Comparative Life Cycle Assessment of a Wooden Chair and a 3D-printed Chair

Final Report with Corrections

AG2800 Life Cycle Assessment

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ABSTRACT

In recent years three-dimensional (3D) printing became accessible to a wider audience and its potential to revolutionize industry is constantly being discussed. In addition to increased opportunities for customization and consumer power, environmental benefits have also been stated as advantages. Manufacturing through 3D printing has no by-products or waste. And yet, recently questions about the negative impacts caused by 3D printing have been raised. The presented life cycle analysis (LCA) aims to compare the environmental impacts caused by two types of chairs for household use within a lifespan of 15 years: a wooden chair made of spruce and produced in Sweden, and 3D-printed chair using acrylonitrile butadiene styrene (ABS) as a material and printed in Stockholm.

The results showed that both chairs have the highest impacts on human toxicity, freshwater and marine ecotoxicity. An interesting part of result was regarding waste scenarios, there surprisingly; incineration of wooden chair had a high positive impact on ionizing radiation, and the reason was energy recovery from incineration that reduces extraction of uranium used in Swedish mix. Another interesting result was from 3DP chair waste scenarios showing that recycling of the chair is more environmentally friendly option.

Overall, the wooden chair has lower environmental impacts and is more environmentally rational alternative. However, considering the material chosen for 3D printing and scenario favourable to wooden chair, the results might be limited.

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1. INTRODUCTION

Three-dimensional printing (3DP) has been technologically possible since the late 1980s. In short 3DP is a process where, based on a computer-aided design, an object is created by printing different layers of material on top of each other. Only in recent years has the technology become available to a wider audience and its popularity is increasing rapidly (Dale Prince , 2014) . 3DP is sometimes referred to as a driver for the 'third industrial revolution', since it has the potential to drastically change current production and business models (Garret, 2014) (Dale Prince , 2014) (M. Gebler, A. J. M. Schoot Uiterkamp, C. Visser, 2014). Where most product development currently relies on mass production on a global scale with complex supply chains, provides 3DP the option to produce customized objects locally and on demand (Garret, 2014). Although, currently still partly limited by technological possibilities, 3DP has already led to the creation of varied examples, ranging from furniture and jewellery to even guns and prosthetics.

Figure 1: Chair design by Patrick Jouin (Jouin, 2014)

Figure 2: Customized prosthetics designed by Bespoke Fairings (Grozdanic, 2013)

Apart from the advantages such as increased opportunities for customization and consumer power it is also said that 3DP could lead to environmental benefits as well. 3DP is an additive process, compared to conventional production practices which consist most often of subtractive processes. This means that 3DP does not lead to the creation of by-products and waste (M. Kreiger, J. M. Pearce, 2013). In conventional processes, for example in wood processes, material such as branches and bark needs to be removed first before the material can actually be used. Since, as mentioned above, 3DP also enables local production, long-distance (fossil fuel dependent) transportation is eliminated in the process as well.

Besides the potential benefits, concerns have already been raised regarding potential negative impacts on 3DP. For example Steven Wright has conducted a study on the emissions to air caused by 3DP, but unfortunately the results were not yet published at the time of writing (3D Printshow, 2014). Since the technology still is very new and constantly in development, few comprehensive studies have been completed regarding the environmental impacts of 3DP versus conventional manufacturing. Kreiger and Pearce (2013) state that *"An ideal study would consist of a cradle-to-*

grave analysis for both conventional and distributed manufacturing, including all infrastructure, packaging, and transportation." Although unfortunately this study will not be the 'ideal study' either, an attempt is made to analyse the main differences in environmental impacts between a conventionally manufactured wooden chair and a 3DP chair.

1.1 Goal and Scope

The main goal of this LCA is to compare the environmental impacts caused by the material extraction, manufacturing and end-of-life phases in the life cycles of two types of chairs for household use. The first type is a locally-produced 3DP chair of acrylonitrile butadiene styrene (ABS), printed in Stockholm using a Makerbot Thing-O-Matic. The second chair is a wooden chair manufactured in Nässjö, Sweden, using Swedish spruce and coated with lacquer. Both types of chairs are produced, used and disposed of in Sweden. The LCA is based on current practices and only aims to allocate the environmental impacts of both chairs; potential changes in manufacturing and disposal processes are not included. Therefore this study is an accounting LCA. Doing so, we intend to identify the hotspots that can be accounted for the most considerable environmental impacts.

1.1.1 Intended application and audience LCA

As stated above, 3DP technologies are still relatively new and they are constantly developed. Continuous improvements are made regarding, for example, the energy efficiency of 3D printers and new printing materials are developed rapidly. However, the environmental impacts of these new processes are not yet known.

At the same time, the wood processing industry is relatively old and relies more on traditional practices. For both industries it would be beneficial to know where in the process they contribute the most in term of environmental impacts in order to develop more sustainable practices, whether this means either tweaking new technologies and materials in the 3DP industry as they are being developed, or improving practices adopted in the wood industry. Therefore, the main intended audience for this LCA will be the 3DP industry and the Swedish wood industry. The LCA may be also interesting to environmentally conscious consumers and researchers within the areas of digital fabrication.

1.2 Functional Unit

The functional unit is set as one chair for common household use with a lifetime of 15 years. The chair must be able to hold 120 kg for up to four hours per day. Since, as will be explained further below, the lifetime of a 3DP chairs is assumed to be approximately 5 years (based on Gijs, 2014) and the lifetime of a wooden chair is 15 years, 1 wooden chair will be compared to three 3DP chairs when comparing the two lifecycles.

A fictional simple chair as shown in figure 1 was created in order to establish the shape and dimensions which will be equal for both chairs.

Dimensions one chair (height*width*depth in cm)

Front legs (2 parts): 44*5*5
Back legs (2 parts): 100*5*5
Seat (1 part): 2*44*44
Support for seat (4 parts): 3*34*2
Back supprt (2 parts): 5*34*5

Total volume: 5572 cm^3

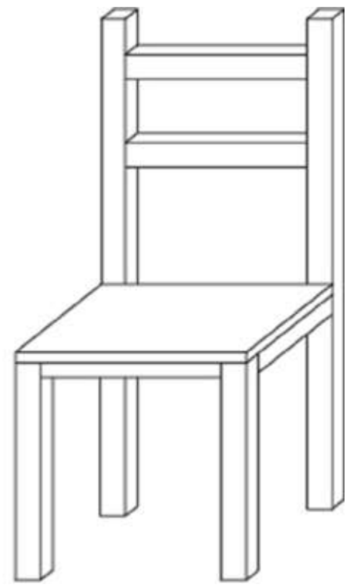


Figure 3: Chair Design and Size

1.3 System Boundaries

The system boundaries include a cradle-to-grave approach for both types of chairs, excluding the use phase. The use phase was omitted since it is not expected to differ significantly for both chairs. Manufacturing of manufacturing tools and equipment for both types of chairs is excluded in this LCA. The 'cradle' for the ABS chair is the extraction of oil. In case of the wooden chair the system starts by extracting the wood from the forest. After processing these raw materials the chair can be manufactured. During these processes there will be various emissions to the air and water. It is assumed that after 15 years the chair will be discarded. Two different waste scenarios for the end-of-life of the chairs are included: incineration with energy recovery and recycling. Other waste scenarios such as landfilling are not considered, since this is not common practice in Sweden which is set as the geographical boundary.

Impacts from processes in the future are included as they are a part of the SimaPro modelling. A more elaborate description of both systems can be found below in section *2.1 Process Flow Charts*. We consider a short time horizon for the results of this LCA. The main reason for it is the current limited data availability in the field of 3D printing and the ongoing research which may bring new, more accurate data and, thus, may replace some of the assumptions in the study and make it outdated. Moreover, 3D printing is constantly developing as a technology which may lead to changes in embedded materials and processes.

1.3.1 Allocation procedures

Since one of the waste scenarios is incineration with energy recovery, producing both electricity and heat, an allocation problem arises here. Where possible, this allocation problem was solved using the data provided by SimaPro 7 (Frischknecht et al., 2007). This data provided information on the quantity of electricity and heat which is produced when incinerating a certain amount of the material. The production of heat and electricity was included in the same ratio in our model.
Where no data was provided in SimaPro 7, no assumptions were made regarding the production of heat and electricity, thus the allocation problem remained unresolved.

1.4 Assumptions and limitations

An important limitation to this study is the fact that limited data is available regarding various aspects of 3DP, including material properties and energy usage. Furthermore, our LCA is based on a fictional chair, meaning that all data regarding the wooden chair is based on assumptions as well, however in this case it was attempted to create a realistic scenario. In the two tables below the assumptions for both studied product systems are listed.

Table 1: Assumption - wooden chair

	Data required	**Assumption**	**Motivation**
Transportation	km from forest to chair manufacturing facility	Assumed forest and production in Southern Sweden (200kgkm)	Based on personal information it was assumed that the chair was manufactured in Nässjö, and the wood for it brought from forest around 200km away from the town.
	km from manufacturing facility to Stockholm	Assumed transport from Nässjö to Stockholm (320 kgkm)	Most of the wood manufacturing facilities are located in Southern Sweden
Wood finish	g of wood finish used for one chair	Pigments, paper production 73 g Butyl Acrylate 73g Solvents, organic, unspecified 145 g Weight assumed on total weight paint, not individual substances	Wood stain and acrylic lacquers used in furniture production have similar composition: pigments, solvent and additives.

Life time	no of years a spruce chair can be used	Assumed to be 15 years	Assumption based on the lifetime of softwood spruce (T.C. Scheffer, 1998)

Table 2: Assumption - 3DP chair

	Data required	Assumption	Motivation
Life time	no of years a 3DP chair can be used	Assumed to be 5 years	Based on personal communication (Houdijk, 2014)
Filament (material used for 3DP)	Place of manufacture	Imported from China	China is often used to outsource manufacturing and this is part of the scenario the group agreed upon.
Transportation of filament	km travelled and type of transportation used	Assumed to be transported from Shanghai to Gothenburg by sea, and then from Gothenburg to Stockholm by truck	Part of the scenario the group agreed upon. Shanghai is a common port for loading goods which are transported to Europe by sea.

1.5 Impact categories and impact assessment method

The impact assessment method used in this LCA is ReCiPe Midpoint (Hierarchist). This method was chosen since it is a state-of-the-art method (ReCiPe, 2012). The following impact categories are considered in this study:

- Climate Change
- Ozone depletion
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Human toxicity

- Photochemical oxidant formation
- Particulate matter formation
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Marine ecotoxicity
- Ionising radiation
- Agricultural land occupation
- Natural land transformation
- Water depletion
- Mineral resource depletion
- Fossil fuel depletion

1.6 Normalisation

Normalisation helps to get a better understanding of the environmental impacts of the system (H. Baumann, 2004). Normalisation puts results in a broader context in order to give a common dimension to the results e.g. in a normalised result you do not have different impact categories in percentage as we get in the characterised result, but you are able to compare the most significant and outstanding impact categories for both products or processes. For this step the same methodology was used - ReCiPe Midpoint (Hierarchist), which refers to normalisation values of Europe and the world. The method was recalculated and updated in 2014 (ReCiPe, Normalisation, 2014).

2. LIFE CYCLE INVENTORY ANALYSIS

In this section the Life Cycle Inventory Analysis is described. This includes process flow charts for both types of chairs as well as an overview of the data used to develop the model.

2.1 Process flow charts

The process flow charts are presented for the wooden chair product system and for the 3DP chair product system. The flow charts make a distinction between the foreground and background system as well as which processes are included in the system boundaries (marked green) and which are not included in the system boundaries (marked white).

2.1.1 Process flow chart wooden chair

The process flow chart for the wooden chair starts by cultivating the land and forests which will eventually produce the wood. This step in excluded from the system boundaries. The system starts by felling and delimbing the trees, after which the wood is transported to be processed into planks. In SimaPro 7 (Frischknecht et al., 2007) energy usage during these steps is already included in the data, therefore this is included in the system boundaries. Once the planks are ready, they will be processed further to create the actual chairs, this includes more sawing, applying wood finishes and eventually the wood is assembled into a chair using screws and wood. After the use phase the chair could be disposed in two different ways, either through recycling or through incineration. Both processes lead to avoided environmental burdens, either in the form of recovered materials or as electricity and heat. Last, it is assumed that the site will be reforested after felling the trees to keep the site in use for wood production.
Figure 4: Wooden chair process flowchart

2.1.2 Process flow chart 3DP chair

The process flow chart for the 3DP chair starts by extraction of raw materials which is then transported and manufactured into filaments. These steps fall within the system boundaries, but are part of the background system. After transporting the filament, the chair can be manufactured (manufacturing in this case refers to the actual process of 3DP). After last transport, in this process from the 3DP facility to the customer's home, the chair can be assembled manually. Usually smart design solutions are integrated in 3DP objects, which enable easy assembly, therefore no additional material such as glue or screws will be required in this step. As with the wooden chair, the 3DP chair can be incinerated or recycled after the use phase. In this case the same avoided burdens are included: material recovery and generated heat and electricity.
Figure 5: 3D Printed Chair Process Flowchart

2.2 Data

The following tables provide an overview of the data which has been used to create the model in SimaPro 7 (Pré Consultants , 2008). For both the wooden chair and the 3DP chair a distinction is made between the data in the foreground and background system. Due to data limitations it was chosen to show in the tables only foreground processes.

Table 3: Materials Used in Wooden Chair Production

Material/Use	**Reference in SimaPro 7**	**Unit**	**Total**	**Reference**
Spruce	Spruce Wood, Timber	kg	2,4	Calculated based on volume of the chair and density of the spruce

Steel	Steel, low-alloyed	g	5*16	Assumption made based on the size of the nail used for chair production.
Wood glue	Phenol formaldehyde	g	60,5	(Joint Research Center, 2013)
Pigments	Pigments, paper production	g	73	(Chapman & Hall, 1993) (Dulux Trade, 2011)
Copolymer of butyl acrylate	Butyl Acrylate	g	73	(Chapman & Hall, 1993)) (Dulux Trade, 2011)
Solvents	Solvents, organic, unspecified	g	145	(Chapman & Hall, 1993) (Dulux Trade, 2011)
Cardboard	Corrugated board, recycling fibre, single wall	g	270	(Joint Research Center, 2013)

Table 4: Foreground Processes of Manufacturing of Wooden Chair

Process	**Reference in SimaPro 7**	**Unit**	**Total**	**Reference**
Process timber	Power sawing, with catalytic converter/RER S	hour	1,5	Quantity is an estimate based on personal information
Reforestation	Reforesting, medium intensity site, US PNW/US	m^2	1	Quantity is an estimate based on how much space one tree requires.

Table 5: Materials Used in 3D Chair Printing

Material/Use	**Reference in SimaPro 7**	**Unit**	**Total**	**Reference**
ABS	Acrylonitrile-butadiene-styrene copolymer resin, at plant/RNA	Kg	4	Calculated based on volume of the chair and density

				of the material.
Cardboard	Corrugated board, recycling fibre, single wall, at plant/RER S	G	200	Calculation made based on size of the chair.

Table 6: Foreground Processes of Manufacturing of 3D Printed Chair

Process	**Reference in SimaPro 7**	**Unit**	**Total**	**Reference**
Energy used for printing	Electricity mix/SE S	kWh	16,1625	(Chilson, 2011)

3. LIFE CYCLE INTERPRETATION

In this section the interpretation of the significant characterized and normalized results are presented. First, Section 3.1 will provide the results when comparing one wooden chair to one 3DP chair. Section 3.2 will focus on the complete *lifecycle* of the two chairs, here the waste scenarios are included and one wooden chair will be compared with three 3DP chairs, to represent a use phase of 15 years.

3.1 Results individual chairs

Figure 6 shows the characterized results for each impact category of 3DP chair. It can be seen that packaging is the least contributor in each category, material used for the chair and electricity used for printing have the highest environmental impacts. In 10 categories material contributes to environmental load by 60% and more, whereas in 8 categories impacts from electricity are higher.

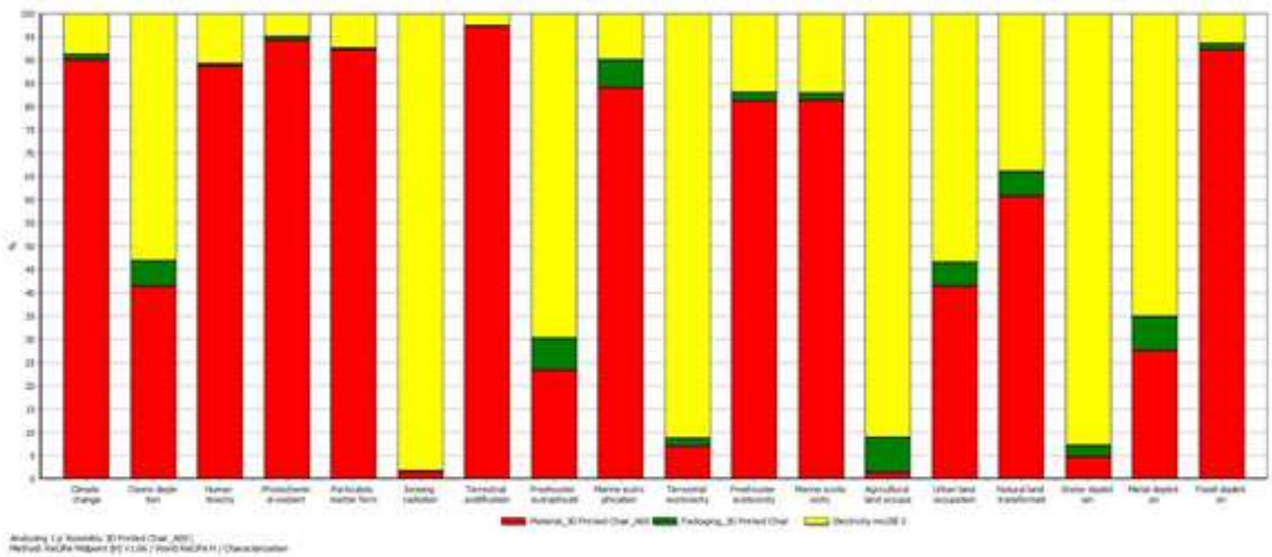
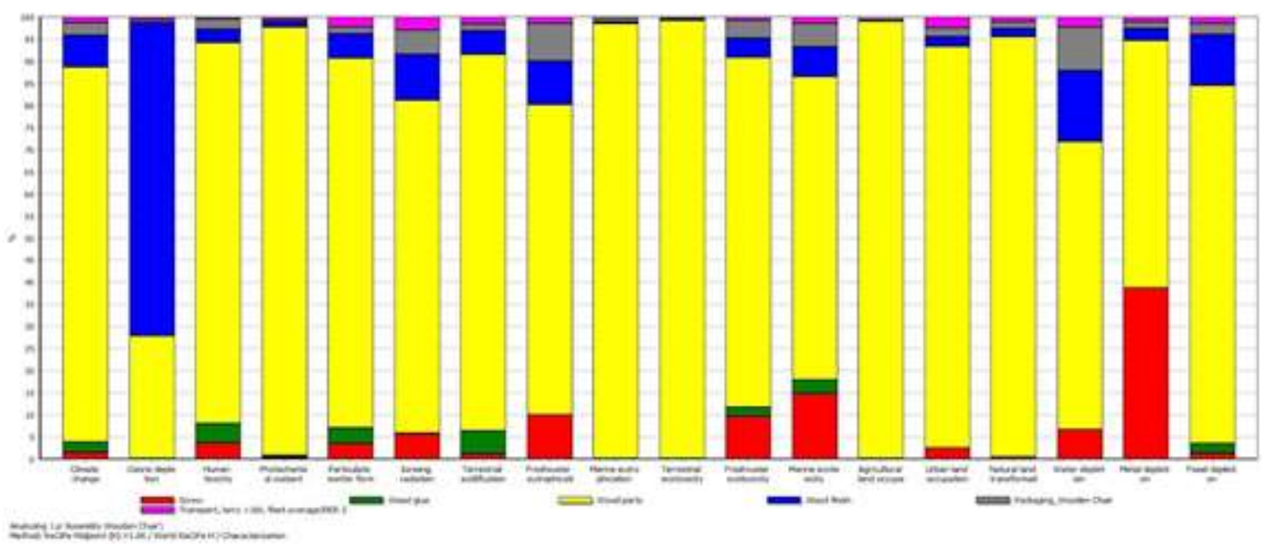


Figure 6: Assembly 3D Printed Chair ABS Characterization

Figure 7 presents the characterized result of the wooden chair. It is clearly seen that wood parts have the highest impact on environmental load. The main factor causing such a significant impact is power sawing, a high energy intense process, used to prepare the wood parts for the chair.



Figu

3.1.1 Comparison between the wooden chair and the 3DP chair

Figure 8 illustrates that environmental impacts of both chairs are quite varied. The 3DP chair contributes more in terms of climate change, human toxicity, particulate matter formation, ionising radiation, terrestrial acidification, freshwater ecotoxicity, water depletions and fossil depletion. The impacts of the wooden chair are higher for photochemical oxidant formation, ozone depletion, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation and metal depletion. The production of wooden chair has high impacts on land use or land transformation due to the land space used for forests, also due to deforestation caused by cutting the trees for manufacturing. Whereas, 3DP chair has high impacts , for instance on human toxicity or fossil fuel depletion due to the material chosen for the production, which is fossil base and contains toxic chemicals.

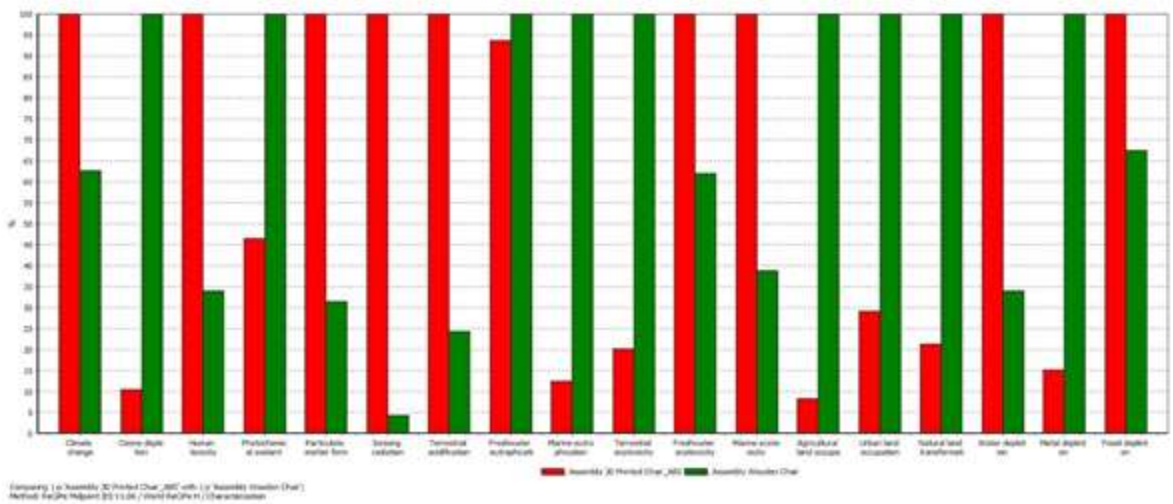


Figure 8: Comparison assembly 1 wooden chair vs. 1 3D chair - characterization

Normalizing these impact categories gives an opportunity to see which of the categories have an actual high impact compared to the average data. As is shown in figure 9, both types of chairs have biggest impacts in human toxicity, freshwater ecotoxicity and marine ecotoxicity. In this overview it becomes clear that the 3DP chair has higher impacts in all these three categories, and it has an especially high impact on human toxicity. Therefore, contributions to human toxicity for the 3DP chair have been analysed in further detail.

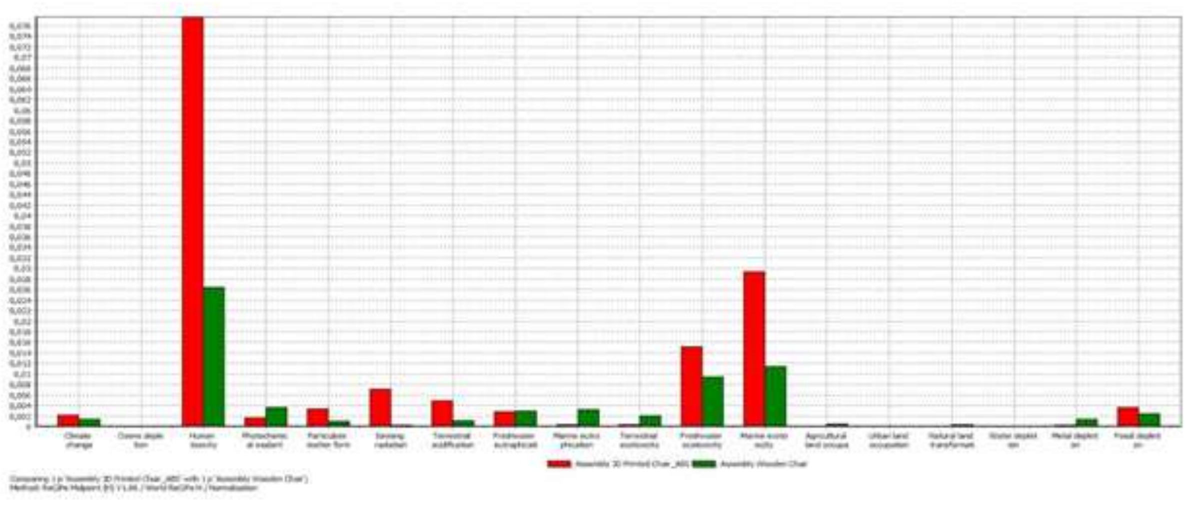
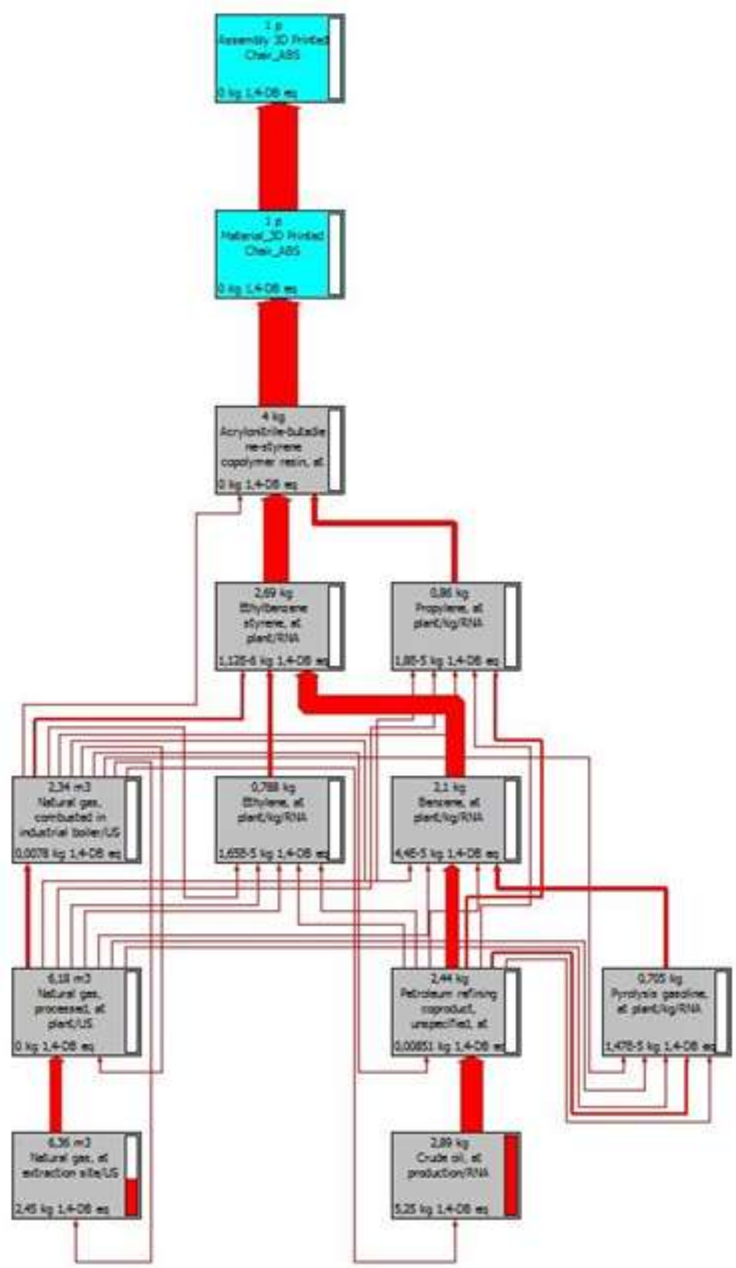


Figure 9: Comparison assembly 1 wooden chair vs. 1 3D chair - normalization

3.1.2 Analysis of human toxicity including analysis of alternatives materials

As can be seen in the network of the 3DP chair, see figure 10 below, the main contributor to the impact on human toxicity is ethylbenzene styrene. This is not surprising, since various harmful health effects could be caused by styrene (United States Environmental Protection Agency, 2000). Alternative, styrene-free, materials are already on the 3DP market and they are commonly used (Houdijk, 2014). However, since the composition of these materials is not made public, this could not be included in the model. An alternative scenario using other materials is described below.



Figu

A styrene-free material which can already be used for 3DP is polylactice (PLA). For this material data is available in SimaPro 7 (Frischknecht et al., 2007). The decision was made not to use PLA for the main analysis in this report, because the material is not strong enough for the purpose to create this chair (Houdijk, 2014). However, the figure below can provide an indication that the impacts on human toxicity could significantly increase if the choice is made to use styrene-free materials. At the same time it should be noted that the impacts of the wooden chair remain to be lower.

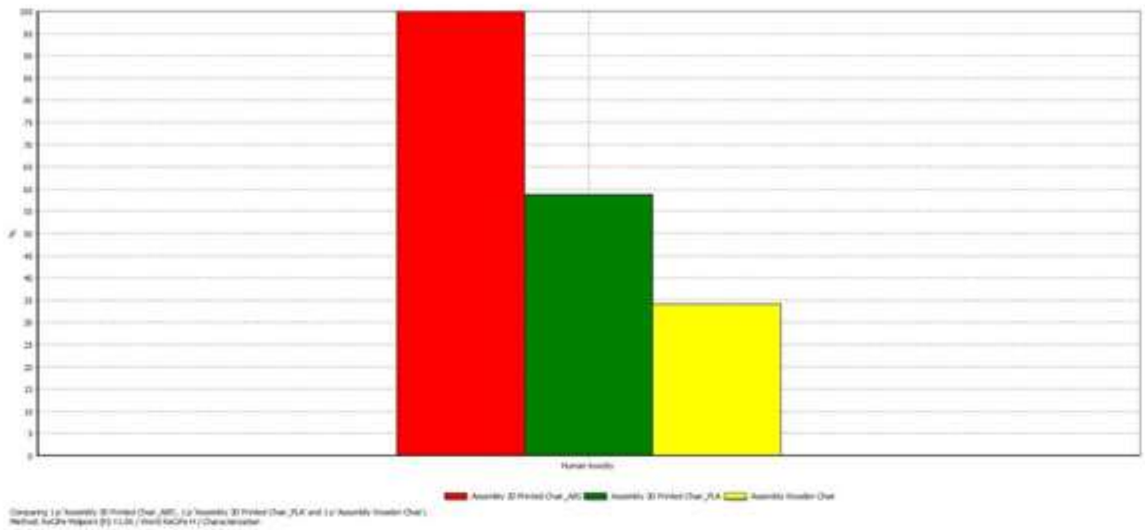


Figure 11: Comparison Human Toxicity 3DP chair ABS vs PLA vs Wooden Chair (1 chair) - Characterization

3.2 Results comparison life cycles including waste scenarios

Apart from the individual chairs, the life cycles of both chairs with two different waste scenarios have been compared as well. Since 3DP chairs are assumed to be disposed after 5 years, three 3DP chairs have been compared against one wooden chair in order to equate a life time of 15 years.

Most interesting observation for this comparison is the fact that impact ionising radiation for incineration of the wooden chair is less than zero (this is not very clearly visible in the graphs below, but this will be described further below in 4.2.1 Analysing incineration wooden chair).

Furthermore, the graph shows that big differences occur between the 3DP chair (including both waste scenarios) and the wooden chair (including both waste scenarios) in ionising radiation, terrestrial acidification and marine ecotoxicity. In all three categories the 3DP has a higher impact.

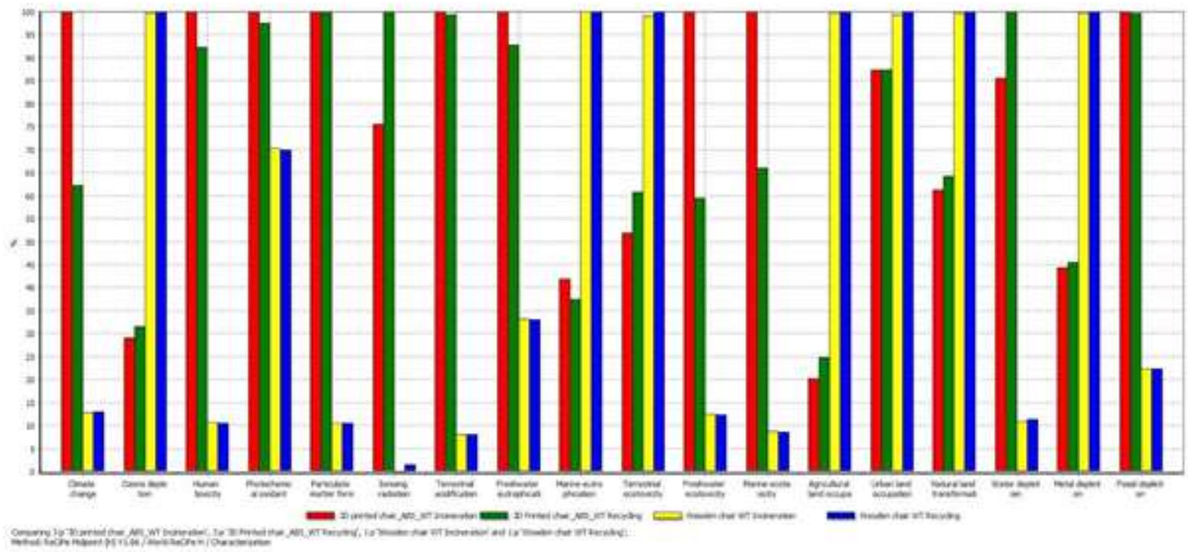
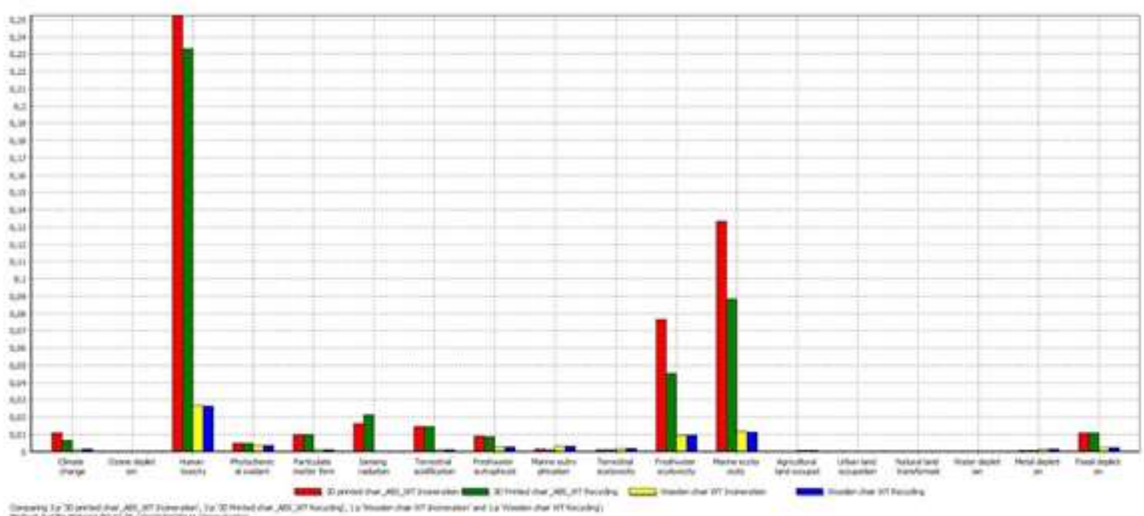


Figure 12: Comparison lifecycle 1 wooden chair vs. 3 3D-printed chairs (for a lifetime of 15 years) - both incineration and recycling - characterization

Analysing the normalised results, it becomes clear that human toxicity, freshwater ecotoxicity and marine ecotoxicity continue to have the most significant impacts, regardless of waste scenario or production method. In addition to that, this graph indicates that in most cases recycling has lower environmental impacts compared to incineration, although the differences between recycling and incineration for the wooden chair are relatively small.



Figu normalization

3.2.1 Analysing incineration for wooden chair

As written above, an interesting result appeared for the scenario where the wooden chair is incinerated. Ionising radiation, and to a smaller extent water depletion, terrestrial ecotoxicity and climate change, all have impacts less than 0% when incinerated. However, analysing these processes further, as shown in the network in figure 14 and 15 below, the positive impacts gained through incineration are bigger than the environmental impacts caused. The main reason for this is that the electricity generated through incineration means that uranium does not have to be mined to generate nuclear electricity which is included in the Swedish energy mix.

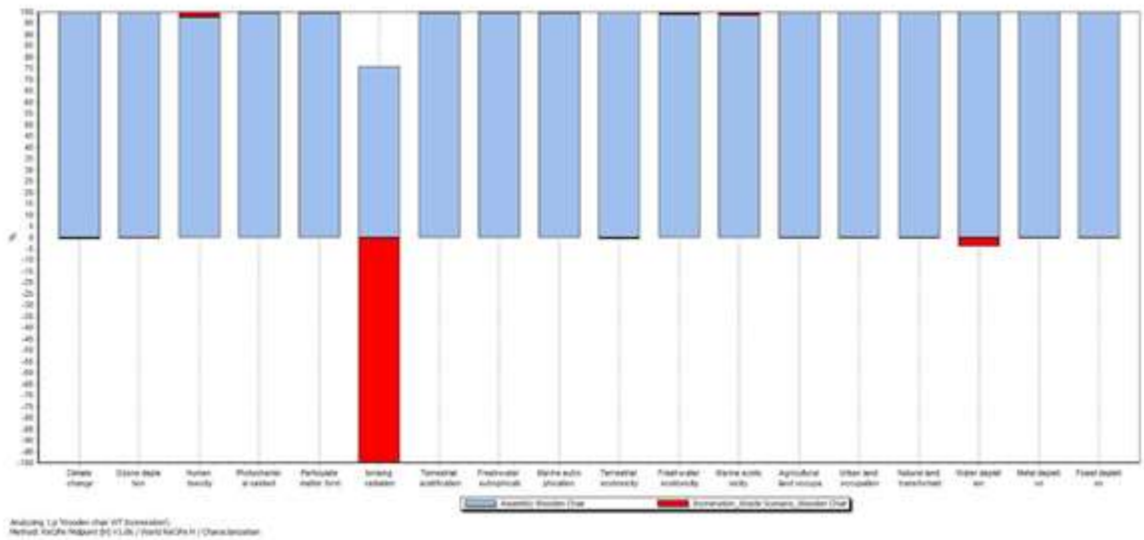


Figure 14: Comparison lifecycle wooden incineration - characterization

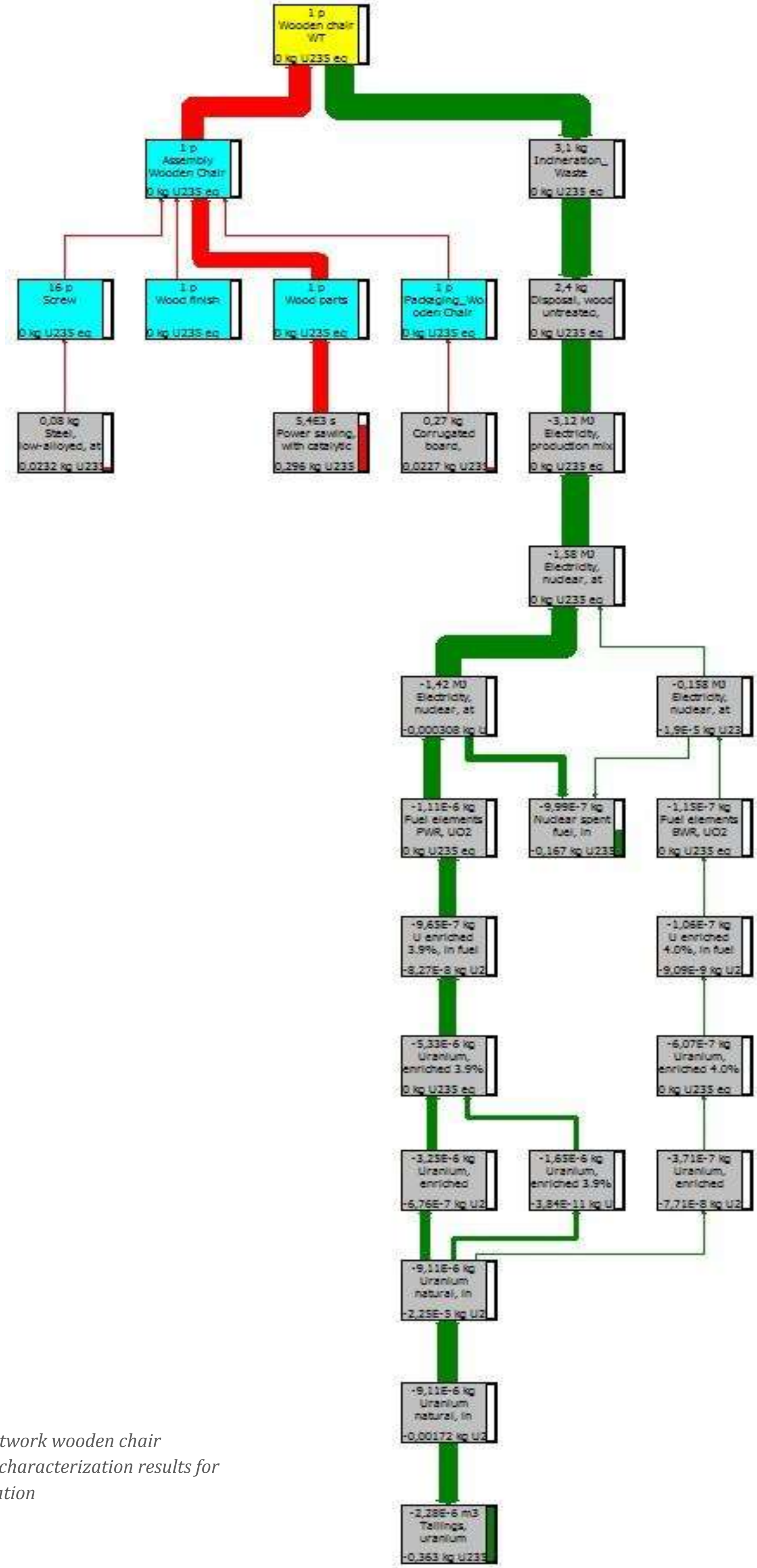
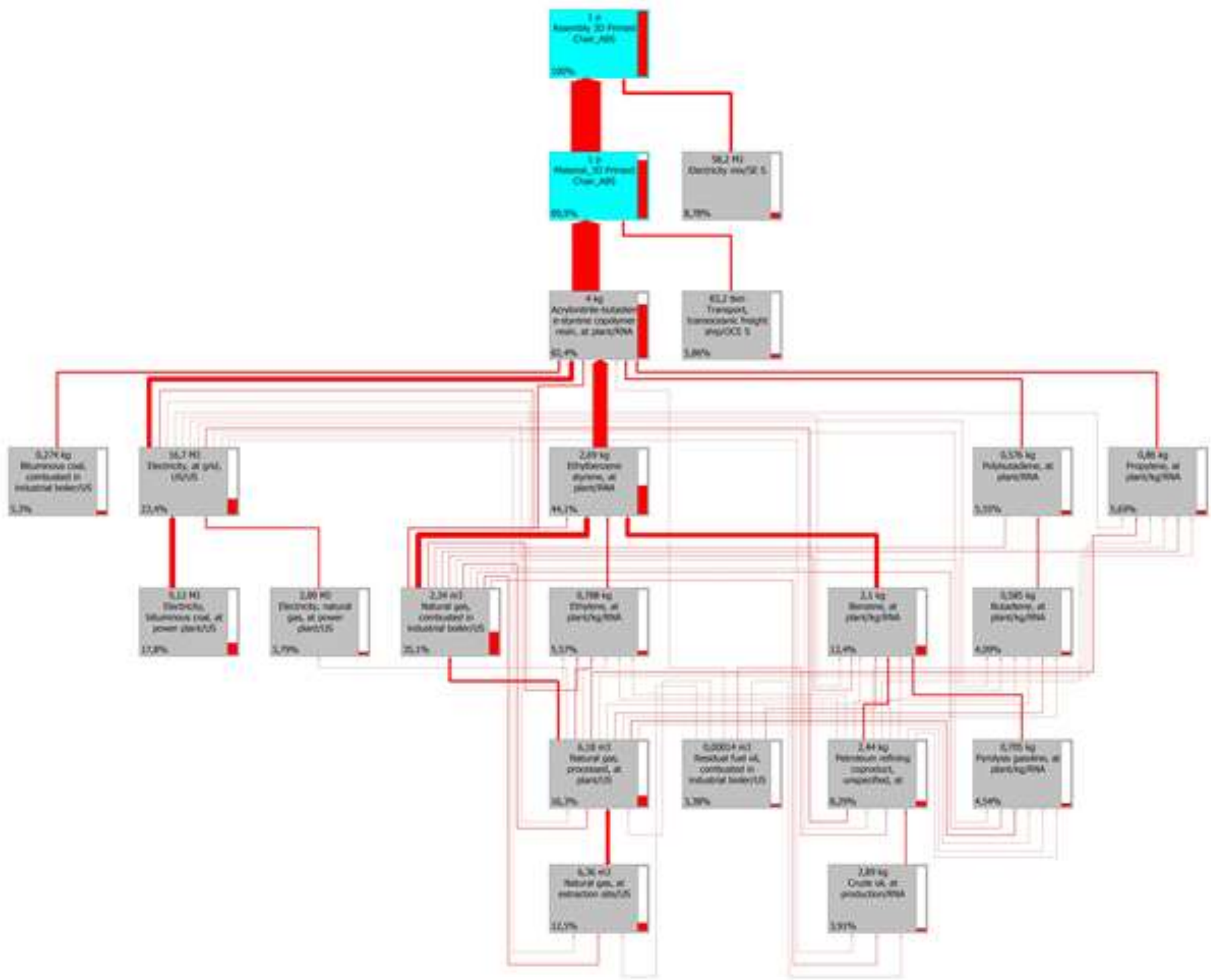


Figure 15: Network wooden chair incineration: characterization results for ionizing radiation

3.2 Identification of Hotspots

In this section the activities which cause the greatest environmental impact, or hotspots, in the life cycles of both chairs, are presented. In the assembly of the 3DP chair in Figure 16 the material, i.e. ABS, stands out as the one with the greatest impact due to the combination of natural gas extraction, processing and petroleum refining, combustion and use of crude oil as raw material. An electricity mixed based on bituminous coal is also a significant contribution to the impact of ABS.



Figu

As shown in Figure 17, in the assembly of the wooden chair the manufacture of the wood parts is where the most significant part of the environmental impact occurs. This is due to the fact the power sawing is, as mentioned above, a very energy-intensive process.

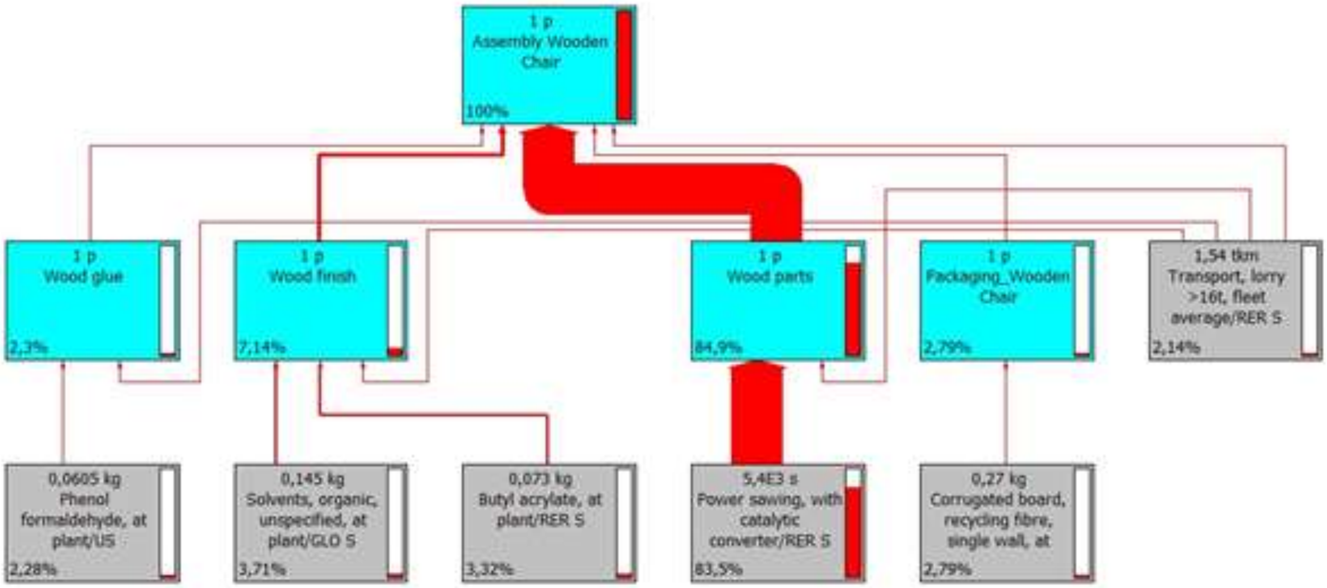


Figure 17: Network of wooden chair: normalization results for climate change (node cut-off 2%)

4. DISCUSSION

The main goal of presented study was to investigate and compare environmental burdens created by both household chairs. Also evaluate if 3D printing could be valuable contributor to future furniture production.

The lifecycle interpretation shows that comparing characterised environmental loads for one wooden chair to one 3DP chair impacts varies between different categories for each chair. For wooden chair the highest impacts are made by power sawing used to prepare wood parts for the production. Whereas, in 3D printing the material chosen for the study (ABS) has the most significant environmental impacts. However, normalised results identifies that both chairs have greatest impacts on the same categories: human toxicity, freshwater ecotoxicity and marine ecotoxicity. And one 3DP chair have higher impact on each of the above mentioned categories. This difference is even more obvious when results using the functional unit of the study are compared (1 wooden chair vs. 3 3DP chairs).

Since most of the impacts of 3DP chair are caused by the material ABS, choosing different material could possibly result in lower environmental impacts. 3D printing is a rather new technology. Further research might come across new, more durable and less environmentally harmful materials which could definitely make 3D printing a leader in future furniture production.

Another option to reduce to a limited extent the impact from ABS is to choose a supplier and a supply chain for the material than involves a more environmental-friendly electricity mix, e.g. a local producer in Sweden if available.

Then again, in this study the scenario for the wooden chair is limiting the impacts from the global value chain, which worked in favour of the wooden chair. Most of the parts, used in production of one wooden chair were assumed to be produced in Sweden. Though, in the real world this is usually not the case. The transportation of parts used in production from various further locations could increase the environmental loads.

Another factor which works in favour of the wooden chair is the fact that the dimensions of the chair are quite traditional and it is very straightforward to produce using wooden planks. Moreover, this study did not consider the optimal design potential of 3D printing. However, had the chair been a lot more complicated, for example as depicted in the introduction, the production of the wooden chair would have required a lot more energy, possibly raw material and expertise, if it even would be possible to produce something similar in wood in the first place. For the 3DP chair it would not make any big difference if the chair would be more complicated, since that is one of the main strengths of the technology.

In order to simplify the study, manufacturing of the manufacturing machines was excluded. However, it could change the results tremendously. Manufacturing of one wooden chair involves high number of various machinery, whereas 3DP chair is made by one printer.

Another interesting part to discuss is the analysis of waste scenarios. Incineration or recycling of the wooden chair does not have that big of a difference on environmental loads. Surprisingly, incineration of the wooden chair results in rather high positive impact on ionising radiation. This is due to the energy recovery from incineration, which reduces extraction of uranium used in Swedish energy mix. The analysis of the same 3DP chair waste scenarios shows that recycling of the chair is more environmentally reasonable option.

In conclusion, the study was limited due to available data and chosen scenarios. However, for the time being a wooden household chair environmentally is a more rational alternative. Maybe in the future with new printing materials 3D printing could replace traditional furniture production.

5. CONCLUSION

The performed comparative LCA of a wooden chair and a 3DP chair with an identical, conventional design showed, in general, that the 3DP chair is causing higher environmental impact. The difference increases as the impacts of the 3DP chair are tripled when applied to the functional unit - one chair for common household use with a lifetime of 15 years. This is based on the assumption that a wooden chair would last for the whole duration required by the functional unit, while the lifetime of the plastic, 3DP chair is only 5 years. An important limitation to that study was the limited data availability regarding various aspects of 3D printing, including material properties and energy usage. The acquired result challenges some existing perceptions of 3D printing as a more environmental-friendly technology than conventional manufacturing. However, it is important to point out that the main reasons for the achieved results are due to some characteristics of the studied scenarios which work in favour of the wooden chair such as a supply chain limited to the geographical boundaries of Sweden and the use of a fossil-fuel-based materials for the 3DP chair. Based on the results recommendations can be made for future case-study based LCA on specific products supported by appropriate data collection which not only reflect a more realistic value chain, but also optimize the potential of both technologies. A study including the environmental impact of building the infrastructure and manufacturing the equipment for both types of products, though unachievable in practice, would be ideal for providing the most accurate results.

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