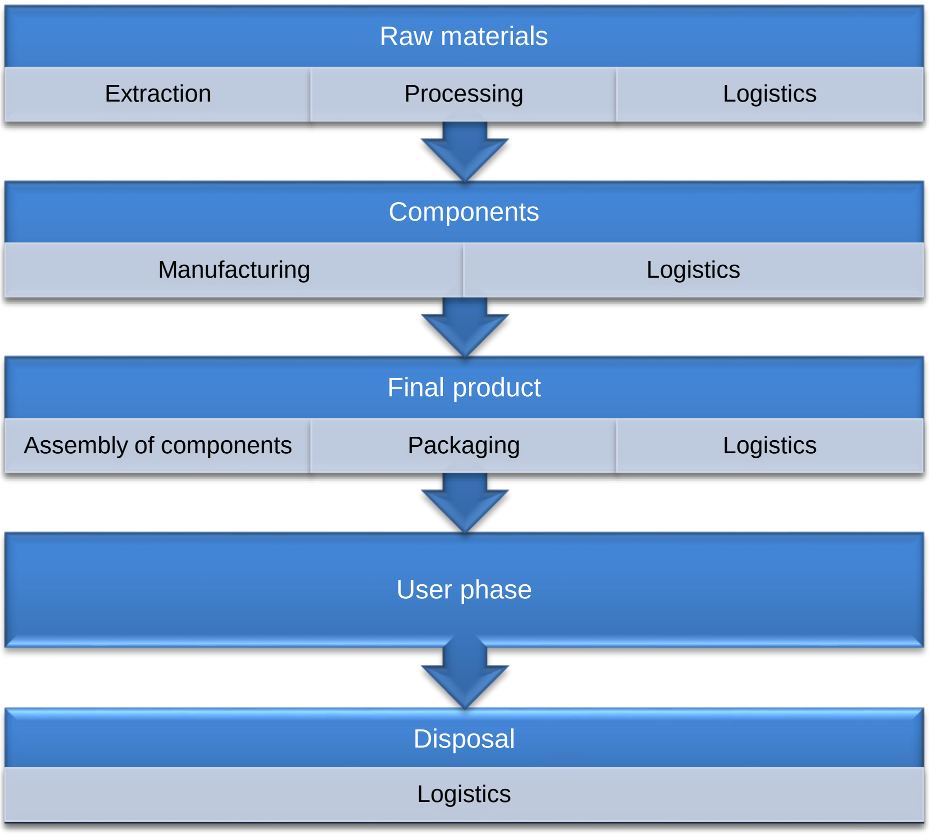

Figure 2: Process diagram

As illustrated in Figure 2, products' life cycles begin with the production of raw materials, which are then made into individual components, the components are then assembled to create finished products, which are then delivered to the points of sale and then to the customers, and after the products' lifespan has ended, disposed of. It is notable that the logistic sub-phase is involved in all life cycle phases but the user phase.

3.1 Raw materials

In this phase, raw materials are extracted from earth, processed to create materials, and then delivered to the component producers.

3.2 Components

In this phase, materials are shaped and formed to create components for the final product assembly. These components are produced in counties across Europe, including domestic production in Finland and outside production in Estonia, Sweden, Latvia, and Germany. Unfortunately, emissions from manufacturing of components were not included in the calculations due to absence of data from component manufacturer companies. This phase also includes delivery to the assembly factory located in Nummela. Logistics in this phase are transport over sea and rail transport, as well as road transport using large delivery trucks.

Component materials

In order to analyze the composition of products, individual component materials were weighed and the results logged (shown in Table 2 below).

Table 2: Weight composition by material, in kg

Component	378AC	377PC	378DC	377RGC	377DEKMC	377PEKMC
Metal	3.15	1.63	4.2	8.69	5	2.87
Fabric	0.078	0.058	0.078	0.058	0.058	0.058
Plastic	0.184	0.098	0.184	0.694	0.154	0.098
Wood	2.9	3.76	2.9	2.9	2.1	3.35
Total weight	6.312	5.546	7.362	12.342	7.312	6.376

The amounts and types of materials vary among the models. Materials used include steel and aluminum alloys, ash and oak woods, plywood, veneer, polyurethanes, polypropylenes, acrylonitrile butadiene styrenes (ABS), and polyamides.

3.3 Production

Final assembly of finished products is completed at the Nummela factory in southern Finland. Emissions from the Nummela factory can be divided into further categories associated with site operations: waste, energy, packaging, and logistics.

3.3.1 Waste

Emissions from waste are calculated on a yearly basis. Waste is sorted and the weight of individual fractions is tracked. To calculate total yearly emissions from a single waste fraction, the weight is multiplied by the respective emission factors. Waste categories involved are cardboard, wood waste, and energy waste. Emissions from all waste categories are summed, and then divided by the total number of products produced during the year, thus approximating emissions from waste for a single manufactured product. With this approach of using averages, product size is not taken into account, and thus smaller sized products will have slightly inflated emission values, while larger products will experience the opposite.

3.3.2 Energy

Energy-associated emissions are calculated in a similar fashion to the waste emissions - total emissions from energy use are divided by the number of products manufactured in the year to generate the single product emission value.

Electricity

Electricity is purchased directly from the supplier company. Total electricity consumption in kWh is multiplied with the emission factor to calculate total emissions for the year.

Heating

Heating consists of two parts - on-site energy from biofuels, and purchased district heating. On-site biofuels used are light and heavy fuel oils. District heating is supplied by the local energy supplier.

3.3.3 Packaging

Emissions from packaging are calculated similar to emissions from waste and energy. Total yearly emissions from packaging materials are divided by the number of total produced items in the year to calculate per item emissions. Packaging materials included are plastics, metals, and cardboard.

3.4 User phase

User phase constitutes the time period between the purchase of the product at the point of sale (or after the delivery of the product if purchased online) and the end of useful lifetime of the chair. During this phase, no emissions are released into the environment, as the sole function of a chair is to provide seating. Cases in which product’s life was ended prematurely before the assumed date due to loss of functionality (broken leg or base) were not considered.

3.5 EOL disposal

End-of-life disposal varies depending on the model's component materials. At the end of the product's life, it is disassembled into individual pieces, which are then further sorted by their origin. Three scenarios describing the disposal possibilities were introduced. Due to time constraints of this project, not all of the scenarios were evaluated for each study – best practice Scenario 1 was used for CFP, Scenario 2 was considered in SLCA, and Scenario 3 was the method of choice in LCIA.

Scenario 1: best practice

In this scenario, all reusable components are reused to the maximal potential, recyclable components are recycled, and the non-recyclable components are disposed of in a manner that minimizes environmental damage.

Scenario 2: no recycling

In this scenario, reusable components are reused, however, no recycling is considered in this scenario.

Scenario 3: worst case

Worst possible case was also considered a possibility. Here, the goal is to create a scenario in which environmental damage is maximized. This is achieved by landfilling of the materials instead of reusing or recycling.

3.6 Logistics

Emissions from logistics are created with the import of components to Nummela, then export of finished products from Nummela to points of sale, and finally the distance between owner's home and the disposal site. Emission factors are taken from VTT's LIPASTO database. Default unit of transportation is ton-kilometer, or the distance that a ton of freight travels.

Inbound

Since the components are purchased from a number of manufacturers from foreign countries, a difference in traveling distances between materials is introduced. Due to the sensitive nature of such information, the manufacturer companies and distances covered from the components' countries of origin to Nummela are omitted from the report.

There are three primary means of transport for the materials, namely transportation on rail, land, and sea. Transportation on land is done with large delivery lorries with load capacity of 9 tons and gross mass of 15 tons. Rail transportation is assumed to be done with the help of container train carriages, while multi-purpose general cargo ships are used for transport of goods over sea. Emission factors for respective means of transport are presented in Tables 3-5.

Table 3: Delivery lorry emissions

Gas	Highway		Urban		Delivery	
g/tkm	50% load	full load	50% load	full load	50% load	full load
CO	0.063	0.033	0.2	0.1	0.16	0.08
HC	0.042	0.019	0.15	0.07	0.12	0.06
NO_x	0.7	0.39	0.8	0.49	0.77	0.46
PM	0.016	0.009	0.04	0.02	0.033	0.017
CH_4	0.0016	0.0008	0.0045	0.0027	0.0037	0.0022
N_20	0.0073	0.0039	0.0073	0.0043	0.0073	0.0041
NH_3	0.0011	0.00056	0.0011	0.00056	0.0011	0.00056
SO_2	0.00075	0.00041	0.00087	0.00052	0.00083	0.00049
CO_2	110.6	60.9	128	76	122	72
CO_2eq	112.9	62.1	130	78	125	73

Table 4: Container train emissions

Gas	g/tkm
CO	0.0044
HC	0.00045
NO_x	0.01
PM	0.0012
CH_4	0.00022
N_20	0.0002
NH_3	0
SO_2	0.0076
CO_2	6.7
CO_2eq	6.8

Table 5: Cargo ship emissions

Gas	g/tkm
CO	0.023
HC	0.0048
NO_x	0.62
PM_{10}	0.013
$PM_{2,5}$	0.01
CH_4	0.0022
N_2O	0.00076
SO_2	0.23
CO_2	27
CO2 eq.	27

Outbound

In addition to the import logistics, final products also travel inside Finland from the factory to warehouses, and then to customers.

4 Carbon footprint

Carbon footprint (CFP) is defined as the sum of all greenhouse gases associated with a product, a process, or a service. Typically, carbon footprints are calculated as the total amount of carbon dioxide equivalent (CO_2eq.) emissions. In order to convert emissions from greenhouse gases to CO_2eq., the global warming potential (GWP) scale is used. GWP is the amount of energy a gas absorbs in a given period of time in comparison to carbon dioxide. Generally, the time period is taken to be twenty, one hundred, or five hundred years, and the values are denoted as GWP_{20}, GWP_{100}, and GWP_{500} respectively. Some of the GWP_{100} values for the more common GHG are presented in Table 6. As can be seen, carbon dioxide has a GWP of 1, while nitrous oxide has a GWP of 298, indicating that a unit amount of nitrous oxide contributes 298 times as much as a unit amount of carbon dioxide. More complex compounds that remain in the atmosphere for longer periods of time trap significantly higher amounts of heat than CO_2, and thus their global warming potentials are in tens of thousands.

Table 6: Global warming potential of GHG [4]

Greenhouse Gas	Formula	100-year GWP
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Sulphur hexafluoride	SF_6	22800
Hydrofluorocarbon-23	CHF_3	14800
Hydrofluorocarbon-32	CH_2F_2	675
Perfluoromethane	CF_4	7390
Perfluoroethane	C_2F_6	12200
Perfluoropropane	C_3F_8	8830
Perfluorobutane	C_4F_{10}	8860
Perfluorocyclobutane	$c\text{-}C_4F_8$	10300
Perfluoropentane	C_5F_{12}	13300
Perfluorohexane	C_6F_{14}	9300

A number of carbon footprint calculators are available on the internet for users to estimate their emissions. However, majority of the calculators do not support user-input data, and thus are limited to values that are present in the database. In this thesis, the Footprinter website was chosen as the tool for the task due to its simple design and the ability to create customized databases with imported values for emission factors.

The study began with the search for emission factors. Countless emission factors of various quality are abundantly available online. Publicly-funded research organizations often publish emission factors used in their research, and the bulk of emission factors used in this study were gathered from such sources. The rest of factors were collected through high-quality sources or, if data was unavailable free of charge, purchased. In carbon footpriting, emission factors are the most important pieces, and hence why it is vital to select only the most appropriate data sources.

Emission factors used in this thesis are almost entirely comprised of Finnish sources, and global emission factors were used if the Finnish values were unavailable.

After all the required emission factors were gathered, they were then imported to the Footprinter.

4.1 Methodology

The Footprinter allows for effortless calculation of products' footprints within the internet browser, thus making it accessible from any modern device that supports viewing of web pages. With the emission factors previously imported, the product components were then added. The component categories used included materials, energy, packaging, logistics and waste, as earlier discussed in Chapter 3: Inventory. Carbon footprints were then calculated automatically, the Footprinter also makes it possible to create graphs for enhanced visual comparisons of product footprints.

4.2 Results

Table 7 presents the results of Sola footprints, and Figure 4 compares the scores graphically.

Table 7: Results of Sola footprints, in kg CO_2eq

	378AC	377PC	378DC	377RGC	377DEKMC	377PEKMC
Energy	1.46	1.46	1.46	1.46	1.46	1.46
Fabric	0.52	0.38	0.52	0.38	0.38	0.38
Metals	2.36	1.22	3.14	10.60	3.74	2.15
Packaging	0.06	0.06	0.06	0.06	0.06	0.06
Plastics	0.64	0.32	0.64	2.50	0.53	0.32
Product logistics	0.08	0.07	0.10	0.16	0.10	0.08
Waste	0.87	0.87	0.87	0.87	0.87	0.87
Wood	1.79	2.15	1.79	1.79	1.30	1.82
Grand Total	7.77	6.54	8.57	17.83	8.43	7.15

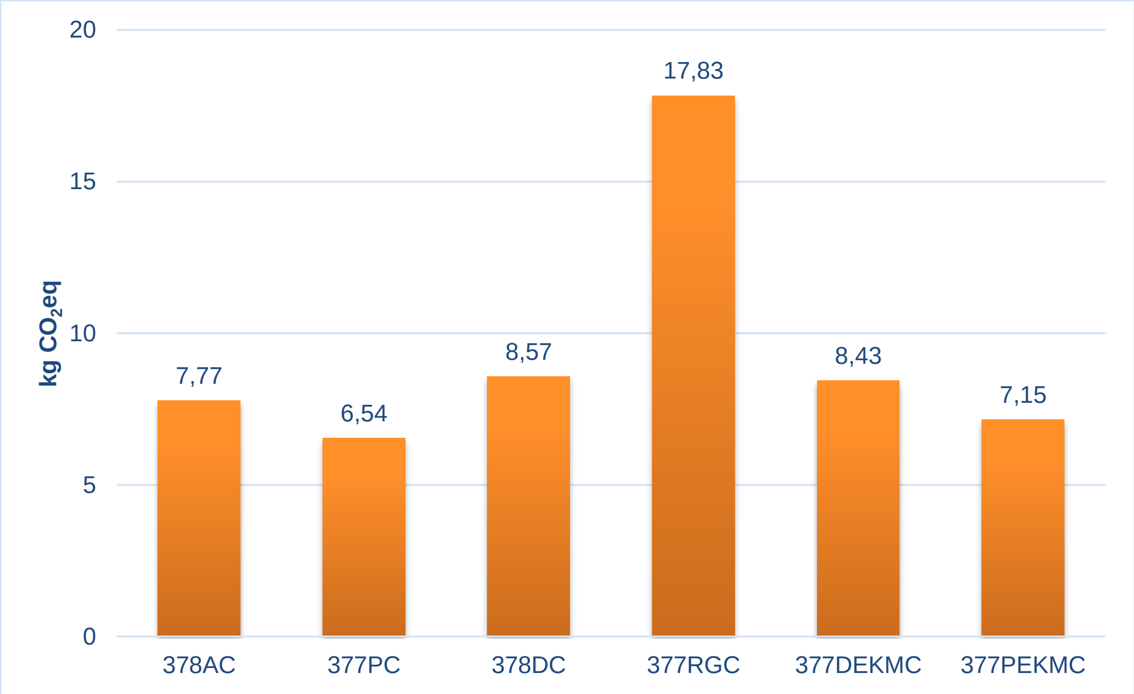

Figure 3: Comparison of Sola footprints

Graphs with phase contributions for each product are presented in Appendices 1-6, and are rearranged in descending order in Appendix 7.

4.3 Discussion

With the help of the visual results, it is evident that the biggest contributor to the total footprint in all products but Sola 377PC is the metal components. Sola 377PC has its largest contributor in the wooden components, shortly followed by the energy consumption and metal components. Together, wood and metal components account for more than half of products' emissions, and thus it can be concluded that the best way to improve the sustainability is to use less materials. Obviously, the amount of materials used for the production is dictated by the design, and extreme changes to the design are not possible. Besides the raw materials, energy requirements and waste production at the Nummela factory seem to both have significant effects on the overall emissions. Hence, by optimizing operation at the assembly factory, the carbon footprint analysis will swing more towards sustainability. Operation optimization could be achieved by increasing the use of renewable energy while limiting fossil fuels in energy generation.

5 SLCA

5.1 Methodology

Sustainability life cycle assessment (SLCA) refers to the qualitative method of evaluating a product's environmental performance. SLCA was developed by The Natural Step group (TNS), and the basis for SLCA is the Framework for Strategic Sustainable development (FSSD), also created by TNS. FSSD was formed in close collaboration with the private and public sectors, as well as the scientific community. At the heart of FSSD lay the four sustainability principles, which can be seen in Figure 5.

Figure 4: Four sustainability principles (The Natural Step, 2011)

The four sustainability principles can be applied to any activity, at any scale, and, according to the framework, when the four system conditions are met by abiding to the aforementioned principles, the system becomes sustainable.

FSSD pays special attention to preventative methods by introducing the ABCD planning method:

- Awareness and defining success
- Baseline, or current state
- Creative solutions
- Decide on priorities

In addition to the ABCD method, FSSD presents the “Backcasting” management strategy. Backcasting is a concept in which the user visualizes the future success, and then thinks of ways to arrive at the desired outcome. The ABCD planning method is also made use of in backcasting.

A typical SLCA study consists of ten steps:

1. Setting goal and scope
2. Creating a shared definition of the sustainable product system
3. Define the system boundaries and life cycle scenario for the sustainability assessment
4. Conduct an inventory analysis of the life cycle
5. Sustainability assessment – Use the sustainability principles to assess sustainability strengths and weaknesses

6. Analysis & synthesis of results – Identifying key impact areas
7. Brainstorm possible solutions
8. Prioritize solutions
9. Create an innovation roadmap
10. Measure and report progress (ongoing) [5,6]

Figure 6 shows possible solutions, as stated in step 7.

How could we overcome the identified challenges connected to Sustainability Principle...?	Brainstormed actions might include...				
	Raw materials	Production	Packaging & distribution	Use	End of life
1 (materials from the earth's crust)	...utilizing recycled or reclaimed materials as raw feedstock, thus reducing the need for extraction of oil from the ground	...a reduction in the overall carbon emissions associated with product production.	...switching to bio-based packaging alternatives that are sustainably sourced.	...a product that enables less fossil fuel sourced energy to be used in application e.g less hair dryer time	...a product design that allows for easy product disassembly, reuse of components and recycling.
2 (substances produced by society)	...sourcing of organic ingredients.	...use of green chemistry concepts in production processes.	...biodegradable packaging.	...developing a solution that eliminates the need for maintenance and cleaning chemicals.	...selecting materials to ensure that the product is biodegradable at end of life.
3 (physical degradation of nature)	...sourcing initiatives that avoid over extraction or preserve biodiversity.	...a reduction in the amount of water needed in production processes.	...a reduction in overall packaging and hence a reduction in overall resource consumption.	...a shift to an ICT-solution which eliminates the need for consumables (in the form of paper)	...ensuring that no product or packaging goes to landfill.
4 (barriers to meeting human needs)	...fair and community trade initiatives and support for traditional livelihoods.	...a breakthrough that ensures health and safety risks for workers are reduced.	...safe packaging and distribution that is far quieter, and hence less impactful, to local neighborhoods.	...a specific product application that is safer to use or addresses health concerns (non-allergenic etc.)	...a built-in maintenance service that creates jobs and lengthens the product's lifespan.

Figure 5: Sustainable solutions, (The Natural Step, 2011)

For the purpose of this thesis work, the SLCA study was conducted using Nativalab's Ouro tool. Ouro allows for cooperation between actors from the entire supply chain mechanism of a product. [7]

In order to compare the SLCA results for different models, a separate SLCA study was performed for each product.

SLCA studies assess products' sustainability as defined in the four principles, and during the whole life cycle. Products' life cycle is further divided into five phases:

1. Raw materials phase
2. Production phase
3. Packaging and distribution
4. Use phase
5. EOL disposal phase

The SLCA questionnaire is designed in such a fashion that is easiest for the user to answer. Four answer possibilities are given:

1. "Yes", which adds a point towards sustainability of the product
2. "No", which does not gain the product a point
3. "Do not know", which is similar to "No"
4. "Not applicable", which does not give a sustainability point but is also not accounted for in the total score

After completing the questionnaire, a color-coded matrix is generated. Products' phases and respective sustainability principles are assigned a number ranging from one to seven, with one meaning "severely unsustainable" and seven "sustainable". Similarly, color coding is used, with red being the least sustainable and bright green the most sustainable.

The data required in order to complete the questionnaire was gathered from Martela's environmental and corporate responsibility reports that are available on the company's website, and, in situation where some of the answers were still uncertain, company representatives were contacted. [8,9,10]

5.2 Results

After performing the SLCA studies for six variations of the chairs, it was determined that all six models shared the same score. This can be attributed to the fact that SLCA is a qualitative method, and consequently, the amounts of materials used are not imperative. Chapter 3: Inventory unveiled that among the six models, the amount of different materials used is the primary variance, while the rest of inventory is practically identical. The score is shown in Figure 7.

	Raw materials	Production	Packaging, distribution, retail	Use and maintenance	End of Life
	3	5	2	6	3
	3	5	3	6	3
	2	5	2	6	3
	6	7	6	7	7

Figure 6: SLCA results

5.3 Discussion

The SLCA results seem to show substantial potential for improvement of sustainability, in particular the packaging and distribution phase, as well as the raw materials and end-of-life phases. The highest scores are the entire use and maintenance phase (maximum score) and the fourth sustainability principle (human needs). Understandably, due to their nature, chair do not cause emissions during use and maintenance. Human needs are regulated by the European legislation and the standards, which also explains the high scores.

6 Life cycle impact assessment

LCA is, perhaps, the most thorough sustainability assessment tool currently available. According to ISO 14040:2006, a typical complete life cycle impact assessment study consists of four separate phases:

1. Goal and scope
2. LCI
3. LCIA
4. Sensitivity analysis

In Goal and scope, the study objectives, system boundaries and limitations are stated. LCI compiles together all inputs and outputs from the system. To carry out the impact assessment, an impact assessment method is selected and then applied. Impact assessment typically is divided into four subcategories: classification, characterization, normalization, and weighting. In classification, the inventory table is reorganized to include grouping of the inputs and outputs into categories, such as raw materials, emissions to air, water, soil, and similar. Following, the table is further aggregated under impact categories that are fully subjective to the author. There are no official ISO standards for these impact categories, although they typically are comprised of the most central environmental problems such as global warming, resource depletion, ecotoxicity, ozone depletion, eutrophication and acidification. In characterization, the relative impact strength of inflows and outflows is assessed using the equivalence factors. Equivalence factors measure the relative contribution to the impact in relation to a reference point, which varies among the impact categories. Normalization and weighting are optional procedures for LCA and can be omitted in rare cases. In normalization, normalized effect scores are calculated. A normalized effect score is the percentage share of the product's contribution to the annual impacts in the area. Weighting allows for improved comparison of the impacts between each other to further determine the relative importance of those effects by creating a single score that establishes environmental performance. Lastly, following the impact assessment, sensitivity analysis is performed to ensure repeatability of the results and evaluate the uncertainties.

It is possible to conduct an LCIA study manually, however, it is extremely time-consuming, and thus this thesis was done with the help of LCA software. The software in question is GreenDelta's openLCA, which is available across all major platforms, including Windows, Mac OS, and Linux. [11]

6.1 Methodology

The purpose of this study was to compare the ecological impacts of six models of chairs from the Sola line of Martela's chairs. Products in question are described in detail in Chapter 1.2.1: Sola. The basis for comparison, or the functional unit, is defined as thirty years of seating accommodation. System boundaries are defined in Chapter 3: System boundaries.

Life cycle inventory, as well as life cycle impact assessment and sensitivity analysis are all conducted within the environment of the openLCA application.

Upon initial launch of the program, the user is presented to the welcome screen, where relevant links to LCI databases, manuals and openLCA case studies are available through the openLCA nexus portal. On the openLCA nexus portal, it is possible to download free LCA data sets or to purchase more comprehensive sets, should such a need arise. After the download, the user then imports the database to openLCA, and the data is ready for use. With the life cycle inventory data loaded into the program, the only thing missing is the impact assessment methods, which can be downloaded from the nexus portal as well.

For the purposes of this study, the ELCD database was used as the main source of LCI data, while the impact assessment methods of choice were CML baseline and ILCD 2011, which are both contained in the openLCA 1.4 LCIA method pack. Both the ELCD database and the LCIA methods pack are available free of charge through the openLCA nexus portal. [12]

OpenLCA divides the data into layers. At the bottom are “Flows”, which are streams of substances. A level above the flows are processes, which are then connected together to create product systems. Product systems are used to model case studies. [13]

There are two options for modelling case studies in openLCA. In case of smaller scale, or less complicated studies, it is possible to simply create a single process, which combines all the inputs of the system throughout its lifetime. In case of more complicated studies, the production chain is divided into separate processes, which are then linked together through a product system. [14]

This LCA study consists of eight distinct phases, and thus the latter option for modelling was used. The phases were named accordingly:

- *Fabric components*
- *Metal components*
- *Plastic components*
- *Wood components*
- *Assembly*
- *Packaging*
- *Delivery*
- *EOL disposal*

The first four phases include the processes required to manufacture the components and their inbound journey to the assembly factory. The assembly phase includes emissions during the assembly, while the packaging phase takes into account emissions from the packaging material (Chapter 3.3:Production for detailed information). The delivery phase comprises of emissions from transportation of assembled products from the factory to the point of sale. The final phase, EOL disposal, contains emissions after the products' useful lifetime has ended, which include emissions from transport to the disposal site and direct emissions from the disposal process. Figure 8 illustrates the phases of Sola 377DEKMC. Since only the amounts of materials used differ between the six products under this study, Figure 8 is applicable to rest of the chair models as well.

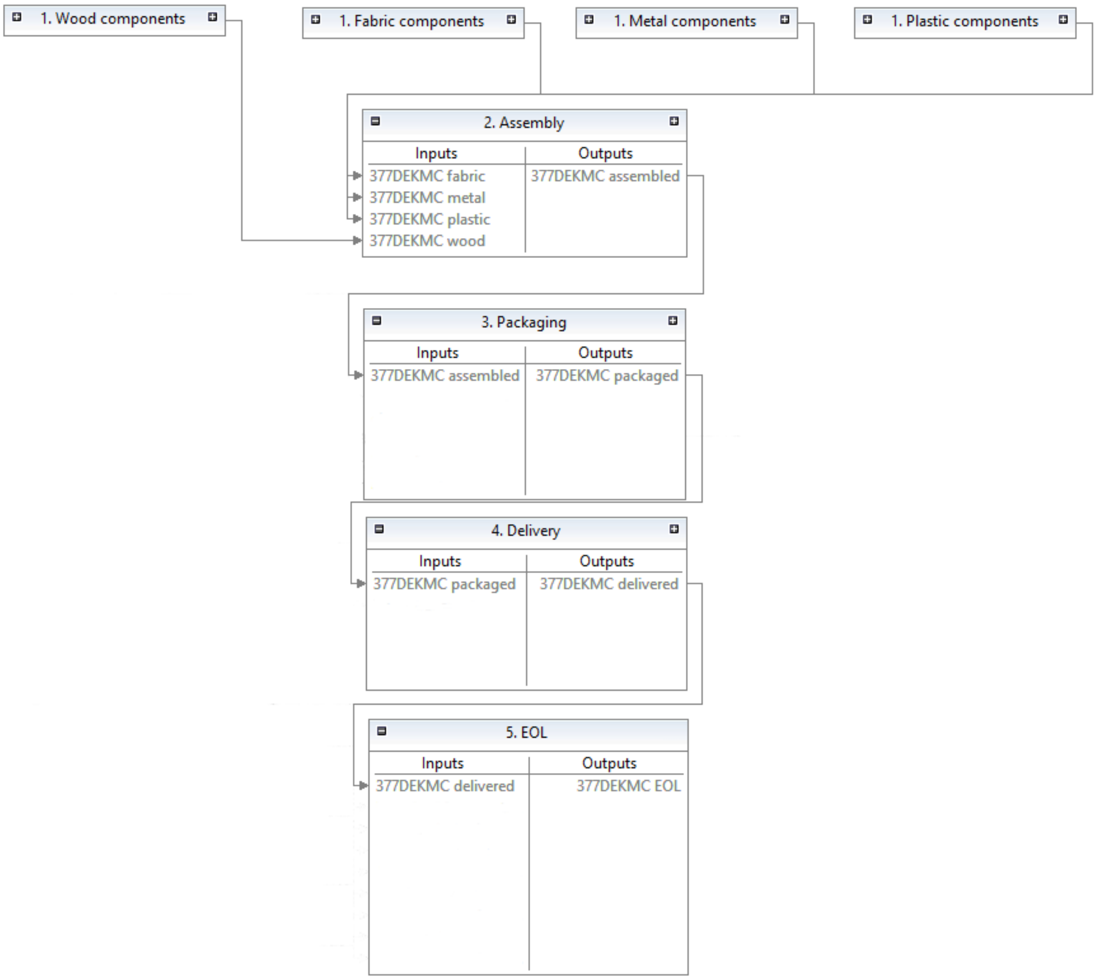

Figure 7: Life cycle phases of Sola 377DEKMC (specific process inputs and outputs have been edited out)

In order to alleviate the issue of the free database not containing the specific processes used in the product chains, pedigree matrices were used. In the pedigree matrix dialog, the user gives scores to determine the relevance of the available data and actual data. openLCA pedigree matrix dialog is shown in Figure 9.

Pedigree matrix

Indicator score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimates
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the data set	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set	Less than 15 years of difference to the time period of the data set	Age of data unknown or more than 15 years of difference to the time period of the data set
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Base uncertainty: 1.0 σg: 1.586302808816493 OK Cancel

Figure 8: Pedigree matrices

Once the inputs and outputs of all phases one through eight were established, six product systems were created (a product system per each model). Next, service providers for each process were specified in order to connect the flows to relevant industrial processes. Following the confirmation of the completeness of inputs and outputs, the impact results were calculated using the CML and ILCD 2011 assessment methods.

6.2 Results

Normalized and weighted results within CML baseline are shown in Appendix 8, and characterized ILCD 2011 results are shown in Appendix 9.

6.3 Discussion

Unfortunately, the LCIA results indicate an error in calculations. The shortcomings of this study can be attributed to one of the following:

- User error
- Low quality of LCI data
- Errors within the life cycle assessment methods
- Software bugs causing issues

Freeware LCA software coupled with free data was definitely not sufficient for this study.

6.4 Sensitivity analysis

No sensitivity analysis was performed due to the flawed results

7 Conclusion and recommendations

In conclusion, three studies were performed, two of which were successful. The CFP study demonstrated the biggest emission contributors to overall carbon footprint are metal and wood components. The SLCA study highlighted the hotspots in the production process chain being the packaging and distribution, raw materials and the disposal phases. While the LCIA study did not produce meaningful results, it brought into the attention the importance of data quality and tools used. For future studies, it is highly suggested to use more detailed and consistent life cycle inventory data.

8 References

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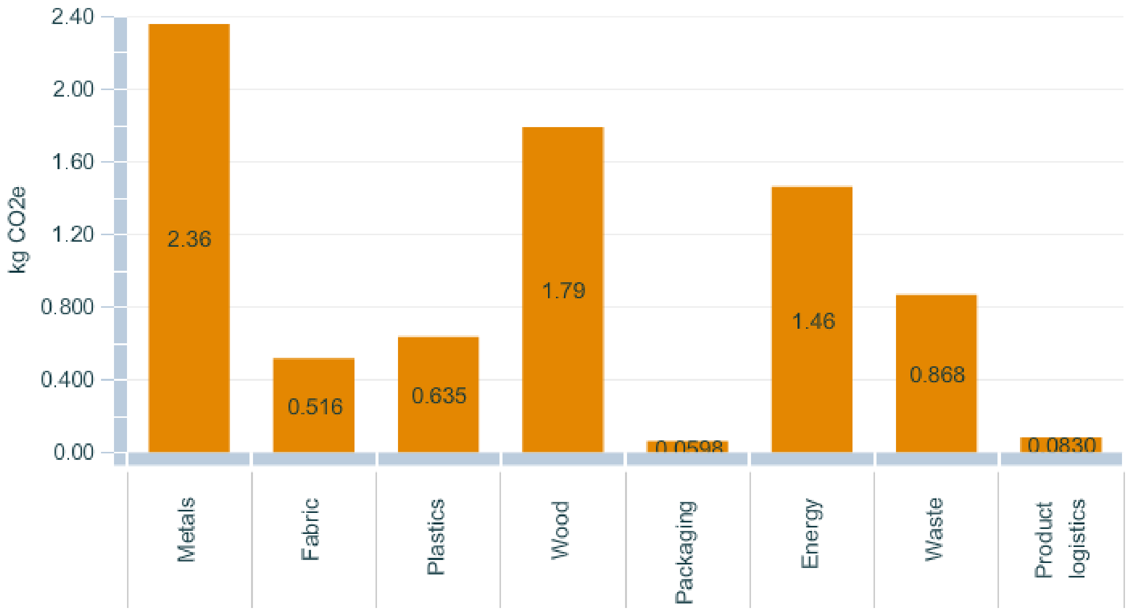
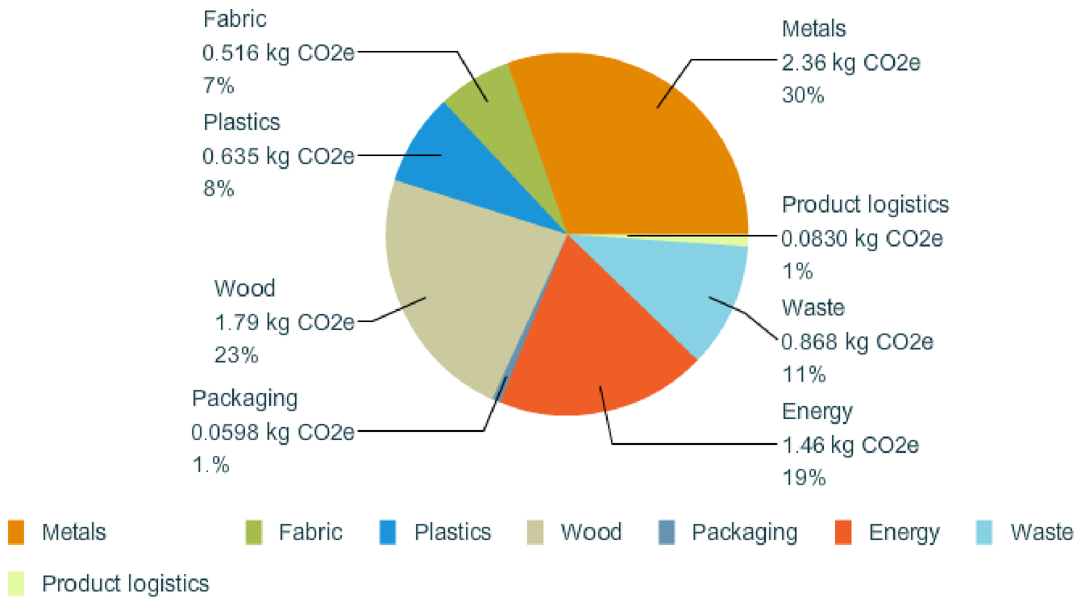
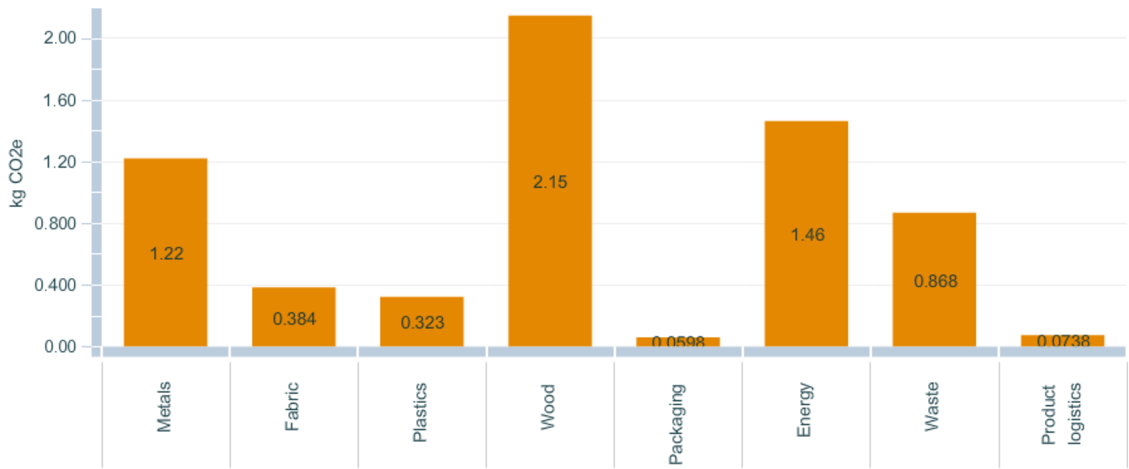
14. Winter, S. openLCA 1.4 case study: LCA comparison of PET water bottles sold in Germany deriving from different production locations . December 2014

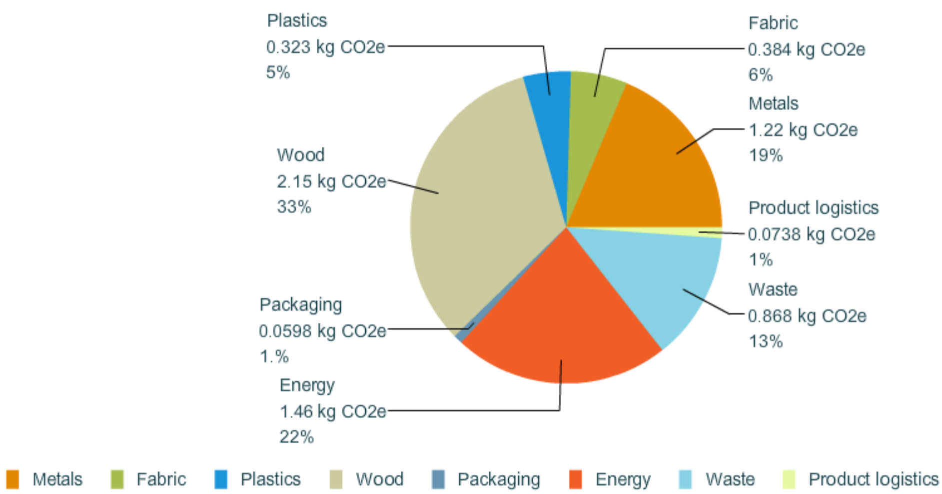
Appendix 1. CO_2 footprint, Sola 378AC



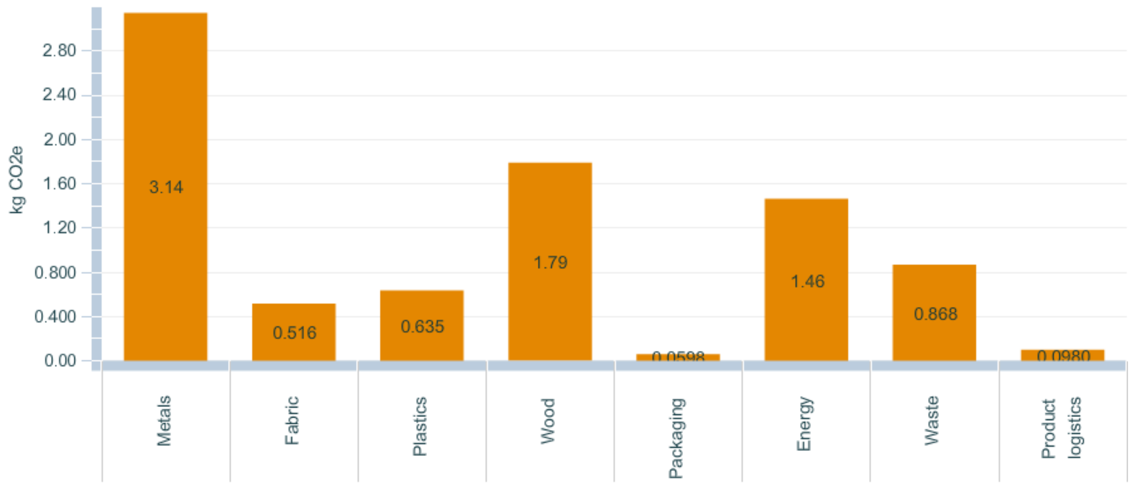


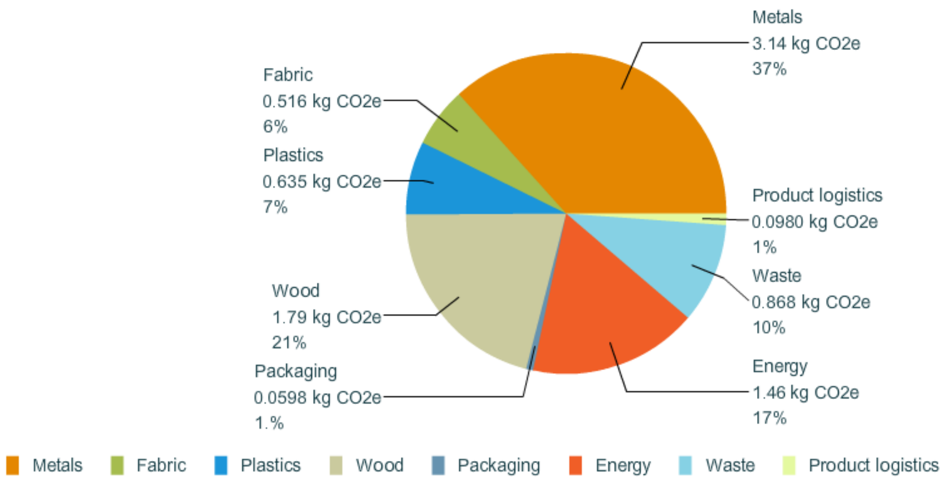
Appendix 2. CO_2 footprint, Sola 377PC



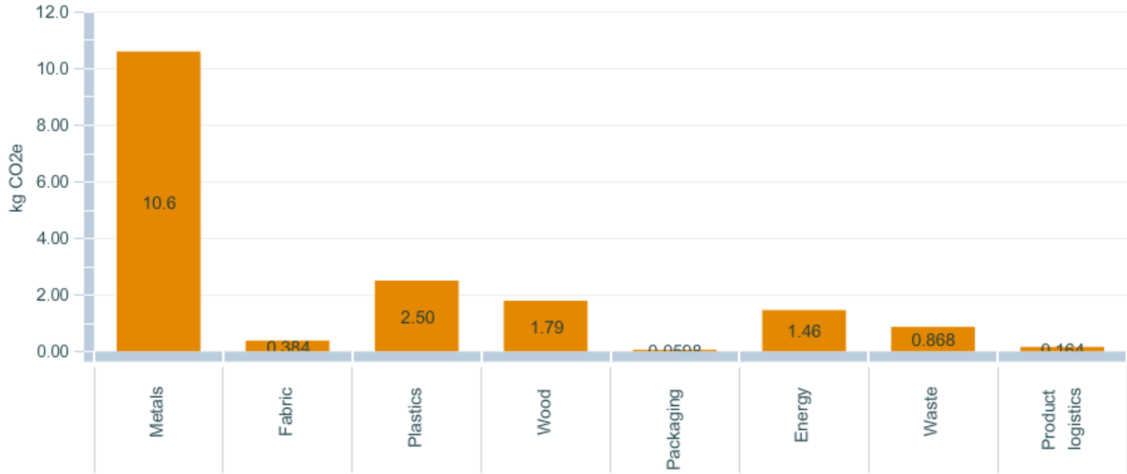


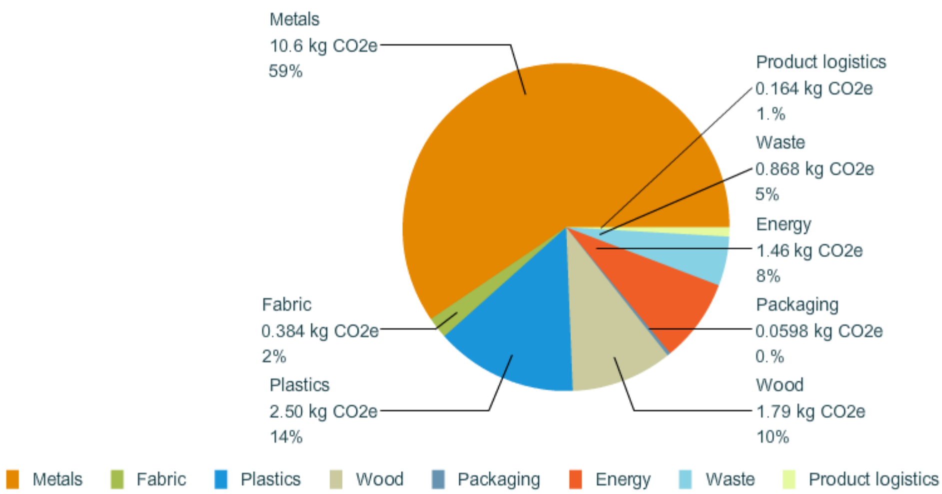
Appendix 3. CO_2 footprint, Sola 378DC



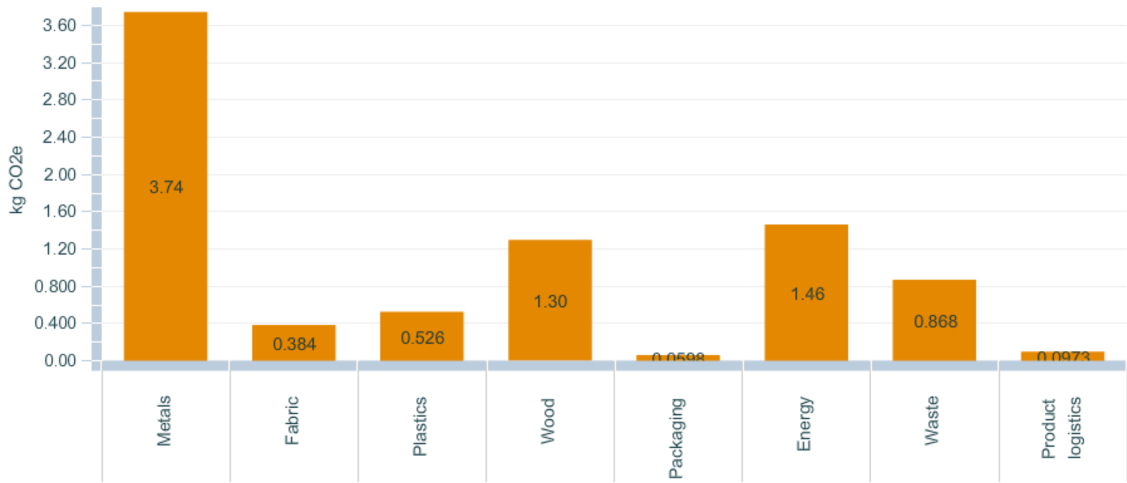


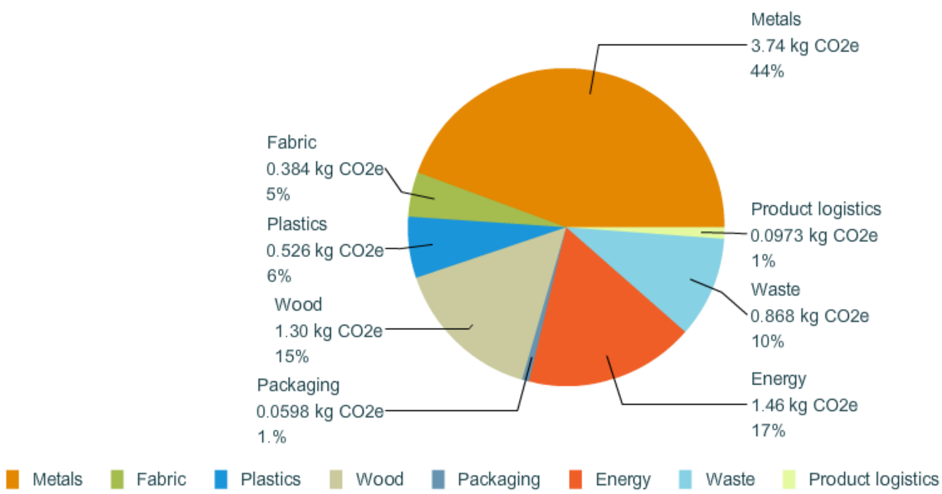
Appendix 4. CO_2 footprint, Sola 377RGC



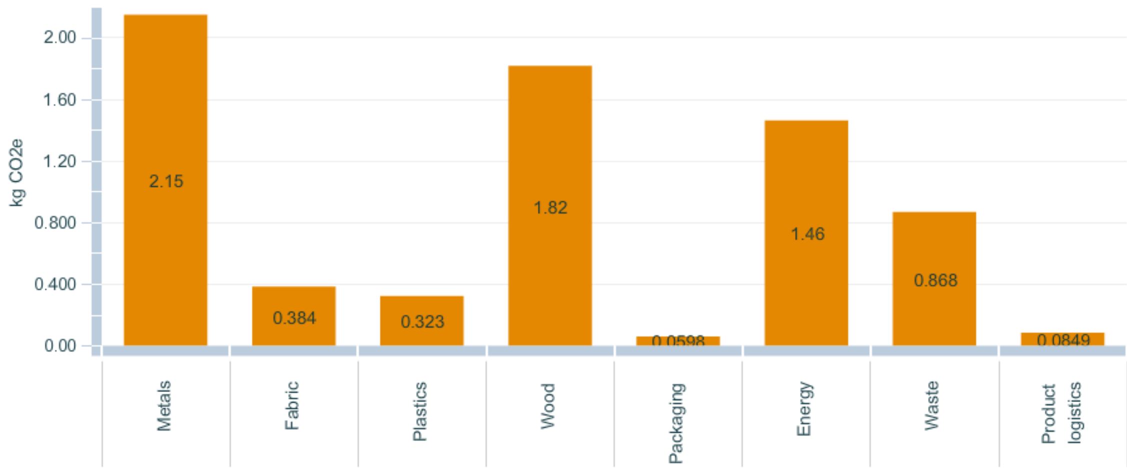


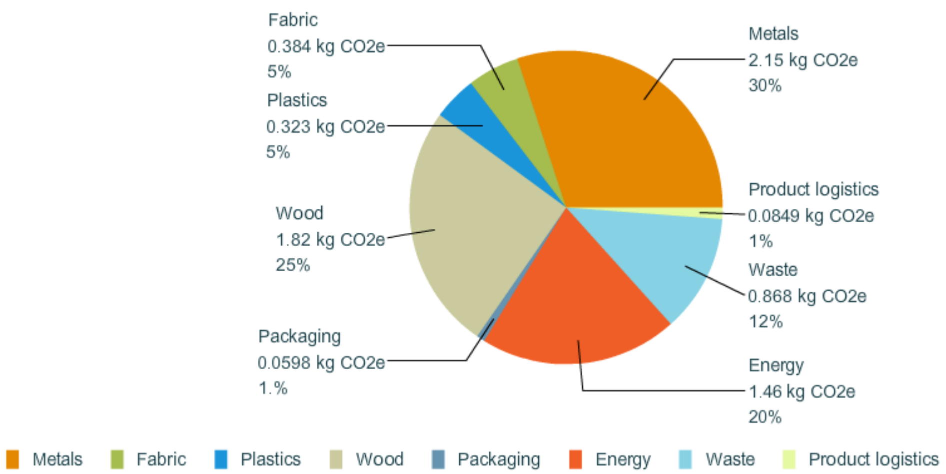
Appendix 5. CO_2 footprint, Sola 377DEKMC



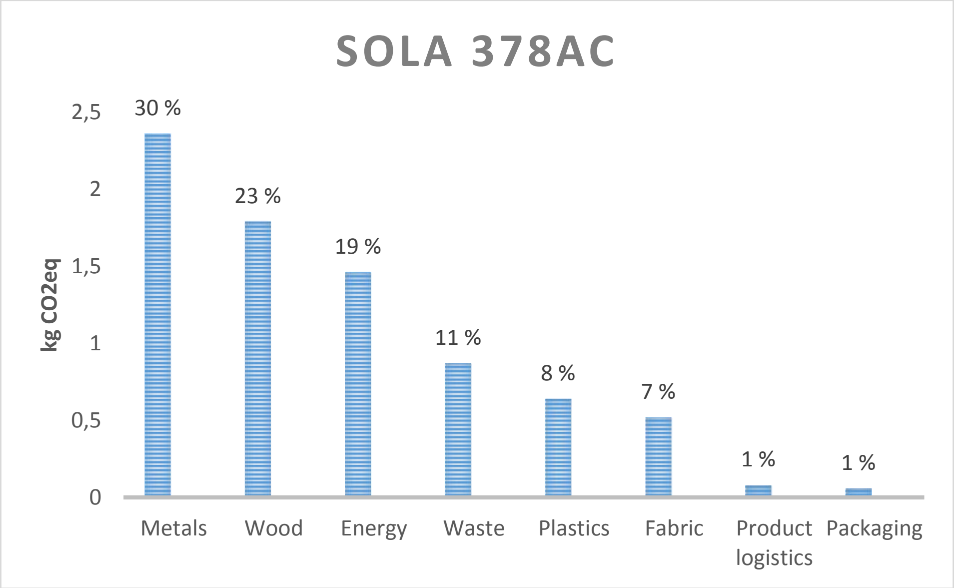


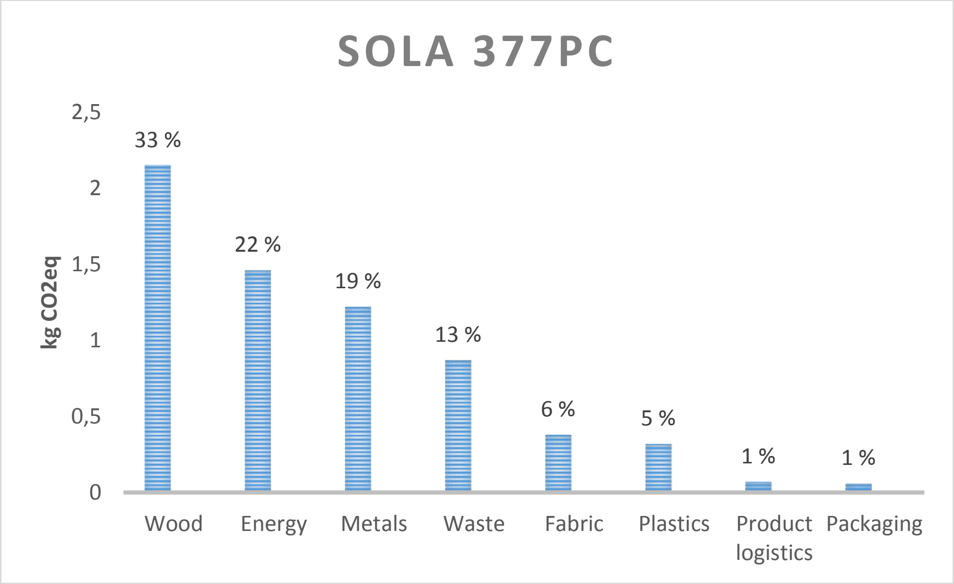
Appendix 6. CO_2 footprint, Sola 377PEKMC

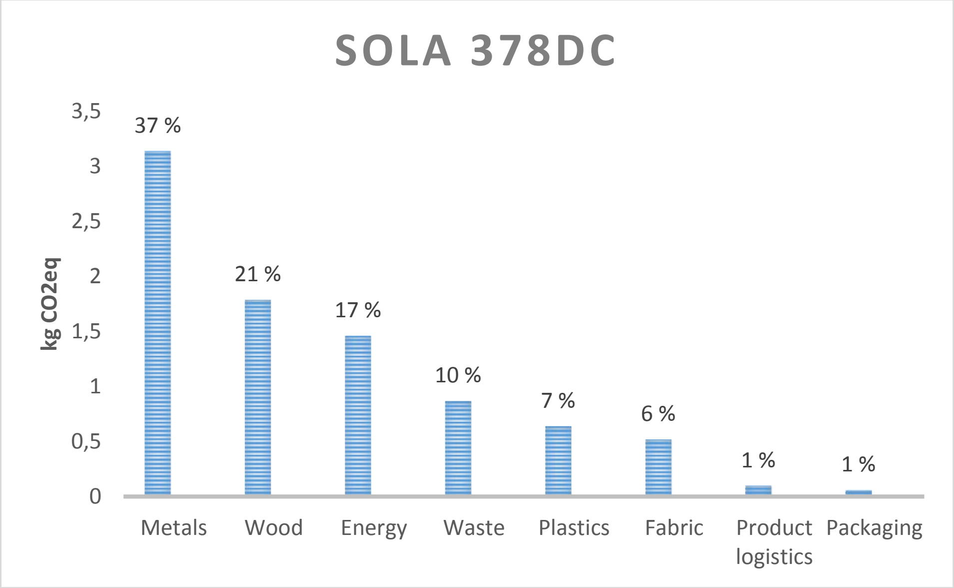


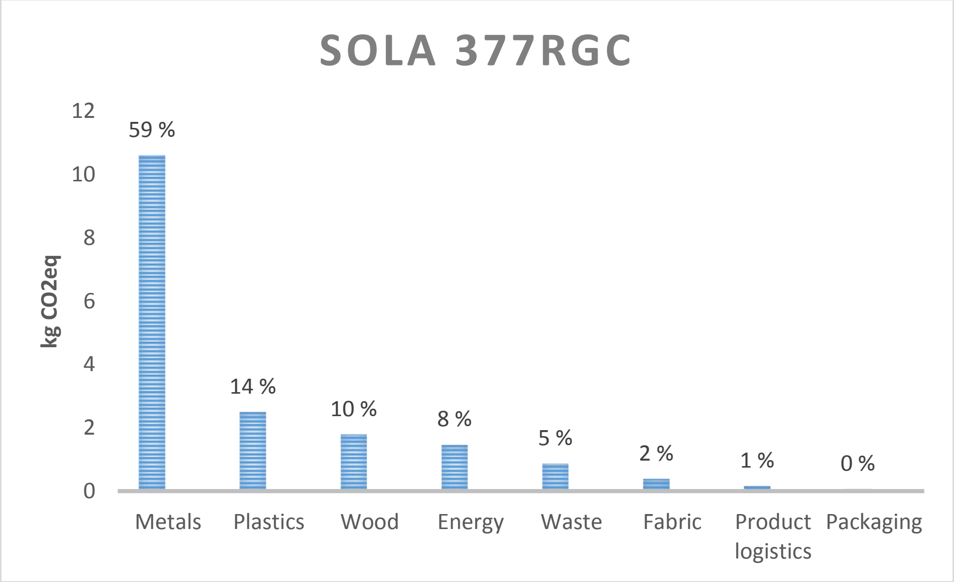


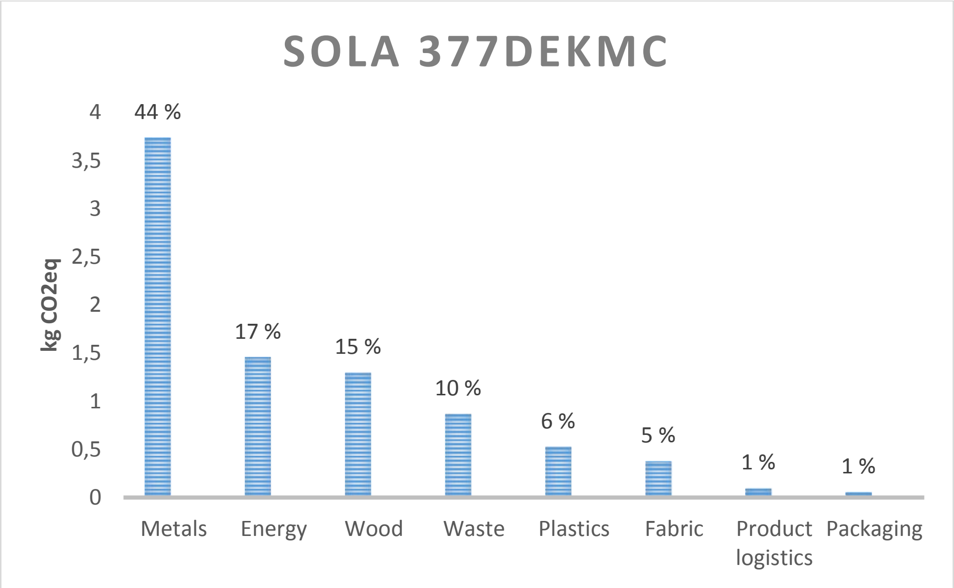
Appendix 7. CO_2 footprint contributions, in descending order






SOLA 378DC
kg CO2eq
3,5
3
2,5
2
1,5
1
0,5
0
37 %
21 %
17 %
10 %
7 %
6 %
1 %
1 %
Metals
Wood
Energy
Waste
Plastics
Fabric
Product logistics
Packaging


SOLA 377RGC
kg CO2eq
12
10
8
6
4
2
0
59 %
14 %
10 %
8 %
5 %
2 %
1 %
0 %
Metals
Plastics
Wood
Energy
Waste
Fabric
Product logistics
Packaging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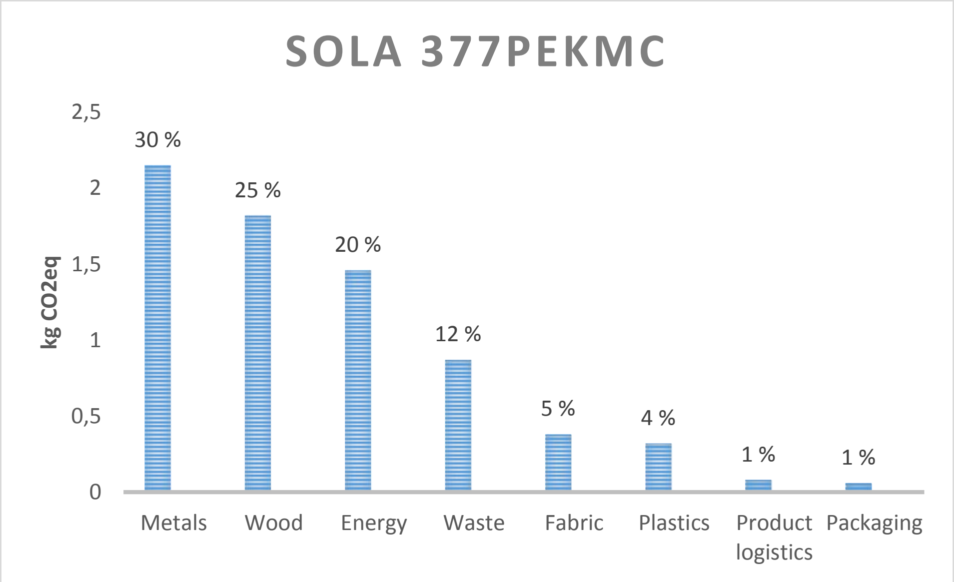
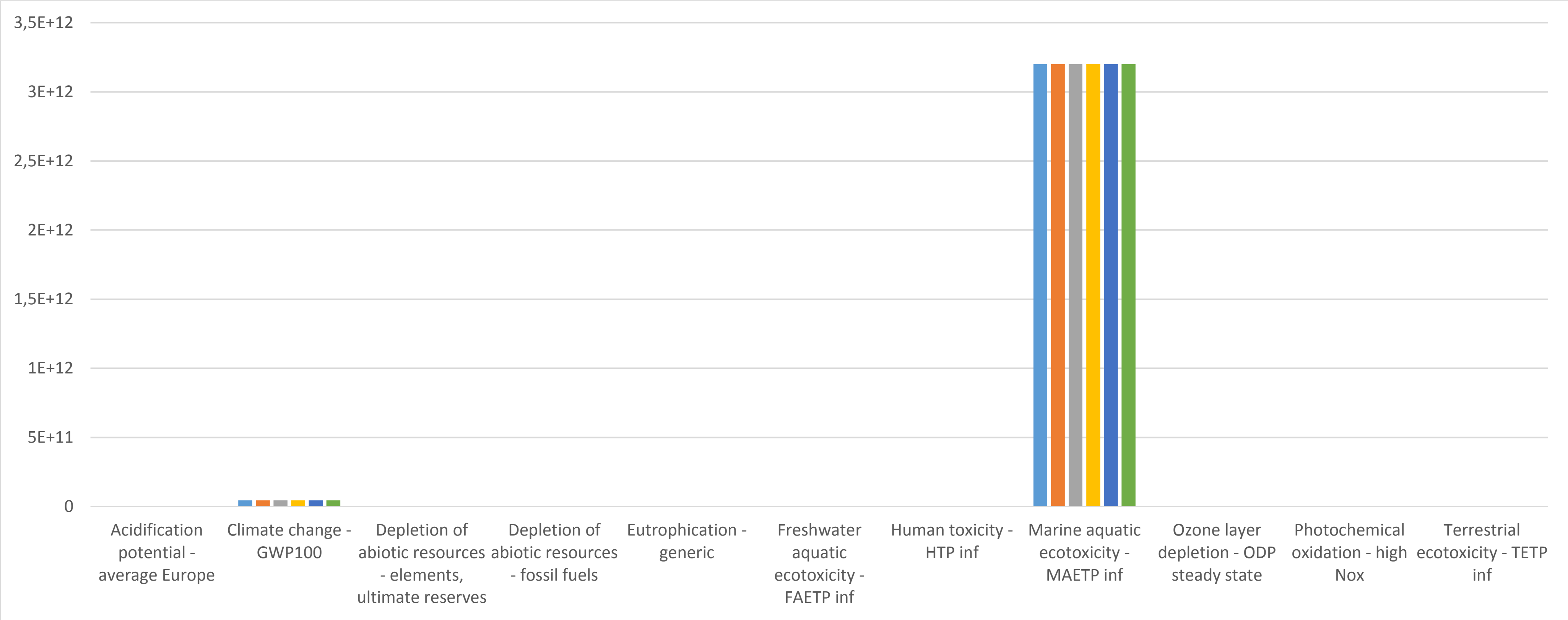
kg CO2eq
4
3,5
3
2,5
2
1,5
1
0,5
0
44 %
17 %
15 %
10 %
6 %
5 %
1 %
1 %
Metals
Energy
Wood
Waste
Plastics
Fabric
Product logistics
Packaging


SOLA 377PEKMC
kg CO2eq
2,5
2
1,5
1
0,5
0
30 %
25 %
20 %
12 %
5 %
4 %
1 %
1 %
Metals
Wood
Energy
Waste
Fabric
Plastics
Product logistics
Packaging

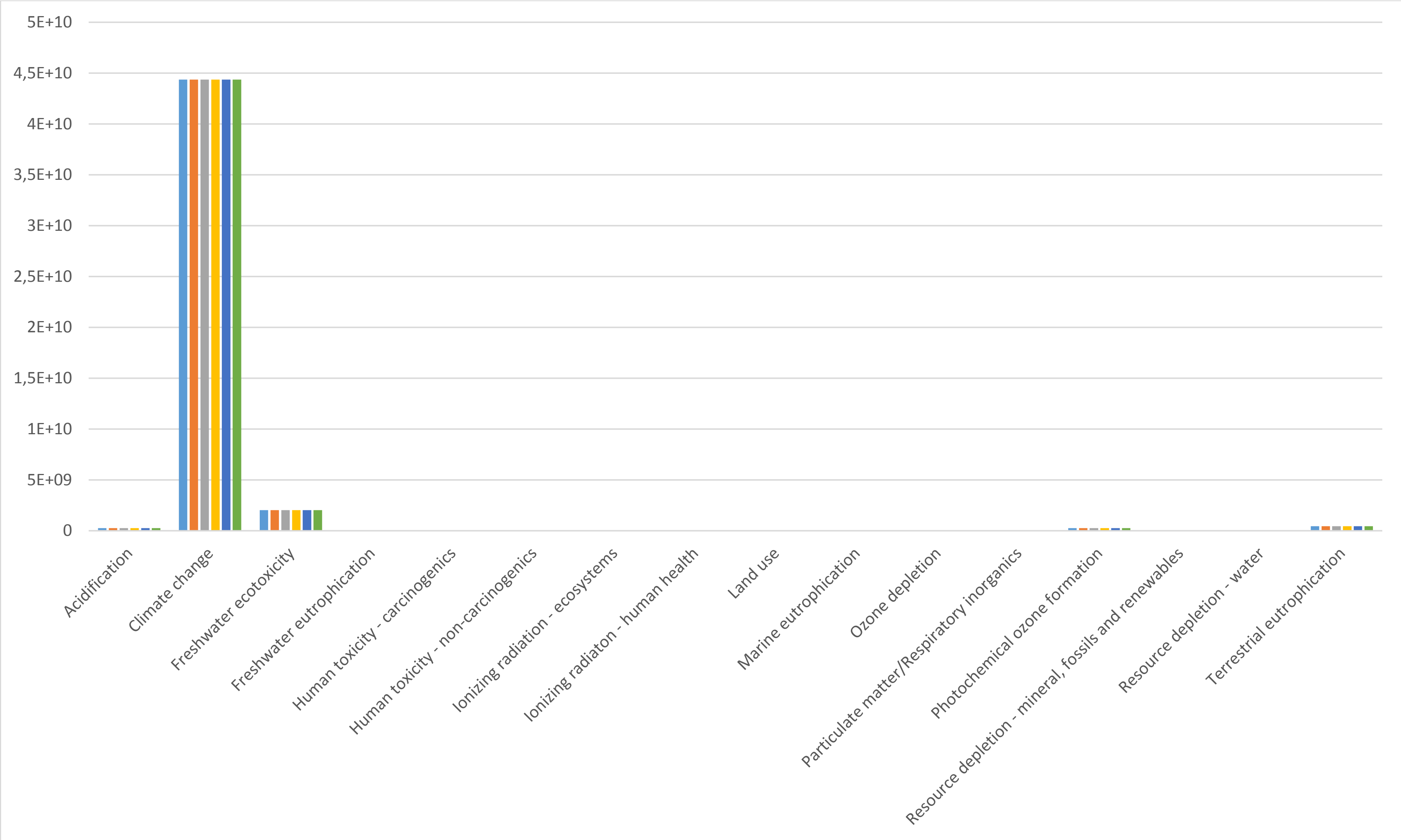
Appendix 8. LCIA normalized and weighted results, CML baseline method

Impact category	Reference unit	377DEKMC	377PC	377PEKMC	377RGC	378AC	378DC
Acidification potential - average Europe	kg SO2 eq.	213771196.2	213771196.2	213771196.2	213771196.2	213771196.2	213771196.2
Climate change - GWP100	kg CO2 eq.	44359731459	44359731459	44359731455	44359731461	44359731455	44359731455
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	439.5097762	439.5097773	439.5097833	439.5097841	439.5097834	439.5097834
Depletion of abiotic resources - fossil fuels	MJ	0	0	0	0	0	0
Eutrophication - generic	kg PO4--- eq.	13487960.79	13487960.79	13487960.79	13487960.8	13487960.79	13487960.79
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.	2565814.92	2565814.919	2565814.919	2565814.922	2565814.92	2565814.92
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.	439323540.1	439323540.2	439323540.1	439323540.3	439323540.1	439323540.1
Marine aquatic ecotoxicity - MAETP inf	kg 1,4-dichlorobenzene eq.	3.20E+12	3.20069E+12	3.20E+12	3.20069E+12	3.20069E+12	3.20069E+12
Ozone layer depletion - ODP steady state	kg CFC-11 eq.	8.72E-07	8.56859E-07	8.55E-07	1.22876E-06	8.75534E-07	8.76178E-07
Photochemical oxidation - high Nox	kg ethylene eq.	13553333.42	13553333.42	13553333.42	13553333.42	13553333.42	13553333.42
Terrestrial ecotoxicity - TETP inf	kg 1,4-dichlorobenzene eq.	232.7793447	232.7793407	232.7793404	232.7794272	232.7793452	232.7793455


3,5E+12
3E+12
2,5E+12
2E+12
1,5E+12
1E+12
5E+11
0
Acidification potential - average Europe
Climate change - GWP100
Depletion of abiotic resources - elements, ultimate reserves
Depletion of abiotic resources - fossil fuels
Eutrophication - generic
Freshwater aquatic ecotoxicity - FAETP inf
Human toxicity - HTP inf
Marine aquatic ecotoxicity - MAETP inf
Ozone layer depletion - ODP steady state
Photochemical oxidation - high Nox
Terrestrial ecotoxicity - TETP inf

Appendix 9. LCIA characterized results, ILCD 2011

Impact category	Reference unit	377DEKMC	377PC	377PEKMC	377RGC	378AC	378DC
Acidification	Mole H+ eq.	252840996.5	252840996.4	252840996.4	252840996.5	252840996.4	252840996.4
Climate change	kg CO2 eq.	44359731452	44359731451	44359731447	44359731454	44359731447	44359731447
Freshwater ecotoxicity	CTUe	2025522709	2025522708	2025522707	2025522709	2025522708	2025522708
Freshwater eutrophication	kg P eq.	2826.70813	2826.708173	2826.708132	2826.708228	2826.70814	2826.708141
Human toxicity - carcinogenics	CTUh	114.1025867	114.1025866	114.1025866	114.1025867	114.1025866	114.1025866
Human toxicity - non-carcinogenics	CTUh	34.49556848	34.49556779	34.49556666	34.49556674	34.49556667	34.49556667
Ionizing radiation - ecosystems	CTUe	1.00979E-05	9.92032E-06	9.89248E-06	1.43264E-05	1.01412E-05	1.01489E-05
Ionizing radiaton - human health	kg U235 eq.	1.021766591	1.003791138	1.000973483	1.449724598	1.026146663	1.026923925
Land use	kg SOC	0	0	0	0	0	0
Marine eutrophication	kg N eq.	39052141.26	39052141.26	39052141.26	39052141.26	39052141.26	39052141.26
Ozone depletion	kg CFC-11 eq.	8.71915E-07	8.56859E-07	8.54525E-07	1.22876E-06	8.75534E-07	8.76178E-07
Particulate matter/Respiratory inorganics	kg PM2.5 eq.	14969252.58	14969252.58	14969252.58	14969252.59	14969252.58	14969252.58
Photochemical ozone formation	kg C2H4 eq.	245939302.5	245939302.5	245939302.5	245939302.5	245939302.5	245939302.5
Resource depletion - mineral, fossils and renewables	kg Sb eq.	29839.60921	29839.60922	29839.60926	29839.60927	29839.60926	29839.60926
Resource depletion - water	m3	536575.6699	536575.6698	536575.6697	536575.6696	536575.6699	536575.6699
Terrestrial eutrophication	Mole N eq.	427260001.2	427260001.2	427260001.2	427260001.2	427260001.2	427260001.2


5E+10
4,5E+10
4E+10
3,5E+10
3E+10
2,5E+10
2E+10
1,5E+10
1E+10
5E+09
0
Acidification
Climate change
Freshwater ecotoxicity
Freshwater eutrophication
Human toxicity - carcinogenics
Human toxicity - non-carcinogenics
Ionizing radiation - ecosystems
Ionizing radiaton - human health
Land use
Marine eutrophication
Ozone depletion
Particulate matter/Respiratory inorganics
Photochemical ozone formation
Resource depletion - mineral, fossils and renewables
Resource depletion - water
Terrestrial eutrophication