Comparative Life Cycle Assessment (LCA) of Conventionally manufactured part vs 3D printed part

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Abstract

This report presents the comparative consequential LCA of a part produced by two different manufacturing process - Conventional Manufacturing (involving milling) and 3D printing process (SLS-Selective Laser Sintering). A specific part made from steel is analysed from cradle to the gate. The LCA is analysed, to provide a framework or guide the manufacturers, to choose the best suitable manufacturing process in terms of environmental impacts. The functional unit of 10 no's of the steel product is considered for carrying out the analysis. Due to unavailability of data or ongoing research on the 3D printing technology, some of the information is assumed or based on the literature study, research labs, and internet.

The major environmental impact categories affected by both the manufacturing processes are Marine Eco toxicity, Freshwater Eco toxicity, Natural land transformation and Human toxicity while considering the long term emissions. When excluding the long term emissions, the major impact categories are Natural land transformation, Metal depletion, Agricultural land occupation and Human toxicity. The life cycle stages that cause these major impacts are the use of electricity in the manufacturing stage and the raw material extraction and processing. Based on a sensitivity analysis of the 3D printing energy requirements it is possible to observe that the environmental impacts related to energy use are decreased but the metal depletion category is not considerably affected. A second sensitivity analysis performed with the conventional manufacturing model implies that its comparison with the 3D printing is not altered except for the metal depletion category in one case.

It is concluded from this study, that the Conventional manufacturing process is more environmental friendly than the 3D printing process for the main scenario considered. In case the manufacturing process is shifted to 3D printing from conventional manufacturing, the environmental impacts would increase further. Hence it is not advisable to selected 3D printing manufacturing process for similar scenario type.

Contents

1. Introduction

Additive manufacturing (3D printing) is evolving into a disruptive technology in the manufacturing sector (Ivanova & Campbell, 2013). Currently this new manufacturing technology is applied for manufacturing of prototypes in various sectors such as aerospace, automotive, medical, etc. Further research is being carried out to analyse if this technology can replace the traditional manufacturing process in the production processes (Sherman , 2009). In this project, an LCA would be carried out for both the manufacturing process to analyse the environmental impacts and provide a framework for the manufacturers as to which is the best process in terms of sustainability point of view.

It has been noticed that the 3D printing process is better than the conventional manufacturing process in terms of the resource efficiency (Despeisse & Ford, 2015). This is due to the less waste material produced in the additive manufacturing process compared to the conventional manufacturing process which is a subtractive process. On the other hand, it has been observed that the energy use of 3D printers in the manufacturing stage is more compared to the conventional manufacturing process (Mani, et al., 2014). Even though both the process has their positives and negatives, it's highly difficult to conclude on which is a better process in terms of environmental impacts is without carrying out an LCA (Faludi, 2013). There has been LCA carried out on 3D printing, but it is analysed for a product made of plastics and not for metals (Bühner, 2013). In this project the LCA would be carried out from Cradle to Gate perspective.

2. Goal of the study

Manufacturing sectors have their vision to become more sustainable in terms of energy use and resource efficiency. Hence, the goal of this project is to analyse the best manufacturing process - Conventional Manufacturing vs 3D printing in terms of environmental impacts. Comparative LCA would be carried out for both the process of manufacturing assuming a sample metallic product. This LCA would be a change oriented LCA as we are analysing if the conventional manufacturing process can be replaced by 3D printing process.

Our study is Consequential LCA as we are investigating what the environmental consequences of 3D -Printing will be against the conventional manufacturing. Even though our part is not a real part used in any assembly, this study can provide very useful data related to energy consumption per unit of mass or time that either of the two processes uses. So depending on the results of our study, a manufacturing company would be able to define which method will save costs related to energy consumption as well as which one is more environmentally friendly.

The main aim of conducting this LCA is to provide a framework or guideline to the manufacturers for selecting suitable and best manufacturing process. The audience for this LCA study would be the manufacturers of different industries such as Automotive, Aerospace, Medical, etc.

3. Scope of the study

a. Functional unit

The functional unit considered for this project is the quantity of the parts produced. We have assumed that the functional unit is equivalent to 10 numbers of the test piece considered for analysis. The test piece considered is not a real part or product used in any industry and hence we consider the number of parts as the functional unit. We also assume that the material properties used in both the processes are same. All calculations carried out in this LCA are based on the function unit of 10 numbers of the manufactured part. The dimensions of the test piece considered in this analysis are shown in Figure 1.

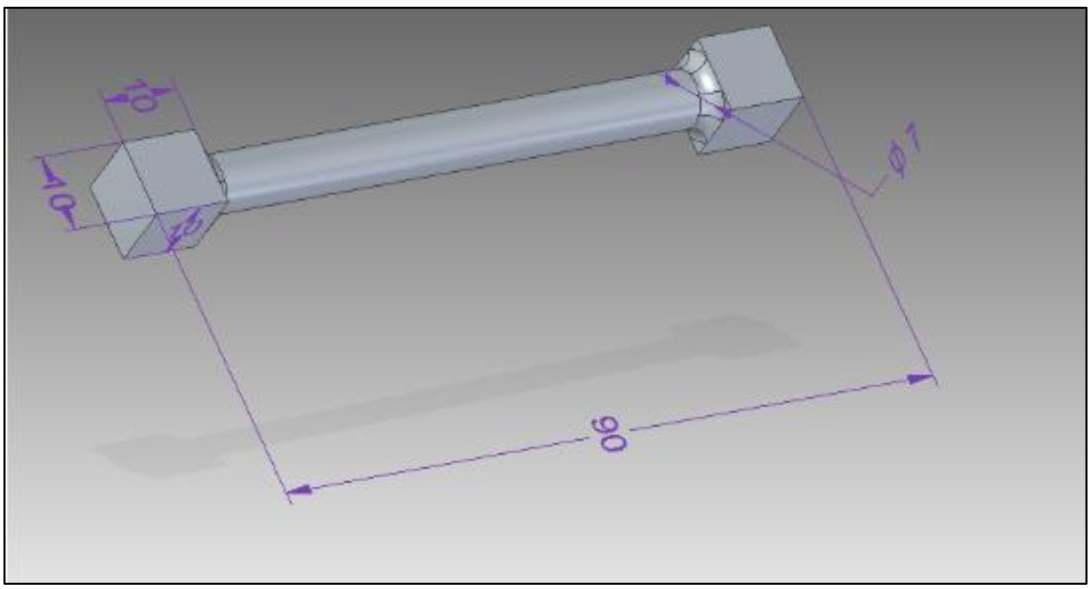

Figure 1: Manufacturing product considered for the LCA analysis

b. System boundaries

This LCA project analyses the manufactured part within the system boundary from Cradle to Gate, i.e. starting from the raw material extraction till it leaves the manufacturers gate for dispatch to its customer. The transport for dispatch, use by customer and the waste management is not considered for this LCA study. However the waste produced during the conventional manufacturing process is considered as recovered but used for production of another product and is defined as an open loop cycle waste scenario.

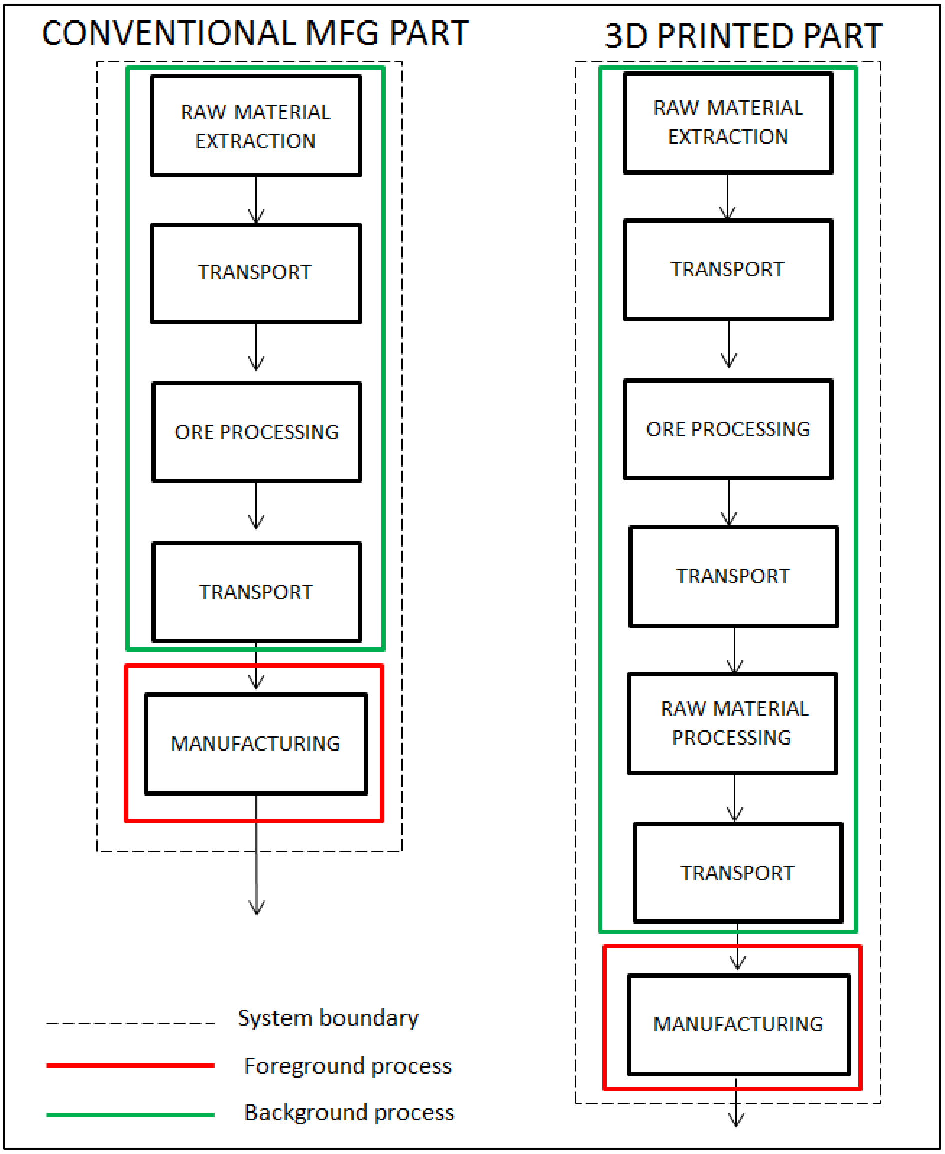

Figure 2: System Boundary considered for the LCA analysis (Cradle to Gate)

The system boundary considered for the LCA is ‘cradle to Gate’ as shown in Figure 2. Cradle represents the extraction of the iron ore and the gate represents the exit of the parts from the manufacturer.

Geographical boundaries: The entire LCA is analysed is limited to the boundary of Sweden.
Time horizon: Not applicable for this project
Cut-off criteria: The cut-off is set at 0%, and hence all the processes are considered. No process is neglected and hence all impacts are analysed.

Allocation procedures: The allocation problem arises in the extraction process and the iron ore processing. Since these ores are used as raw material for manufacturing number of other products and assemblies, the allocation is based on the weight of the material used for the production of the metallic test piece considered for this LCA Study.

Also the allocation problem arises in the transportation stage because the truck is used for carrying other items apart from the mineral ore of the processed part. In this case also the weight of the material transported is considered to resolve the allocation issue. For the whole LCA study the allocation problem is solved based on the physical unit - weight of the FU.

c. Assumptions and limitations

Due to lack of access to certain information and limitation imposed by SimaPro, some assumptions are made to be able to complete the model.

Raw material -Steel Processing: The product considered is manufactured from low-alloy Steel. From the SimaPro database, the origin of this specific product is from Quebec in Canada. Our geographical position of interest is Sweden. The steel used is assumed to be extracted and processed in Luleå, thus for the analysis Quebec is going to be assumed as Luleå. Also the properties of the conventional manufactured part are assumed to be the same as the 3D- Printed and the density is 7.6 g/cm^3. The steel blocks produce from Luleå have dimensions 110x16x16mm and have a total weight of 0.3kg.

Transportation: All the transportation is assumed to be through road with a truck (*Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Alloc Def, S*).

Conventional Manufacturing: Three cases of conventional manufacturing are considered for sensitivity analysis in order to investigate the environmental impacts: Metal working, Milling and a manually created operation based on time consumed for manufacturing. The two first scenarios exist in SimaPro, therefore there is no assumptions were made. The last scenario though is a case where educated assumption has been made for manufacturing time of our product. Also the machine used is not available in SimaPro, hence a 5-axis milling machine has been considered from the catalogue in internet (Haas Automation Inc, 2016). By knowing the energy consumption of the machine and the processing time, approximated total energy consumption is found.

Atomization: A process called Atomization is considered for the analysis in 3D printing manufacturing, where the raw metal will be transformed into powder before using it for 3D printing. Because this process does not exist in SimaPro, average energy consumptions related to that have been found in literature (The EPRI Center for Materials Production, 2000).

Electric Arc Furnace: For the disposal scenario EAF is used in the conventional manufacturing process. This method is not supported by SimaPro, thus average energy consumptions related to that have been found in literature. An amount of 80% from the final product is assumed to be sent to EAF, and the rest is sent to a DummyDisposalScenario. (Institute of Industrial Productivity, 2016)

3D Printing: Information related to 3D Printing is gathered from the KTH Production Lab, as it is not supported by SimaPro. Approximations related to manufacturing time and parts have been done, as the exact information had not been stored in any database. (Lab, 2016)

Recycling: For conventional manufacturing 80% of the scrap material is assumed to be recycled. For 3D-Printing there is no disposal scenario as no extra material is produced during the manufacturing process. There are though defective part created, but according to KTH Production lab, it is not defined yet if these parts can be recycled, thus waste scenario is not included during 3D - Printing. (Lab, 2016)

Electricity: Marginal source of electricity is used for all scenarios as the production times is assumed and multiplied with the electricity to define the kWh (E*lectricity, medium voltage {SE}| market for | Alloc Def, S*).

d. Impact categories and impact assessment method

The ReCiPe Midpoint (H) V1.12/ Europe Recipe H is the method used to assess the impact categories (Recipe, 2013). This method is valid only in the Europe region. The following impact categories are included in this method. (ReCiPe, 2008)

- Climate change
- Ozone depletion
- Terrestrial eco-toxicity
- Freshwater eco-toxicity
- Marine eutrophication
- Human toxicity
- Photochemical oxidant
- Particulate matter formation
- Terrestrial acidification
- Freshwater eutrophication
- Marine Eco toxicity
- Ionizing Radiation
- Agricultural land occupation
- Urban land occupation
- Natural land transformation
- Water depletion

- Metal depletion
- Fossil depletion

The comparative LCA analysis in this report includes all the impact categories mentioned below but focuses mainly on the top 4 major environmental impact categories identified from the normalisation results discussed later in the report.

e. Normalisation and weighting

The normalisation is used for comparing different impact categories with each other. The results are projected as ratios without any units for ease of comparing different impact categories. Normalisation of the results can identify the top major/ significant impact categories caused due to the life cycle of the product.

Weighting is an optional final step in LCA after classification, characterisation and normalisation. In this step, a weighting factor (based on the significance of the impact category) is multiplied to the normalisation results to get a single score for the environmental performance of a product or scenario. Since the weighting factor can vary depending on the views of the different people, it can affect the final result of the analysis and hence is not carried out in this analysis and report. (Brilhuis-Meijer, 2015)

4. Life cycle inventory analysis

a. Process flowchart of Conventionally Manufactured Product

In Figure 3, the lifecycle of conventional manufacturing is shown. The extraction and processing of iron ore into steel is taking place in Luleå, where steal blocks of 3kg are created. Next step, as the raw material is ready, it is to be sent to the manufacturing facility of Scania AB in Södertälje. The Conventional Manufacturing is assumed to be carried out at Scania in Södertälje. From CAD software calculations, it has been concluded that 80% of material is removed from the initial block (110*16*16) for the production of the finished product. This steel waste scrap from manufacturing is recycled with the use of an Electric Arc Furnace. 80% of the scrap is sent to Sandvik AB, where such a recycling facility exists but considered to be used for producing another product forming an open loop waste scenario. The benefits of recycling are not considered in this analysis, but the energy utilised for recycling is considered as part of the life cycle. In reality the rest 20% should be sent back to Luleå for the production of the raw material, but it is not considered in this project.

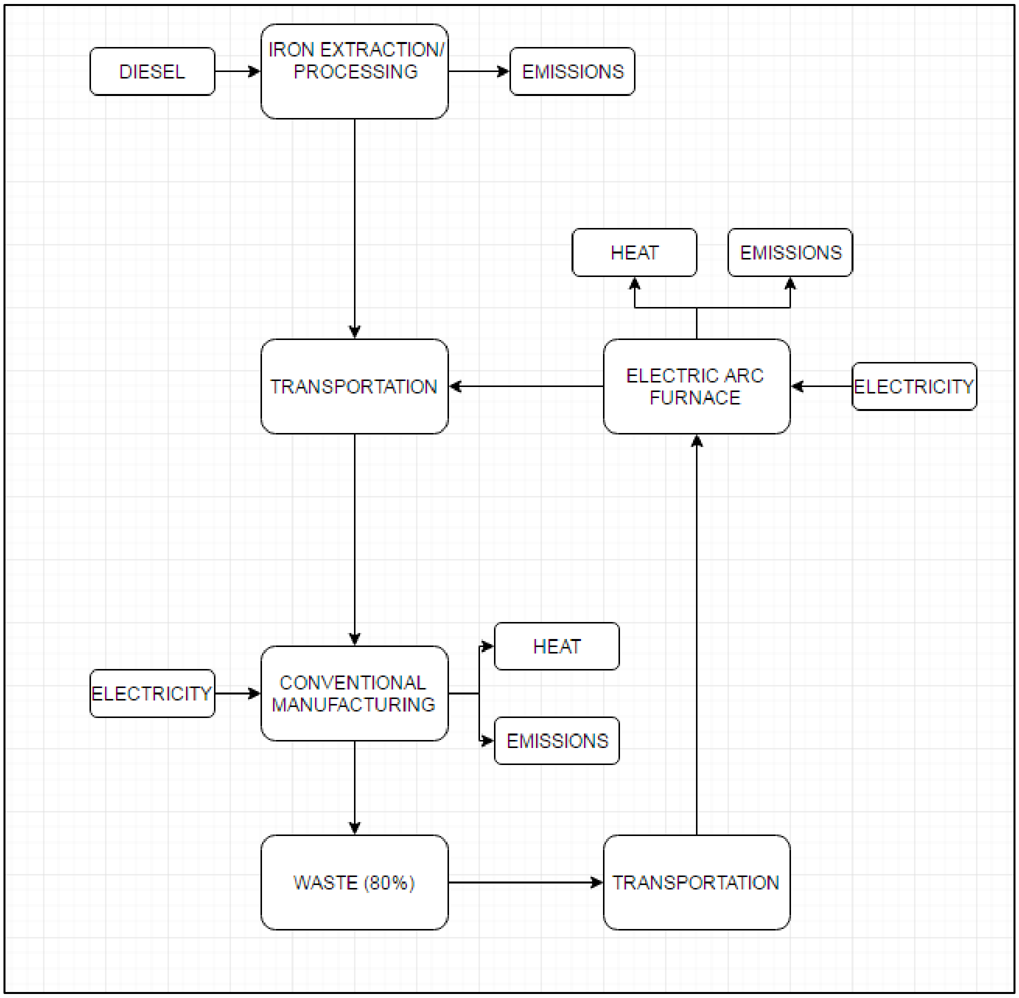

Figure 3: Detailed Life cycle stages for the conventionally manufactured part

b. Process flowchart of 3D Printed Product

In Figure 4, the lifecycle of conventional manufacturing is shown. The extraction and processing of Iron is the same as previously described. The next step in this scenario is the transport of the steel raw material to a facility in Söderfors. Over there the steel is being transformed into powder with a procedure called atomization. When the powder is finished it is assumed to be transported to Scania AB, where the 3D-Printer is available, and be used for the creation of the finished parts. Disposal does not exist for 3D - Printing as no excess material/ waste is being produced during the manufacturing process.

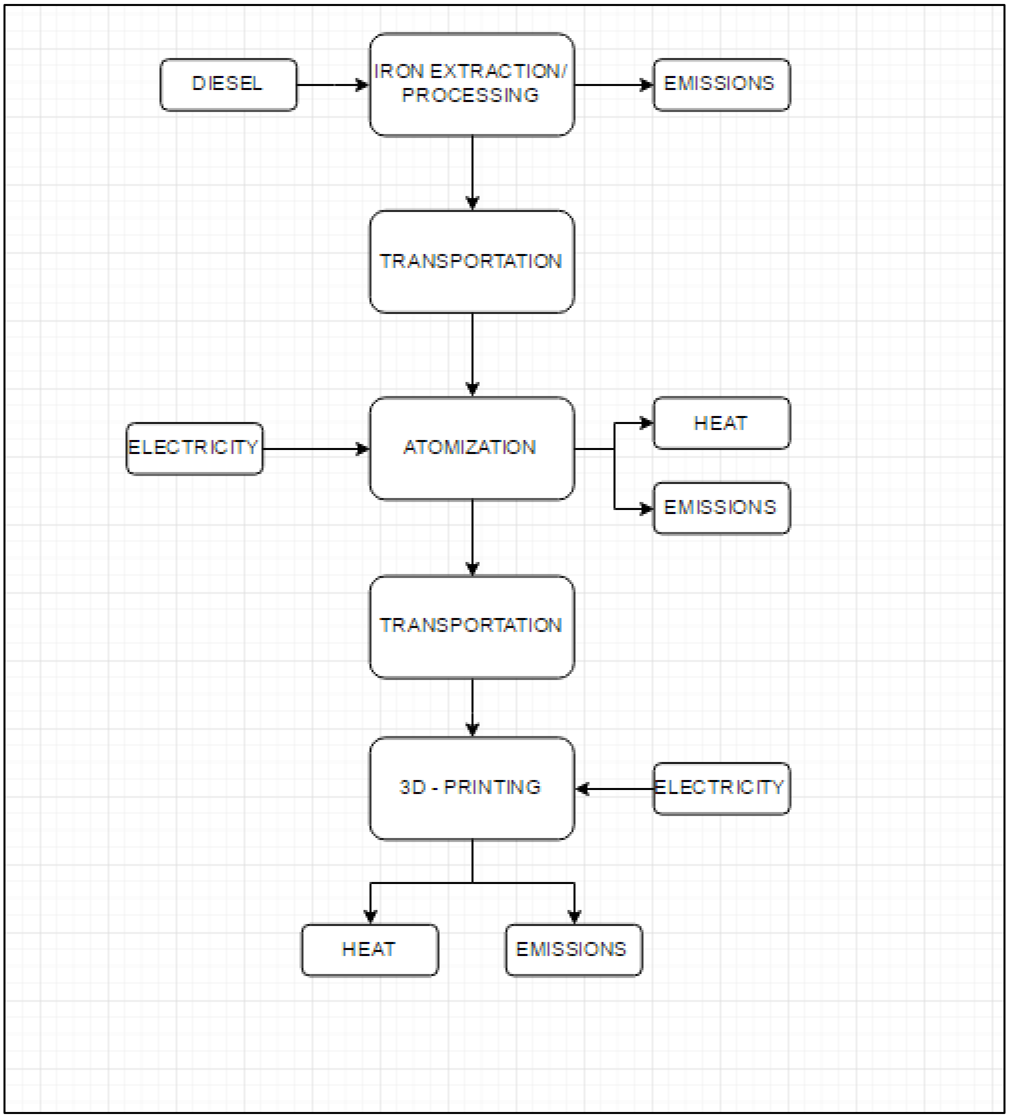

Figure 4: Detailed Life cycle stages for the 3D printed part

c. Data

In this chapter the data sources and used for analysis in our study are stated and explained. The data has been mainly taken from Ecoinvent 3 wherever applicable and the rest is acquired from literature review and the KTH Production Engineering department. For the input processes in SimaPro see Appendix. The chapter is divided into 3D Printing, Conventional Manufacturing and Common (common processes for both scenarios where the same datasets are used)

3D printed manufacturing

Atomization: This is the procedure where the steel raw material is transformed into powder. For this occasion SimaPro's libraries were not sufficient, therefore literature study had to be done to obtain the model that would be used. It was observed that an average amount of energy 8.4 MBtu/ton is used during the atomisation process (The EPRI Center for Materials Production, 2000). The functional unit is ten parts produced and serves perfectly the calculation to realize the energy required to create the needed powder. The electricity used has been *Electricity, medium voltage {SE}| market for | Alloc Def, S*.

3D-Printing: As 3D-Printing is a rather new technology, SimaPro has no sufficient information to add this specific process in its libraries. Therefore, investigation was carried out to obtain information related to 3D printing process. KTH Production Department has a newly acquired 3D Printer. The model is the Q10plus and is produced by Arcam AB. It was considered a good strategy to use it as a reference as data could be obtained from a valid source like the KTH lab (Lab, 2016). The test piece used for the LCA analysis is one that has already been produced by KTH Lab. Thus information related to the 3D printing time, quantity were collected and utilised for the LCA analysis. Production time was 20 hours for the creation of 10 parts (Lab, 2016) and the peak energy requirement for the 3D printer is 7 kW (Arcam AB, 2016).The electricity used has been *Electricity, medium voltage {SE}| market for | Alloc Def, S*.

Conventional Manufacturing

Manufacturing: The scope of the project is to define the environmental impact of conventional manufacturing against 3D-Printing, thus the manufacturing part is an important subject to obtain realistic or at least comparable results. Initially, it was concluded that the dataset obtained from Ecoinvent 3 *Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def, S for* 3 kg (Functional Unit) would be sufficient for the study. Later it was decided to have a more specific scenario, as the part selected is manufactured with milling process. SimaPro has in its database *Steel removed by milling, small parts {GLO}| market for | Alloc Def, S* which is the process required. The waste produced for manufacturing the test piece is approximately 87% of the total raw material and it was subtracted from the three kg of steel (Functional Unit).

As mentioned in the 3D-Printing data chapter, there are no datasets for the process of 3D printing in SimaPro, thus the energy consumption is calculated by multiplication of the machine's operational energy consumption and the time required for completion of the manufacturing of the test pieces. As the study is a comparative one, it has been decided that the energy consumption during the formation process of our product in conventional manufacturing should be carried out in a similar way, for better comparison results. Thus an industrial 5 – Axis milling machine has been chosen for the study (Haas Automation Inc, 2016). Again there had to be assumptions related to the time of processing. The total time for conventional manufacturing has been assumed to be 6 min/piece, which includes setup time, processing and removing from the fixture. The electricity used has been *Electricity, medium voltage {SE}| market for | Alloc Def, S.*

All three scenarios have been produced and kept for our study. For the comparative study our third mentioned process has been used for conventional manufacturing. The other two scenarios are later used in the sensitivity analysis discussed later in this report.

Electric Arc Furnace (Recovery): The recovery part of the steel scrap is done with the use of an Electric Arc Furnace. The SimaPro libraries do not support this function and for this reason the model had to be constructed manually. From literature review it was found that the average energy consumption to recover a ton of steel with the EAF procedure is 350 KWh (Institute of Industrial Productivity, 2016).

As it is a recovery/recycling process, this procedure is created as a disposal scenario. When creating disposal scenarios the assembly has to be stated, as well as the different waste scenarios. In reality, for the production of steel, scrap material is used. Therefore it has been chosen that 20% of the scrap from manufacturing process of our products is sent for the raw material creation and 80% is being recycled, with the use of Electric Arc Furnace. For this project though, the investigation is on a "worst case scenario", thus no benefits from any recycling will be included. Thus the 20% of scrap is sent to DummyWasteScenario in SimaPro. One kg of material is used to find, what the consumption would be for this process. The electricity used has been *Electricity, medium voltage {SE}| market for | Alloc Def, S*.

Common

Iron Extraction and Basic Oxygen Furnace: As Iron Extraction is a subject that has extensively been investigated by Environmental Sciences there are extensive sources of information related to this subject. SimaPro's libraries has a complete selection of iron extraction processes (i.e. types of iron, finished products from iron, post-processing), therefore the data input for this occasion was selected from the Ecoinvent 3 library. As the final product of interest is low- alloyed steel, the possibility of using the dataset for steel from SimaPro was investigated. It was concluded that it would be a perfect fit, as it includes the extraction process, as well as the post- processing (Basic oxygen furnace). Thus the chosen dataset was *Steel, low-alloyed {GLO}| market for | Alloc Def, S.*

Transportation: For all the transport between each location *Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Alloc Def, S* from the Ecoinvent 3 library is chosen. The unit is in tkm and the amount has been a calculation of the distance between the location (obtained from online maps) and the Functional Unit. The Functional Unit serves perfectly this calculation as it has chosen to be ten pieces and the total weight can be easily calculated.

5. Life cycle interpretation

a. Normalisation Results – 3D printing

Normalisation results can be used for comparing different impact categories, as these impacts are individually converted by a multiplication factor, to have all the impacts in a single unit or ratio form. From this analysis we would be able to identify the significant impact categories of both the manufacturing process separately. The significant impact categories with long term emissions and excluding short term emissions are discussed below for both the manufacturing process: 3D printing and Conventional manufacturing. The life cycle stages causing these impacts are also identified.

Including long term emission:

The major impact categories in the 3D printing process are Marine Eco toxicity, Freshwater Eco toxicity and Natural Land Transformation as shown in Figure 5. All the three impact categories are caused due to the use of electricity in 3D printing and also due to the raw material used i.e. steel as shown in Figure 6. Since the peak value of electricity usage (7kW) is assumed throughout the 3D printing process and considered for the life cycle analysis, the sensitivity analysis is analysed by changing the values of the electricity used for 3D printing and discussed later in this report.

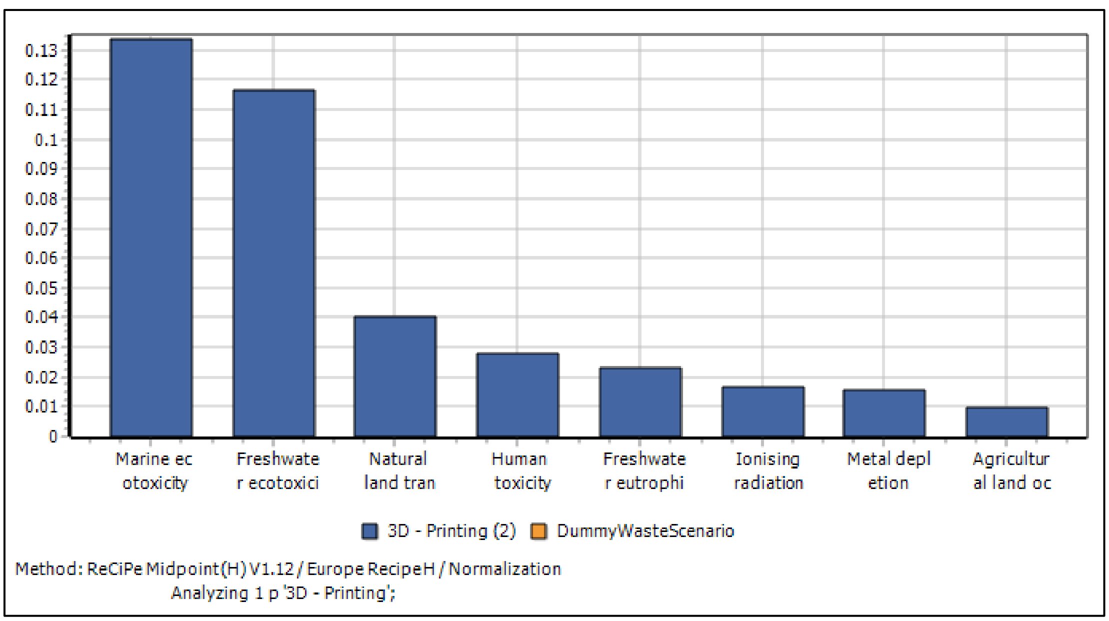

Figure 5: Normalisation Results of 3D printing (including long term emissions)

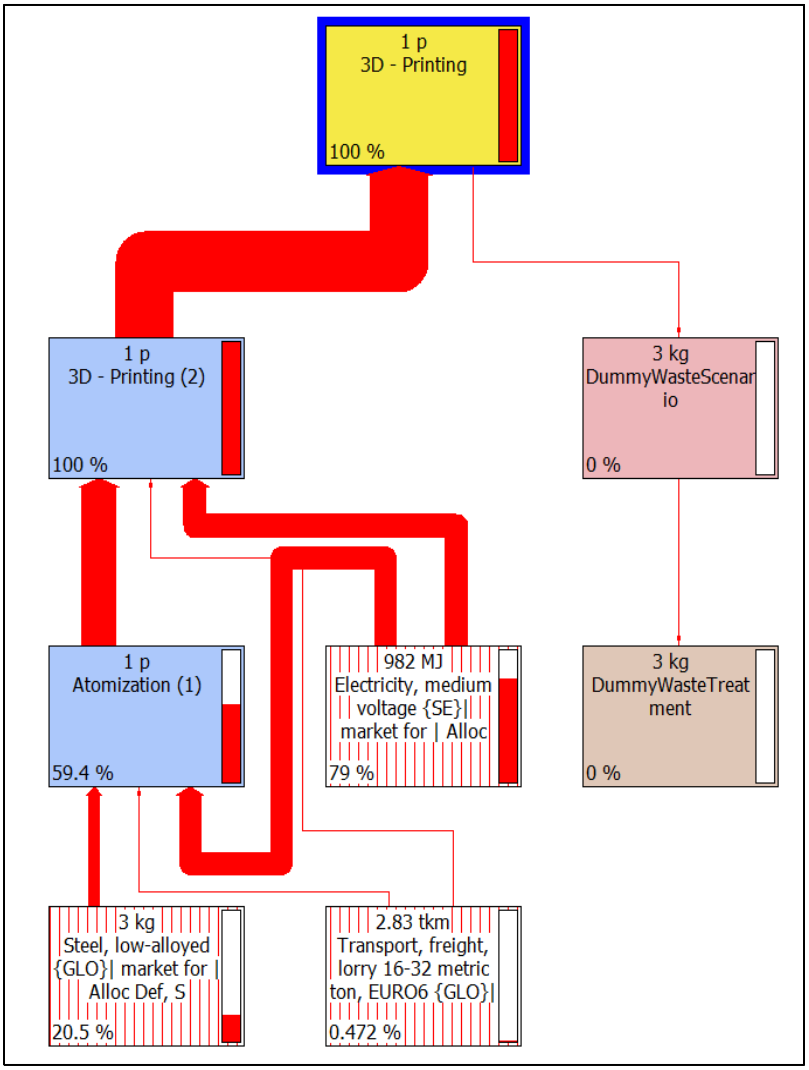

Figure 6: Normalisation - Marine Eco toxicity (including long term emission) - 3D printing

<u>Excluding long term emission:</u>

On a short term basis, the major impact categories in the 3D printing process are Natural Land Transformation, Metal depletion and Agricultural land occupation as shown in Figure 7. These impacts are hugely because of the electricity used during the life cycle from cradle to gate and also due to the raw material steel used for the manufacturing as shown in Figure 8.

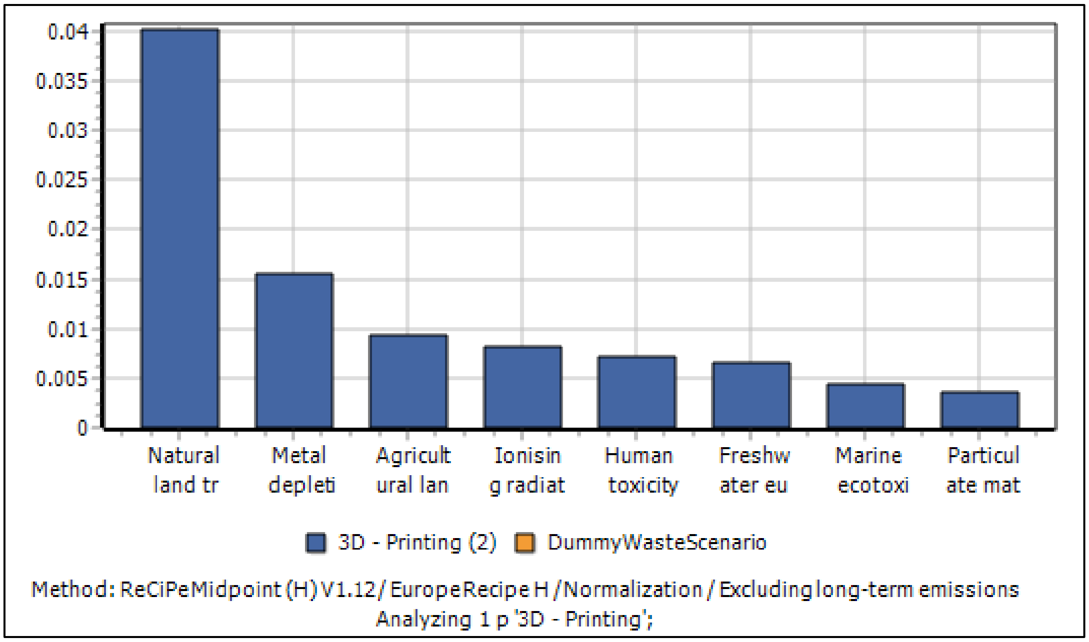

Figure 7: Normalisation Results of 3D printing (excluding long term emissions)

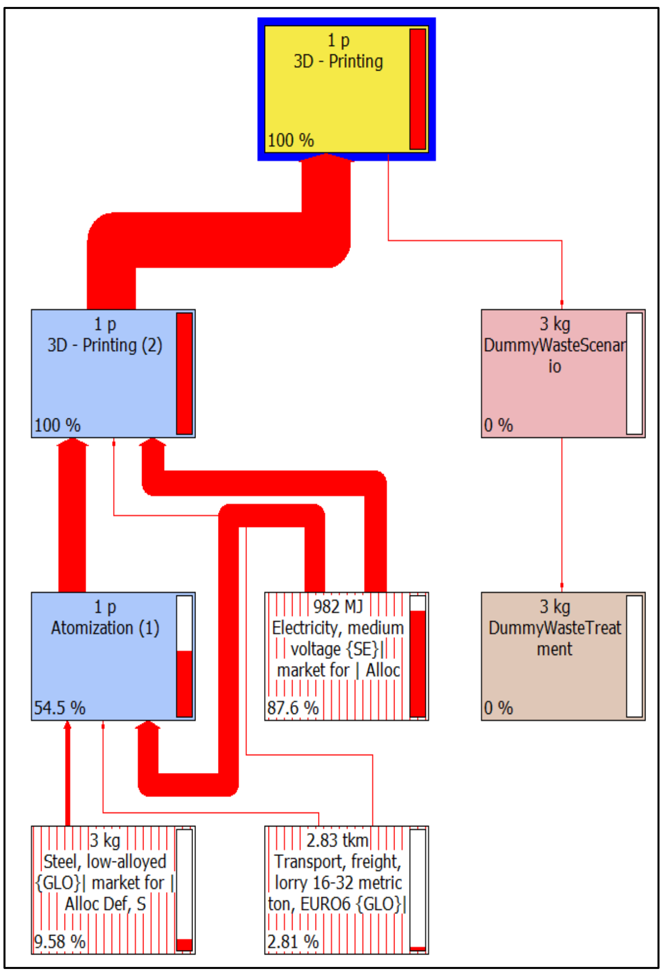

Figure 8: Normalisation - Natural land transformation (Excluding long term emission) - 3D printing

b. Normalisation Results – Conventional Manufacturing

<u>Including long term emission:</u>

The major impact categories in the conventional manufacturing process are Marine Eco toxicity, Freshwater Eco toxicity and Human Toxicity as shown in Figure 9. The Marine Eco toxicity, the freshwater Eco toxicity and human toxicity is caused mainly due to is caused due to the material steel extraction and processing used for manufacturing the product as shown in Figure 10.

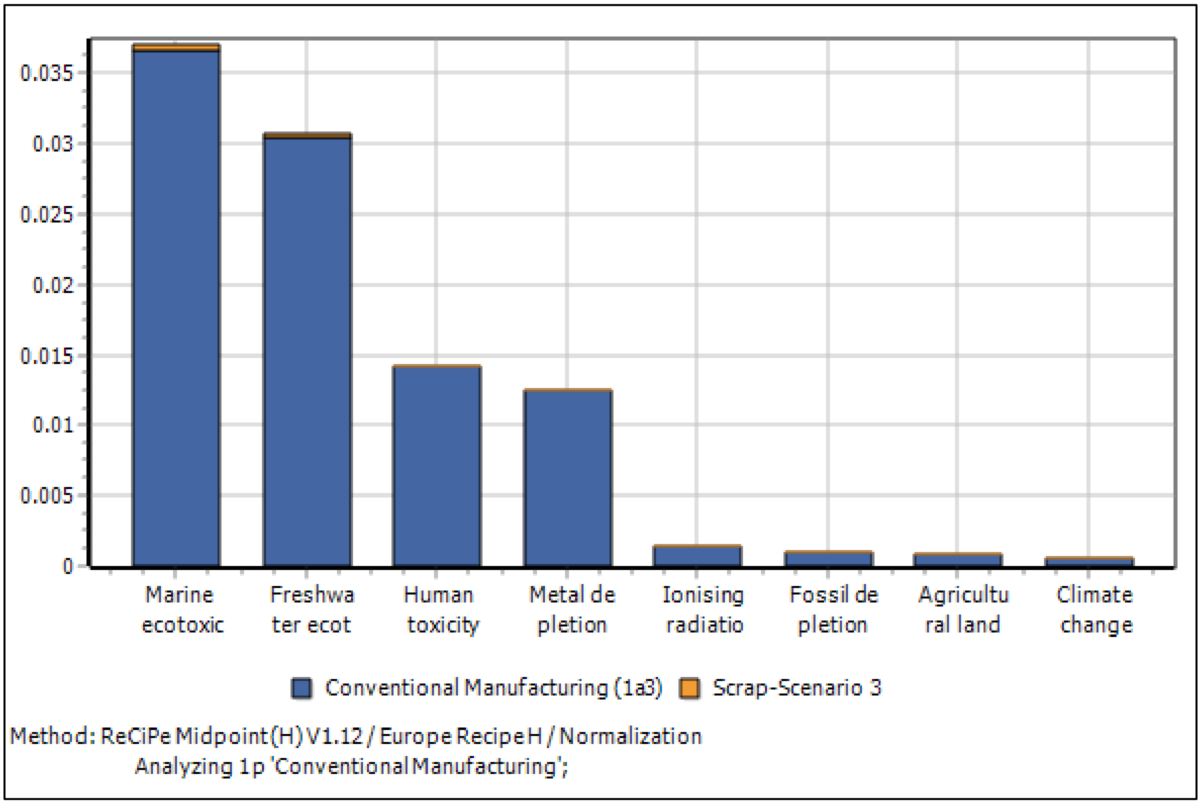

Figure 9: Normalisation Results of Conventional manufacturing (including long term emissions)

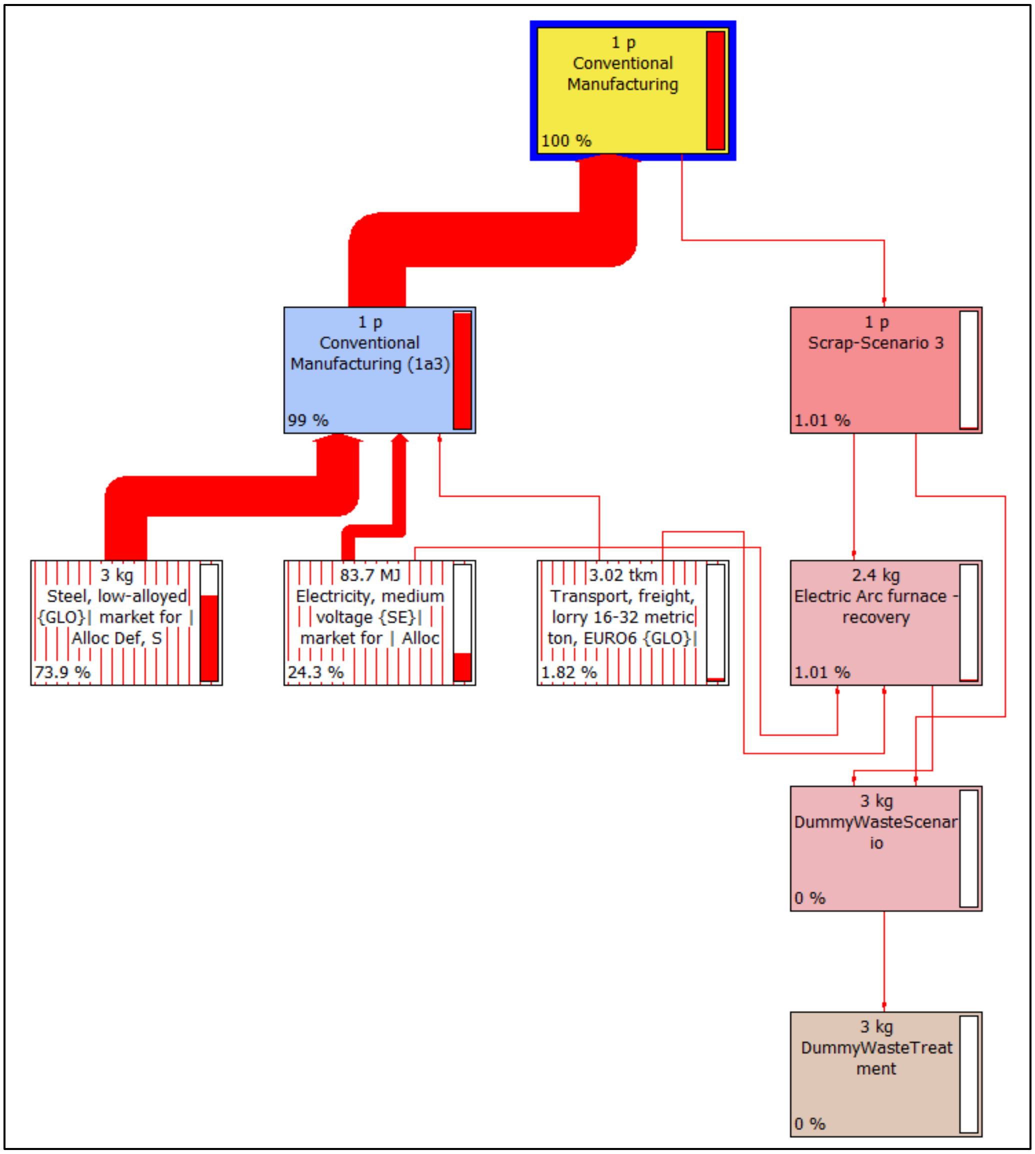

Figure 10: Normalisation - Marine Eco toxicity (including long term emission) - Conventional Manufacturing

Excluding long term emission:

The major impact categories in the conventional manufacturing process are Metal depletion, Natural Land Transformation, and Human Toxicity as shown in Figure 11. These impacts are mainly due to the raw material steel used for manufacturing (material extraction process and processing) as shown in Figure 12.

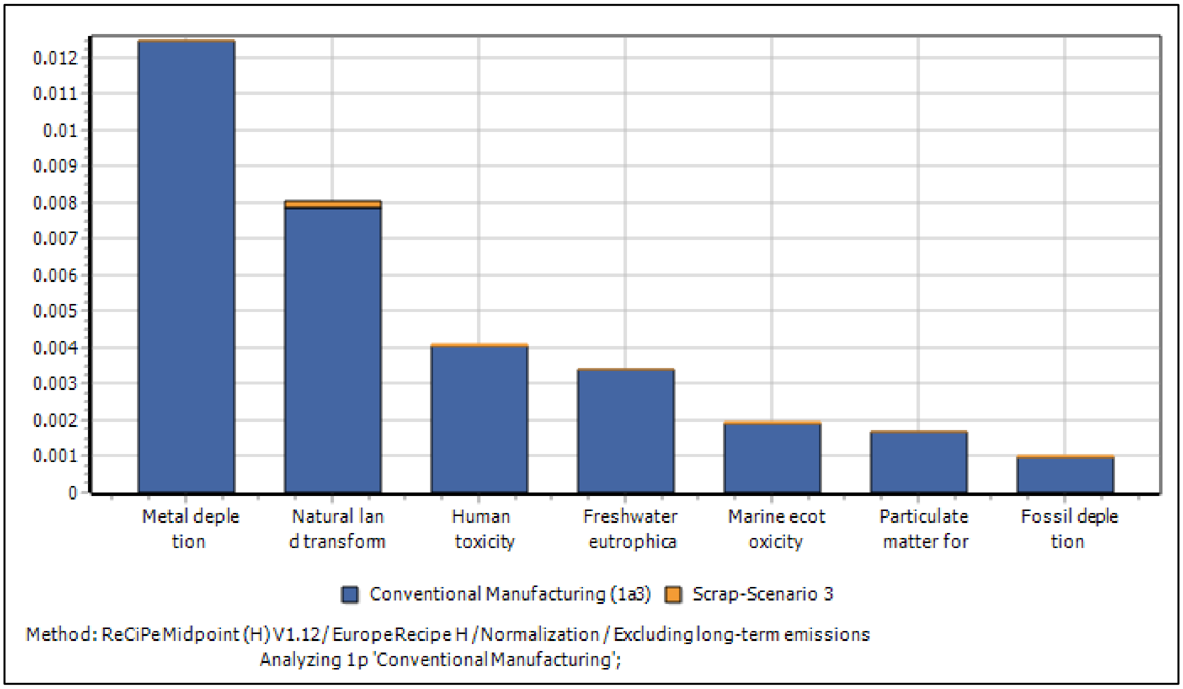

Figure 11: Normalisation Results of Conventional Manufacturing (excluding long term emissions)

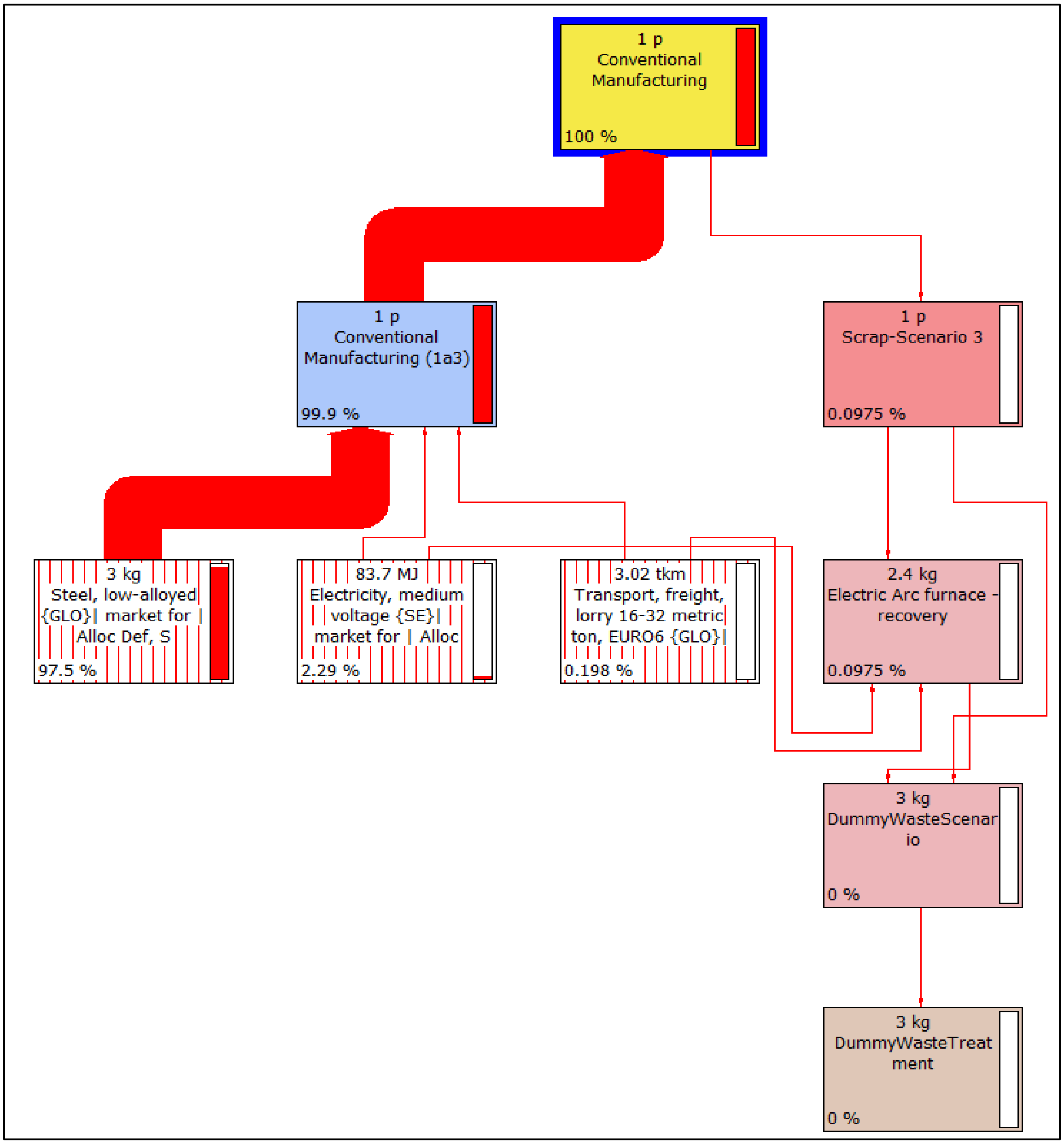

Figure 12: Normalisation - Metal depletion (Excluding long term emission) - Conventional Manufacturing

<u>Normalisation Analysis:</u>

It is clear from the results that the long term emission impacts are a quite different from the short term emissions as shown in Table 1. In long term emission case, significant impact categories are the Marine Eco toxicity, Fresh water Eco toxicity, and natural land transformation. While excluding the long term emissions, the significant impacts categories are natural land transformation, metal depletion and agricultural land occupation in case of 3D printing process. Also the major cause of these impacts is the energy use for manufacturing in both short and long term emission cases. The impact due to energy use is more than the impact caused due to the material extraction and processing in case of 3D printing process.

Emission period	Impact Categories	Conventional Manufacturing	3D printing
On Long term emission	Marine Eco toxicity	0.0371	0.134
	Freshwater Eco toxicity	0.0308	0.116
	Natural Land Transformation	0.00804	0.0401
	Human Toxicity	0.0143	0.028
Excluding long term emissions	Natural Land Transformation	0.00804	0.0401
	Metal depletion	0.0125	0.0155
	Agricultural land occupation	0.000836	0.0094
	Human Toxicity	0.00409	0.00716

Table 1: Normalisation values for the significant impact categories for both the manufacturing process

c. Characterisation Results

Based on the characterisation results it can be concluded that the impacts of the 3D printing is more than the impacts of conventional manufacturing in all the impact categories. Conventional manufacturing is environmentally friendlier in both cases of excluding and including long emissions.

<u>Including long term emission</u>

While analysing the long term emission results in characterisation it is noticed that, there is a huge difference in the ionising radiation impact category caused by both the process as shown in the Figure 13. The 3D printing process produces 105 kBq U235 eq. compared to the conventional manufacturing which produces only 9.2 kBq U235 eq. as shown in Figure 14. The other impact categories that have a huge difference in the impact caused by both the process are Agricultural land occupation, Climate change, and human toxicity. In all the above impact categories the 3D Printing process causes the major impact.

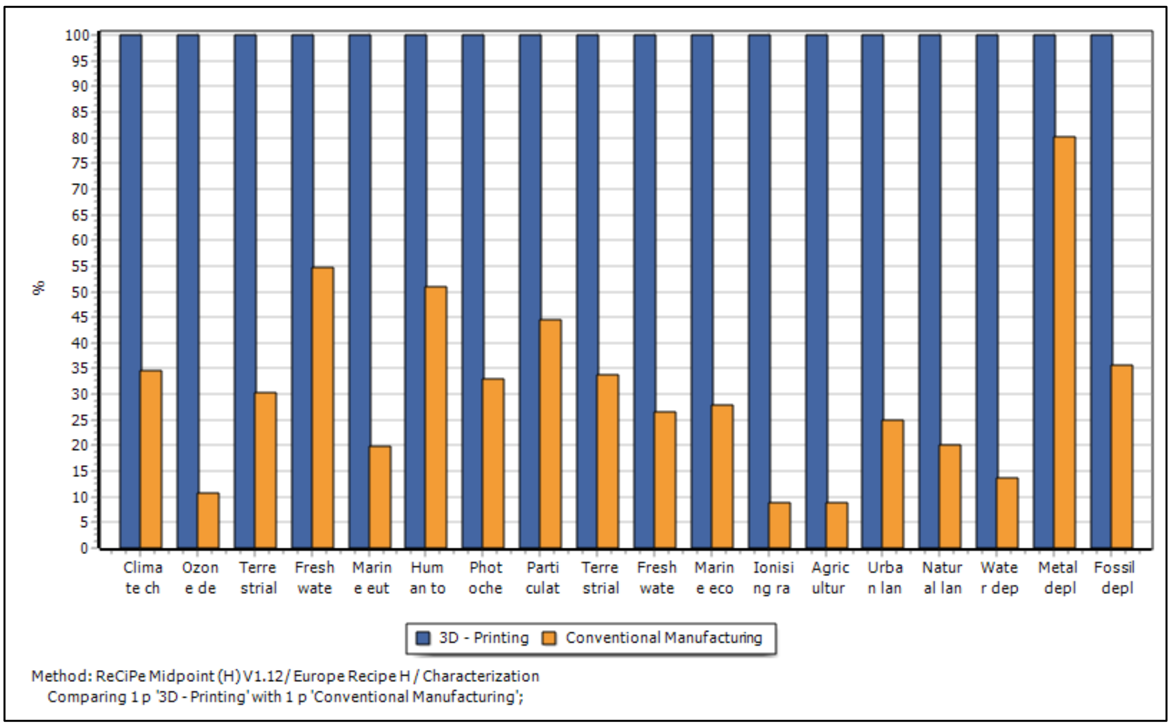

Figure 13: Characterisation Results comparing the 3D printing vs Conventional manufacturing (including long term emissions)

Sel	Impact category	Unit	3D - Printing	Conventional Manufacturing
☑	Ionising radiation	kBq U235 eq	105	9.22
☑	Agricultural land occupation	m2a	42.5	3.78
☑	Climate change	kg CO2 eq	19	6.58
☑	Human toxicity	kg 1,4-DB eq	17.6	8.98
☑	Metal depletion	kg Fe eq	11.1	8.89
☑	Fossil depletion	kg oil eq	4.39	1.57
☑	Water depletion	m3	1.86	0.254
☑	Freshwater ecotoxicity	kg 1,4-DB eq	1.28	0.339
☑	Marine ecotoxicity	kg 1,4-DB eq	1.16	0.322
☑	Urban land occupation	m2a	0.584	0.146
☑	Terrestrial acidification	kg SO2 eq	0.0981	0.0297
☑	Photochemical oxidant formation	kg NMVOC	0.0853	0.028
☑	Particulate matter formation	kg PM10 eq	0.0566	0.0252
☑	Freshwater eutrophication	kg P eq	0.00961	0.00526
☑	Marine eutrophication	kg N eq	0.00919	0.00183
☑	Natural land transformation	m2	0.00648	0.0013
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	0.00432	0.00146
☑	Ozone depletion	kg CFC-11 eq	1.48E-5	1.6E-6

Figure 14: Characterisation results (with long term emissions)

<u>Excluding long term emission</u>

While analysing characterisation results by excluding the long term emissions, it is noticed that, there is a huge difference in the ionising radiation impact category caused by both the process. The 3D printing process produces 50.9 kBq U235 eq. compared to the conventional manufacturing which produces only 4.49 kBq U235 eq. The other impact categories that have a huge difference in the impact caused by both the process are Agricultural land occupation and Climate change. In all the impact categories the 3D Printing process causes more impact compared to the Conventional manufacturing process.

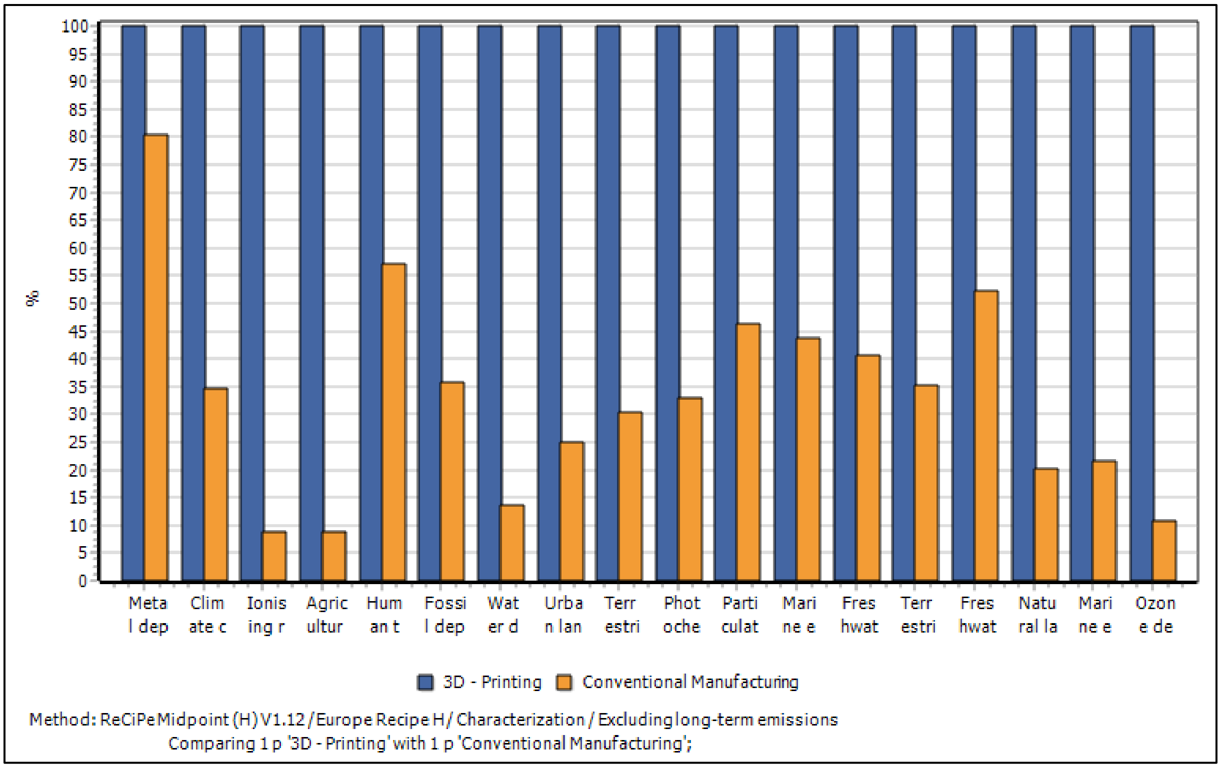

Figure 15: Characterisation Results comparing the 3D printing vs Conventional manufacturing (excluding long term emissions)

Sel	Impact category	Unit	3D - Printing	Conventional Manufacturing
☑	Ionising radiation	kBq U235 eq	50.9	4.49
☑	Agricultural land occupation	m2a	42.5	3.78
☑	Climate change	kg CO2 eq	19	6.58
☑	Metal depletion	kg Fe eq	11.1	8.89
☑	Human toxicity	kg 1,4-DB eq	4.5	2.57
☑	Fossil depletion	kg oil eq	4.39	1.57
☑	Water depletion	m3	1.86	0.254
☑	Urban land occupation	m2a	0.584	0.146
☑	Terrestrial acidification	kg SO2 eq	0.0981	0.0297
☑	Photochemical oxidant formation	kg NMVOC	0.0853	0.028
☑	Particulate matter formation	kg PM10 eq	0.0541	0.025
☑	Marine ecotoxicity	kg 1,4-DB eq	0.0384	0.0168
☑	Freshwater ecotoxicity	kg 1,4-DB eq	0.0107	0.00436
☑	Natural land transformation	m2	0.00648	0.0013
☑	Marine eutrophication	kg N eq	0.00473	0.00103
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	0.00407	0.00143
☑	Freshwater eutrophication	kg P eq	0.0027	0.00141
☑	Ozone depletion	kg CFC-11 eq	1.46E-5	1.58E-6

Figure 16: Characterisation results (excluding long term emissions)

Characterisation Analysis:

Conventional manufacturing is more environmental friendly than the 3D printing process in all impact categories and also on long term and short term cases as shown in the Table 2. It can be observed from Figure 14 & 16, that the ionising radiation and the human toxicity impact increases when including the long term emissions in case of 3D printing and also the conventional manufacturing. Whereas there is no major change in the impact categories Climate change, Agricultural land occupation etc.

Emission term	**Impact Categories**	**Unit**	**Conventional Manufacturing**	**3D printing**
On Long term emission	Marine Eco toxicity	Kg, 1,4-DB eq.	0.322	1.16
	Freshwater Eco toxicity	Kg, 1,4-DB eq.	0.339	1.28
	Natural Land Transformation	m2	0.0013	0.00648
Excluding long term emissions	Natural Land Transformation	m2	0.0013	0.00648
	Metal depletion	Kg Fe eq	8.89	11.1
	Agricultural land occupation	m2a	3.68	42.5
	Human Toxicity	Kg, 1,4-DB eq	2.57	4.5

Table 2 : Characterisation results for the significant impact categories of both manufacturing process

Overall Analysis

The 3D printing machine uses higher electricity compared to the conventional manufacturing process and the significant impacts are caused due to the higher electricity usage in this scenario of manufacturing 10 test pieces considered for the analysis. The 3D printer consumes around 140 kWh and the conventional manufacturing uses only 22.4 kWh. Therefore the 3D printing has higher impacts than the conventional manufacturing process. The major process that causes impacts in the conventional manufacturing is the extraction and the processing of metals i.e. iron ore and steel making process in this analysis.

d. Sensitivity Analysis

In order to analyse the relevance of certain assumptions and in which way they can affect the results, a sensitivity analysis is performed. In this case, two sensitivity analyses are performed. First, the power supply of the 3D printing is decreased to 3kW, being compared with the original 7 kW (Arcam AB, 2016). The fact that the energy requirement of the 3D printer might not be continuously at its peak during the whole operation time could possibly affect the results. Also, the conventional manufacturing previously employed is compared with two other possibilities, i.e. a milling process available in the Ecoinvent database and a milling machine from Haas Automation Inc (2016), an external source. This second sensitivity analysis intends to compare how different models can affect the results of the conventional manufacturing process in relation to the 3D printing.

3D printing with lower energy requirement

Sel	Impact category	Unit	Lifecycle 3D - Printing	Lifecycle 3D - Printing 3kW
☑	Marine ecotoxicity		0,134	0,103
☑	Freshwater ecotoxicity		0,116	0,089
☑	Natural land transformation		0,0401	0,0298
☑	Human toxicity		0,028	0,0236
☑	Freshwater eutrophication		0,0232	0,0198
☑	Metal depletion		0,0155	0,0145
☑	Ionising radiation		0,0168	0,0119
☑	Agricultural land occupation		0,0094	0,00665
☑	Particulate matter formation		0,0038	0,00312
☑	Fossil depletion		0,00282	0,00224
☑	Terrestrial acidification		0,00285	0,00222
☑	Climate change		0,00169	0,00134
☑	Photochemical oxidant formation		0,0015	0,00118
☑	Urban land occupation		0,00144	0,00109
☑	Marine eutrophication		0,000908	0,000675
☑	Ozone depletion		0,000671	0,000479
☑	Terrestrial ecotoxicity		0,000522	0,000411

Figure 17: Normalization results comparing different 3D printing power supplies (with long term emissions)

Sel	Impact category	Unit	Lifecycle 3D - Printing	Lifecycle 3D - Printing 3kW
☑	Natural land transformation		0,0401	0,0298
☑	Metal depletion		0,0155	0,0145
☑	Agricultural land occupation		0,0094	0,00665
☑	Human toxicity		0,00716	0,00617
☑	Ionising radiation		0,00815	0,00577
☑	Freshwater eutrophication		0,00651	0,00552
☑	Marine ecotoxicity		0,00442	0,00361
☑	Particulate matter formation		0,00363	0,003
☑	Fossil depletion		0,00282	0,00224
☑	Terrestrial acidification		0,00285	0,00222
☑	Climate change		0,00169	0,00134
☑	Photochemical oxidant formation		0,0015	0,00118
☑	Urban land occupation		0,00144	0,00109
☑	Freshwater ecotoxicity		0,000976	0,00079
☑	Ozone depletion		0,000665	0,000474
☑	Terrestrial ecotoxicity		0,000493	0,000389
☑	Marine eutrophication		0,000467	0,00035

Figure 18: Normalization results comparing different 3D printing power supplies (excluding long term emissions)

By decreasing the energy requirement for the 3D printing process it is possible to visualize with the normalized results that the environmental impacts connected to energy use are the ones mostly affected. Including long-term emissions, marine Eco toxicity is significantly decreased because of the lower energy requirement. Excluding long-term emissions, natural land transformation becomes the major impact, followed by metal depletion. In this case, natural land transformation suffers a relatively large reduction compared to the other environmental impacts, since it is also related to the energy supply of the 3D printer. On the other hand, decreasing the energy requirements of the process does not affect metal depletion considerably, since the amount of metal used by the 3D printing process itself remains the same.

Conventional manufacturing models

Lifecycle 1a uses a metal working process from the Ecoinvent database for the conventional manufacturing. Lifecycle 1a2 uses a milling process also from the Ecoinvent database. Lifecycle 1a3 is based on Haas Automation Inc (2016).

Sel	Impact category	Unit	Lifecycle 1a	Lifecycle 1a2	Lifecycle 1a3	Lifecycle 3D - Printing
☑	Marine ecotoxicity		0,048	0,0468	0,0368	0,134
☑	Freshwater ecotoxicity		0,0399	0,0387	0,0305	0,116
☑	Freshwater eutrophication		0,0196	0,0183	0,0126	0,0232
☑	Human toxicity		0,0185	0,0183	0,0142	0,028
☑	Metal depletion		0,0151	0,0159	0,0124	0,0155
☑	Natural land transformation		0,0119	0,0118	0,00789	0,0401
☑	Particulate matter formation		0,00264	0,00237	0,00169	0,0038
☑	Fossil depletion		0,00172	0,00145	0,000995	0,00282
☑	Terrestrial acidification		0,00147	0,00121	0,000858	0,00285
☑	Climate change		0,000996	0,000843	0,000582	0,00169
☑	Photochemical oxidant formation		0,0007	0,000637	0,00049	0,0015
☑	Urban land occupation		0,000543	0,000576	0,000353	0,00144
☑	Marine eutrophication		0,000232	0,000206	0,000179	0,000908
☑	Terrestrial ecotoxicity		0,000197	0,000193	0,000173	0,000522
☑	Ionising radiation		0,000173	0,000147	0,00144	0,0168
☑	Agricultural land occupation		0,000133	0,000101	0,000814	0,0094
☑	Ozone depletion		3,25E-5	2,93E-5	7,08E-5	0,000671

Figure 19: Normalization results comparing different conventional manufacturing models (with long term emissions)

Sel	Impact category	Unit	Lifecycle 1a	Lifecycle 1a2	Lifecycle 1a3	Lifecycle 3D - Printing
☑	Metal depletion		0,0151	0,0159	0,0124	0,0155
☑	Natural land transformation		0,0119	0,0118	0,00789	0,0401
☑	Human toxicity		0,00499	0,00505	0,00407	0,00716
☑	Freshwater eutrophication		0,00447	0,00442	0,0034	0,00651
☑	Particulate matter formation		0,00264	0,00237	0,00167	0,00363
☑	Marine ecotoxicity		0,00236	0,00236	0,00191	0,00442
☑	Fossil depletion		0,00172	0,00145	0,000995	0,00282
☑	Terrestrial acidification		0,00147	0,00121	0,000858	0,00285
☑	Climate change		0,000996	0,000843	0,000582	0,00169
☑	Freshwater ecotoxicity		0,00074	0,000688	0,000393	0,000976
☑	Photochemical oxidant formation		0,0007	0,000637	0,00049	0,0015
☑	Urban land occupation		0,000543	0,000576	0,000353	0,00144
☑	Terrestrial ecotoxicity		0,000197	0,000192	0,00017	0,000493
☑	Agricultural land occupation		0,000133	0,000101	0,000814	0,0094
☑	Marine eutrophication		0,000129	0,000117	0,0001	0,000467
☑	Ionising radiation		7,61E-5	6,54E-5	0,0007	0,00815
☑	Ozone depletion		3,23E-5	2,91E-5	7,02E-5	0,000665

Figure 20: Normalization results comparing different conventional manufacturing models (excluding long term emissions)

With the sensitivity analysis it is possible to perceive that the metal working process and the milling process from the Ecoinvent database yield very similar results in this case. In general, the metal working process has slightly higher environmental impacts. The milling process, however, has a higher impact on metal depletion, surpassing also the 3D printing lifecycle. The milling process has a higher impact on metal depletion likely because of the manufacturing process that is considered in the Ecoinvent database.

In turn, the conventional manufacturing based on Haas Automation Inc (2016) has lower impacts than the other two conventional manufacturing models, showing also considerably lower values for metal depletion and natural land transformation. The fact that the Ecoinvent models have more comprehensive datasets regarding environmental impacts from manufacturing processes than a model based on the energy use of a milling machine from an external source can be the cause for this.

6. Conclusions and Recommendations

a. Conclusion

The LCIA normalisation results of the two manufacturing process, shows that both the manufacturing process have almost similar significant impact categories on long term and short term emissions. The Marine Eco toxicity and Freshwater Eco toxicity are the most significant in long term emission for both the manufacturing process. The third significant impact category is Natural land transformation for 3D printing while Human Toxicity is for conventional manufacturing. Also the major and significant impacts mentioned above are due to the electricity used during the manufacturing and the steel (extraction and processing of ore) used for the manufacturing. The significant impacts in the 3D printing are due to the high electricity usage for the scenario analysed, while the major impacts in the conventional manufacturing occur due the raw material extraction and processing of the ore for.

It could be concluded from the characterisation results of both the manufacturing process, that the impacts caused during the 3D printing process is higher than the impacts caused during the conventional manufacturing process in all the impact categories. The major difference in impacts caused by both the manufacturing process is ionising radiation impact, agricultural land occupation, climate change and the human toxicity.

Considering the scenario (printing 10 test pieces) and within the system boundary ‘cradle to gate’, it can be concluded that the Conventional manufacturing process is better than the 3D Printing process in terms of the environmental impacts caused.

Reducing the energy consumption of the 3D printing process is related to energy efficiency, thus being favourable to environmental impacts related to energy use. The sensitivity analysis of the 3D printing energy requirements delivered the expected results. Compared to the conventional manufacturing, however, the 3D printing process is also time-consuming, which increases the amount of energy employed overall. If both production methods would have the same energy requirements in kWh, the 3D printing still takes considerably longer, hence increasing the energy consumption and the associated impacts.

Changing the model of the conventional manufacturing only affects the results in relation to the 3D printing when the milling process from the Ecoinvent database is selected. In this case, the metal depletion of the milling is above the metal depletion of the 3D printing. The value of the metal depletion impact is still considerably close to the values delivered by the conventional manufacturing lifecycle employing the metal working process and the 3D printing lifecycle. It is possible to say that the different models for the conventional manufacturing do not affect the comparison with the 3D printing except for the metal depletion impact in the case of selecting the milling process from the Ecoinvent database.

b. Recommendations

For manufacturing scenarios similar to the case analysed, it is recommended to the manufacturers to carry out conventional manufacturing process, as it has lesser impacts compared to 3D printing process on the whole life cycle analysis. In case if they wish to only proceed with the 3D printing process, the following are the recommendation to the manufacturers to reduce the environmental impacts caused by this process.

With regard to impact caused due to the electricity:
The 3D printing technology needs to be developed further to reduce the energy usage for printing, cooling and warming up of machine since it consumes a huge energy compared to the conventional manufacturing process. There could also be further developments made in reducing the time consumed for printing i.e. improving the productivity and efficiency of the 3D printer. Currently it is assumed that the Swedish electricity mix consists of non-renewable source of energy which is the reason for the huge impacts caused. Hence, to reduce the environmental impacts caused due to the use of electricity, shift to renewable source of energy such as solar, wind, hydro etc should be considered. The number of products printed in one setting in a 3D printer can be increased to optimise the usage of the electricity which therefore reduces the environmental impacts.

With regard to the impact caused due to the material extraction and processing:
The mineral extraction and processing is another stage which causes significant impacts on the natural land transformation and the human toxicity. This can be reduced by having better recycling and recovery of the metals to reduce the exploitation in the extraction which thereby increases the energy usage. The 3D printing process has the capability to print complex composite structure, reducing the usage of material but with the same strength properties. Therefore, the design of the product (solid product considered) could be improved (to composite structure) to reduce the use of material which thereby reduces the material extraction impacts.

c. Future Studies

The complexity of the metal product can increase the energy use in the conventional manufacturing, especially if the quantity produced also increases. In comparison, regarding the complexity of the product, the 3D printing process is not as affected as the conventional manufacturing. While the energy requirement for the conventional manufacturing might significantly increase whenever producing a complex product, it might only slightly change for the 3D printing. A larger amount of products can also relatively reduce the production time per unit, decreasing energy consumption as well. Hence, an analysis based on a larger amount of a more complex product can be a matter for further studies.

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Appendix - Input Processes

LCA	Product Stage	SimaPro Name	Assembly	Process
Conventional Manufacturing	Manufacturing	Conventional Manufacturing 1a	*Steel, low-alloyed {GLO}| market for | Alloc Def,S*	*Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def,S* *Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Alloc Def,S*
Conventional Manufacturing	Manufacturing	Conventional Manufacturing 1a2	*Steel, low-alloyed {GLO}| market for | Alloc Def,S*	Steel removed by milling, small parts {GLO}| market for | Alloc Def,S *Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Alloc Def,S*
Conventional Manufacturing	Manufacturing	Conventional Manufacturing 1a3	*Steel, low-alloyed {GLO}| market for | Alloc Def,S*	*(Milling Machine Energy Consumption) x(Total Time of Production)* Electricity, medium voltage {SE}| market for | Alloc Def, S *Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Alloc Def,S*
Conventional Manufacturing	Recycling	Disposal Scenario 1/1a/1a	Conventional Manufacturing 1a/1a2/1a3	*(Average Energy consumed per kg) x(Functional Unit)* Electricity, medium voltage {SE}| market for | Alloc Def, S *Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Alloc Def,S*

LCA	Product Stage	SimaPro Name	Assembly	Process
3D Printing	Powder Creation	Atomization (1)	*Steel, low-alloyed {GLO} | market for | Alloc Def, S*	*(Average energy consumption per kg) x (Functional Unit)* *Transport, freight, lorry 16-32 metric ton, EURO6 {GLO} | market for | Alloc Def, S* *Electricity, medium voltage {SE} | market for | Alloc Def, S*
3D Printing	Manufacturing	3D – Printing (1)	Atomization (1)	*(3D printer energy peak energy consumption)x(Time used for printing)* *Electricity, medium voltage {SE} | market for | Alloc Def, S* *Transport, freight, lorry 16-32 metric ton, EURO6 {GLO} | market for | Alloc Def, S*
3D Printing	Manufacturing	3D – Printing (2)	Atomization (1)	*(3D printer energy average energy consumption)x(Time used for printing)* *Electricity, medium voltage {SE} | market for | Alloc Def, S* *Transport, freight, lorry 16-32 metric ton, EURO6 {GLO} | market for | Alloc Def, S*