Tampere University

Heli Saastamoinen

THE LIFE CYCLE ANALYSIS OF THE MATERIAL USAGE FOR CAMOUFLAGE RADIO UNIT (CRU)

Master's thesis
Materials Science and Environmental Engineering
Associate Professor Mikko Kanerva
Professor Yvonne van der Meer (Maastricht University)
December 2020

ABSTRACT

Saastamoinen, Heli: THE LIFE CYCLE ANALYSIS OF THE
MATERIAL USAGE FOR CAMOUFLAGE
RADIO UNIT (CRU)

Master’s Thesis
Tampere University
Master’s degree program in Material Sciences
December 2020

When becoming aware of the environmental impact of all manufactured goods has become more important than ever due to the accelerating climate change. When comparing different materials and manufacturing methods can prove vital for the efforts to mitigate emissions and other negative effects. The comparing of different material choices needs to be made with comprehensive data and life cycle assessment is an irreplaceable tool to provide such results. There are lots of assumptions circling around and not all of them are fact-based. LCA can provide some insight into how environmentally friendly some materials are.

In this thesis, four materials were chosen to be compared for their environmental impact. The materials chosen were steel, plastic, natural fibre reinforced composite and, carbon fibre reinforced composite. On a theoretical level, parts were manufactured using the selected materials. The different versions of raw material acquisition, manufacturing processes and, disposal scenarios were compared to find out the version with the smallest environmental impact. Most of the data was available in LCA software, but for the composite manufacturing, a physical prototype had to be made. The physical prototype was used to acquire the data for thee composite manufacturing calculations. The power consumption of the manufacturing process was measured. Comparing the results reveals that plastic is the most environmentally friendliest material out of the ones studied.

Keywords: Life cycle assessment, LCA, natural fibre composite, carbon fibre composite, power measurement

PREFACE

This thesis was done for the faculty of Material sciences of Tampere University. It is a part of the LuxTurrim5G+ smart city project. The importance of knowing our direct and indirect impact on the environment was a key motivator for this thesis. Ensuring a better tomorrow is based on decisions made today. Those decisions, however, should be fact-based and people are keen on believing whatever fits their narrative instead of what is the truth. Educating the ignorant has always been the purpose of research and that is what I'm aiming for with mine as well.

I want to thank my examiner associate professor Mikko Kanerva for his guidance and patience. I want to thank my colleagues who motivated and encouraged me on this subject that was new to everyone. Their interest and suggestions gave me momentum when I felt stuck at a dead end. Special thanks to Pravin Luthada for borrowing his robotics equipment and knowledge. He is a busy person and yet arranged time to help with this project. I want to thank my family and friends who supported and incited me even when they did not know or understand the subject of this thesis completely. This thesis would not have been finished without them all.

In Tampere, Finland, on 7 December 2020

Heli Saastamoinen

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

LCA	Life Cycle Assessment, life cycle analysis
Radome	radar dome
GHG	greenhouse gas
CO_2	carbon dioxide
CH_4	methane
N_2O	nitrous oxide
HFCs	hydrofluorocarbons
PFCs	perfluorocarbons
SF_6	sulfur hexafluoride
NF_3	nitrogen trifluoride
SF_5CF_3	trifluoromethyl sulfur pentafluoride
I	environmental impact
P	size of the population
A	affluence
T	technology factor
ICT	information and communications technology
PLA	poly-lactic acid
ATH	aluminium trihydrate
MDH	magnesium hydroxide
WEEE	Waste Electrical & Electronic Equipment
5G	fifth-generation technology
V	volume
r	the radius of the cylinder circle
h	height of the cylinder
6G	Sixth generation technology
PA	polyamide
AFP	Automated Fiber Placement
ELCD	The European reference Life Cycle Database
CAD	computer-aided design
3D	Three-dimensional
$Al(OH)_3$	aluminum hydroxide
TiO_2	titanium dioxide
UV	ultraviolet
LCIA	life cycle impact assessment
ILCD	International Reference Life Cycle Data System recommendations
ODP	Ozone Depletion Potentials
CFC-11	trichlorofluoromethane
VOCs	volatile organic compounds

1. INTRODUCTION

1.1 The global problem

The climate change is a phenomenon where Earth's natural warming and cooling periods have been altered by human actions. The climate is now warming faster than it has warmed during the last few thousands of years [1]. Such an accelerated warming has many negative effects on the environment. The recent warming speed is too fast for evolution to keep up and, thus, many animal species face extinctions as they run out of suitable habitats [1]. The humans living in coastal regions won't fare much better. The sea level may rise 30 cm -180 cm by the end of the century and popular living areas are likely going to flood, forcing people to move elsewhere [1]. A mass exodus to the inner lands will create a huge demand for already sought-after materials and is likely going to end in large-scale humanitarian crises. These are only a few examples of how climate change might eventually affect the environment and population. The effect it will have on the whole planet has been merely roughly estimated and even the most positive predictions are promising various changes to the known natural order of things.

As the climate change has been recognized as an unavoidable event it has become crucial to try to lessen the environmental impact it causes. The environmental impact would be smaller if the amounts of so-called greenhouse gasses (GHGs) released into the atmosphere were reduced. The greenhouse gasses are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), trimethyl sulfur pentafluoride (SF_5CF_3), halogenated ethers (e.g. $C_4F_9OC_2H_5$, $CHF_2OCF_2OC_2F_4OCHF_2$, $CHF_2OCF_2OCHF_2$) and other halocarbons not covered by the Montreal Protocol (e.g. CF_3I, CH_2Br_2, $CHCl_3$, CH_3Cl, CH_2Cl_2) [2]. While most of these gasses are naturally occurring, their amount at present in the atmosphere accelerates the historically and statistically slow natural climate change process. The only way to mitigate the amount of emissions of the greenhouse gasses is to affect their sources. These gasses mostly come from the energy industry or are from the manufacturing processes. Finding alternative and more efficient methods to manufacture products and to harvest energy has become a mandatory action to further prevent the effect of the climate change.

There has been proposed a formula to vision the importance of technological advancement in preventing the climate change. The formula reads:

$$I = P * A * T$$

where *I* is the environmental impact, *P* is the size of the population, *A* is the affluence and *T* is the effect of technology. The goal is to decrease the size of the *I* value and that is only possible by affecting the other values. The size of the human population is expected to rise from the current seven (7) billion to ten (10) billion by the end of the century [3]. Even if it's theoretically possible to limit the population size by using means like the one-child policy, not many governments are keen on using such population control methods just yet. The governments affecting the population size is a slow process by any account and, thus, not very feasible. An affluence or the quality of living is something that heavily affects the environment. The more people buy and own products, the greater is the demand for manufactured goods and energy. In the terms of equality, every single human should have access to high living standards, but, unfortunately, the planet couldn't withstand that. For everyone to have equal living conditions would mean dramatic downgrades for the richest populations. Such phenomena happening is unlikely. This makes the only option to lessen the environmental impact of climate change is to advance technology [4].

Humans generate the majority of the climate change-accelerating emissions and therefore the authorities affecting people's consumption habits play a key role in slowing down the global warming process. Consumers can affect their carbon footprint by choosing products with the smallest overall environmental effects. Industry in general is responsible for around 21 % and transportation for approx. 14 % of greenhouse gas emissions globally [5]. These are the sectors consumers can affect in a relatively short timescale, so they are in a focus. A consumer making purchase decisions based on the product's whole life cycle can make a difference in the level of effect it has on the climate change.

1.1.1 What is life cycle assessment?

The Life Cycle Assessment (LCA) is a tool used to scope the environmental impact of a product or a service in its entirety. From the refinement of raw materials to the assembly, transportation, energy consumption, and recycling, LCA sums up all the emissions and other environmental effects the product generates during its lifetime. LCA (sometimes called life cycle analysis) can be used by the company itself to investigate if altering the production methods would benefit the company and its values. LCA can also be used to compare similar products and to find where their differences lie. LCA makes it possible to emphasize certain aspects if something, in particular, is more of a concern than the general result.

The comparison of the products based on their environmental effect considers the products' whole life cycle. Even if some raw material seems more harmful to the environment, the finished product and its options for recycling might make it a better option in the long run. LCA can be used to fully compare different products and production methods to find the best version available. As more companies do LCA to their products, it gives consumers a possibility to compare different types of products with one another. The results may reveal that some products are not as harmless as they seem.

LCA is a tool like any other, it can only provide data and not dictate how that data is used. There have been cases where the advancement in a technology has greatly decreased the environmental impact of a one product group. However, this smaller impact is seen as a permit to consume more of the product. This has happened with the light bulbs. As the led-based bulbs replaced the old-fashioned bulbs and older energy-saving bulbs, the demand for the led bulbs has only accelerated. The number of lightbulbs in the world is at an all-time high. The number of light bulbs alone is enough to negate the positive impact the energy-effective led bulbs have [6].

The LCA has been partly standardized. Certain phases need to be made to ensure that the LCA study meets the standard (ISO 14040). These four steps are: 1. definition the goal and scope of the study: the decision what is being studied, what things affect the studied object, what aspects are and aren't included in the study and, how the results should be assessed; 2. Inventory analysis: the collection and the calculations of the relevant data; 3. Impact assessment: the analysis of the collected data, the asking for possible corrections and additions to the collected data; and 4. Interpretation: the decision making based on the results, discussion on the results and, possible improvements based on them. Each of the above phases affects each other and, during the study, any changes in one phase should cause the re-evaluation of the other phases.

1.1.2 The importance of LCA

As environmental values have become more of a trend, some companies have made their products to reflect the change of consumer values. The products are made through seemingly greener processes and out of greener materials and are marketed as such. A closer inspection would reveal that the original product would have a less negative environmental impact than the new “greener” one. A huge per cent of consumers are not aware of this kind of greenwashing happening and are quite blindly buying into the eco-friendliness scam. The companies having comparative LCA made and published for each product and process would give an insight into which products are actually what they have promised to be. LCA is something that should be mandatory for every single product because the current marketing is not interested in verifying the advertised claims (author’s opinion).

Consumers at large are quite unfamiliar with the manufacturing processes and know little about how e.g. Information and Communications technology (ICT) operates. The overall impact of ICT on the environment is often overlooked, because it rarely directly affects the users. The ICT was responsible for around 1,5 % of the total electricity usage in 2010 [7]. It is estimated that data centres will use approx. 3-13 % of the global electricity 2030. When the product is not a physical object, it is hard to grasp the effect it will have on the environment. The users of mobile services, in general, are not aware of their impact on the rising energy demand. When they think that changing from material goods to immaterial goods is automatically better for the environment, that may not be the case.

Many companies of the ICT plan to use and are using renewable energy sources for their electricity. However, the ICT field is growing quite rapidly and the current amount of renewable electricity on the market is not enough for everyone. Some countries are not keen on switching to renewable sources of energy if their natural reserves of carbon-based sources of energy are lucrative. This leads to a relatively large amount of increase in greenhouse gas emissions without the consumers not being aware of the issue [8].

Products often have factors in their processes that get often overlooked and are not counted in the products final impact on things. This applies to all immaterial and material products. It might lead to an imbalanced comparison between two or more products because not everyone involved is aware of what aspects are covered and what are not covered.

1.1.3 Challenges of LCA studies

The inventory analysis is the most critical part of LCA, but it is also the phase where most of the problems occur. Modern products are complex and the workload of covering all raw material origins and processes, manufacturing steps and additives, and transportations of goods can be arduous. Sometimes, no data has ever been collected from certain processes and firsthand measurements are required. However, some manufacturers are not keen on having to stall their production lines for projects that are not seen as important or they cannot simply measure singular steps of the process. Manufacturers provide the energy consumption of the entire plant because that is all they have at hand and some prefer to rely on the databases. The quality of the data and the amount of the data are crucial if accurate results are something desired.

As LCA studies are covered by a relatively new field, the number of professionals on the field is not abundant. Most of the individuals conducting an LCA study are making it for the first time. The person performing a LCA study should be somewhat familiar with the chosen product materials, processes, operation of the product and its disposal. Most of the LCA studies recognize this problem and mention that the results might not be entirely accurate. The limited availability of LCA tools and databases affect the quality of the published studies. There are some free or inexpensive tools for fledgling researchers, but they have smaller databases or have more limited fields of use. It is recommended to mention the software code and version used in the study. The databases and their versions should be mentioned in the study as well, so that repeating the study process is possible.

LCA studies have yet to be made mandatory and most of the recently published studies are made of curiosity rather than to give products more value. This leads to numerous studies with varying goals, different methods of calculations, inconsistent levels of scope definitions, and incomparable results [9] A person comparing results from different studies must remain vigilant and know what parameters to analyze from the studies. It should be noted that LCA studies are usually focusing on one lifespan of one product. This leaves the effects of recycling out of the studies. Some products may seem less environmentally friendly than others due to their materials. However, the studies may have overlooked that the material in question is fully recyclable and thus its long-term effects are smaller after a lifespan or two.

Every LCA study is a product of its time. Laws and directives guide the production and material choices based on the opinions the general publics. Some countries have regulated strict and aggressive aims for environmental policies compared to others. A study needs to ensure that correct locations are selected for each process, as there might be great differences even in how neighboring countries handle their recycling etc. The will of the people might change suddenly and unexpectedly, and the laws and directives follow those whims at a little slower pace. LCA studies are sometimes done for products with relatively long lifespan. It is difficult to choose options e.g. a disposal scenario for them because you can’t know which methods are obsolete by the time the product is disposed of. It is quite impossible to foresee the technological advancements over ten to thirty years from now on. Some of the possibilities only rumoured now might be the reality by then. This puts the product with LCA done recently to a slightly disadvantageous position compared to products that have yet not been analyzed. The same product may seem completely different after years if the disposal scenario, for example will evolve to an environmentally friendlier version in just a couple of years.

Material and production costs are a major factor that affects the design and market potential when a company plans to manufacture products on a larger scale. Often, the materials and methods with the lowest prices are chosen. Sometimes, the countries with the lowest costs have questionable politics and ethics, and, thus, might not be the reasonable selection in the long run. An unfit material provider might hurt the manufacturing company's image, or the material provider might become unavailable due to restrictions issued by an international verdict. This possibly leads to some inaccuracies in LCA studies focusing on the effect in the future, because of the unpredictable and fluctuating international politics.

1.2 Materials

Multiple different materials are suitable candidates for the product considered in this thesis (see chapter 2). The most suitable material groups have been selected for the comparison in the following text. The materials in general are metals, plastics (polymers), and fibre reinforced polymer composites. All these materials have suitable qualities potential to the product as well as reasonable material production and manufacturing costs.

1.2.1 Metals

Metals are a widely used group of materials and their properties are well known. This means they are widely manufactured, and their production is efficient. The materials are malleable, but typically tough in use, resistant to rather high stresses, and can be chosen and customized to fit the intended use. Like all materials, they have some unfavourable qualities as well. Metals in general have high density compared to other materials. Some of them are prone to corrosion in moist environments and must be protected. Their extraction from nature is costly to the environment in terms of land use and resources, because of the requirements of ore refinement and its side effects. Some metals are very rare and expensive, and there are no reasonable possibilities to increase the planet's limited resources.

Metals are suitable for recycling because they do not degrade greatly in subsequent production cycles. The recycling of metals is also recommended because of the price and effort it takes to acquire virgin materials. Metals are often alloyed to improve the base metals' qualities. Upon recycling, it is possible to separate the alloyed materials due to the metals different melting temperatures. Iron-based metals are the most used metals in the world, but due to their applications and the base metals' nature, the recycling can be challenging. Iron-based metals tend to rust when exposed to chemicals or used in contact with other types of metals. The alloying protects iron but increases the expenses and, depending on the application, might be a vain process. Other protection methods, such as coating the metal with paint add more steps to the (recycling) process. Proper product design lengthens the product's lifespan and makes also the end-of-life phase easier.

1.2.2 Plastics

The basic structure of plastics is the hydrocarbon backbone. They consist of long carbon molecule chains, called polymers, with each polymer type having its own unique additional repeating molecular unit. The exact structure with possible functional group gives the different plastics their unique features. The amount of variation among the polymeric materials ensures that plastics can be used in multiple applications and can be adjusted to fit the target in mind. Even more, a blend with additive materials can enhance plastics for some of their qualities. Polymer raw materials can be derived from petrochemical oil derivatives or from organic sources ensuring that they can be produced nearly indefinitely.

Plastics are divided into two categories: thermoplastics and thermosets. The difference between the two is that thermoplastics can be reformed multiple times by using heat. Their polymer chains will increase their energy (molecular motion) and this will allow reshaping (by heating-cooling) [10]. Thermosets, on the other hand are cannot be reshaped greatly after the chemical cure-reaction has onset. This is due to the polymer chains forming strong bonds between each other and create a web that cannot be disentangled once having formed. Figure 1 shows the difference between the two. Most used plastics in packaging are thermoplastics due to their easier processability and lower price. Thermosets are generally used in applications that require stiffness, often to even to replace metallic structures e.g. in cars, aeroplanes, and boats [11].

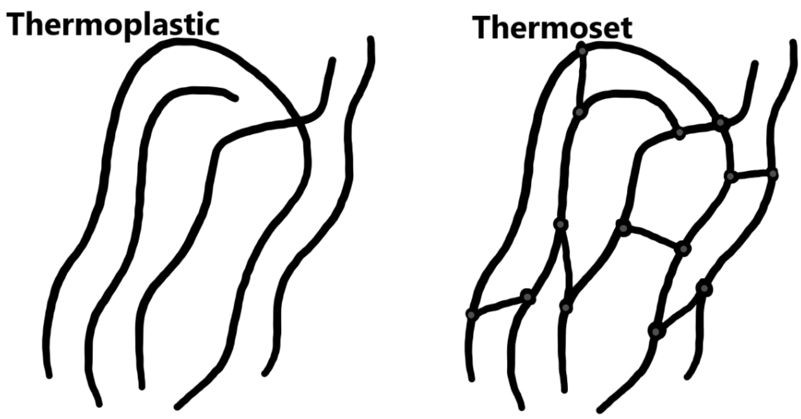

Figure 1. The different structure of polymer chains in thermoplastics and thermoset polymers

Plastics have a wide price range and the price depends on the qualities the material has. The toughest plastics are usually the most laborious to manufacture and thus the most expensive. Because of the hydrocarbon-based nature of plastics, they, in general, have lower heat resistance compared to metals. Plastics in general can only withstand temperatures up to 300°C before they begin to deteriorate. Plastics are produced widely and are relatively cheap materials (per kilo) to be used in mass production.

The recycling of plastics requires more research. Virgin materials are cheap for oil-based plastics as they are a gasoline production spinoff. This might change in the future, however, since oil is a limited supply. Plastics are also challenging for consumers to recycle due to the numerous amounts of different types of plastics that are used. If various types of plastics are mixed, the resulting material often has only the worst qualities available and none of the good. The mixed material might not even be processable due to the varying melting temperatures and other processes affecting qualities. Even the same polymer plastics can be hard to combine into a working solution, because of all the additives and fillers.

1.2.3 Composites

Composites are made of multiple materials to achieve optimal product qualities. Composites consist of a matrix material that works as the binding component, giving its own effect on the qualities. The other part of the composite is the reinforcement material(s) that will give the composite the qualities which neither material(s) would alone have.

Composites are manufactured in multiple ways. Matrix material largely determines the applicable methods. For metals and concrete, the matrix material is often mixed with the reinforcement material beforehand and then cast into a mould or poured into a mould in which the reinforcement material has been set in place. Polymer matrices are more versatile. Matrices are either thermoplastic or thermoset polymers. They can be hand-laminated, injection moulded, vacuum-moulded, autoclave-moulded, and pressure bag moulded etc.

1.2.4 Composite materials

Composites can be made with multiple materials and with numerous combinations (ratios). Some examples of used matrices: metals, plastics and concrete. The matrix material is required to be in a liquid-like state to spread evenly around the reinforcement material. This limits the materials combinations to some degree, as not all materials can withstand the temperatures the other materials require to attain the liquid state. The matrix usually makes around 30%-70% of the composite, depending on the intended manufacture method and the intended final (design) operation [12].

Reinforcement materials include a wider range of materials to choose from as they are not restricted as much by the materials flow properties. Reinforcement material as per their name is used to give the composite material better physical properties than the matrix material alone would have. The reinforcement (materials) have excellent qualities but due to their particulate or fibrous form they need to be bonded together. Fibres, fabrics and particles are the most common forms of reinforcement product types. Depending on the length, the fibres give the composite high strength (long fibres). Fabrics are used to ease the manufacture of composites. For tailored properties, fabrics are often set in multiple layers and on different angles from one another to reach the design strength level per application [13]. Particles are used to fill the matrix to a degree and affect the price of particle-filled composites.

1.2.5 Biodegradable and natural fibre composites

Bio-based and biodegradable materials are one option when the goal is the mitigation of climate change. A huge amount of disposed polymer products is still left to landfill sites or are left into nature where they'll stay unchanged for hundreds of years. Some countries have taken the next step and are collecting polymer composites for energy by incinerating them. Small amount of composites are re-used in other products. Recycling and energy-incineration are dependent on the amount of waste available. The types re-use applications for which recycling is worth the effort is currently low, meaning that incineration is becoming a trend in composite disposal [14].

From an environmentalist point of view, composting would be a good option to dispose polymer-composite products. The degradation speed of common plastics is extremely slow, and it'll take hundreds of years for a piece to break into small particles. Even then, it would live as a microplastic for a long time before it will finally break into base elements. The slow degradation speed would fill up the world with disposed of plastic and, thus, letting them just degrade at landfill sites passively is not a realistic solution. Using biodegradable plastics will ease the problem common plastics' longevity causes. Some polymeric materials, such as poly lactic acid (PLA) are biodegradable and suitable for products with a short lifespan. PLA is thermoplastic that can bio-degrade in certain environments and can be made from bio-based raw material stock, that makes it relatively environmentally friendly plastic material [15]. As mentioned before, LCA can reveal if something is not an as good option as it was thought to be. PLA and some other bio-based materials are not more environmentally friendlier than common materials [16]. It is finally up to consumers to decide how the environment should be affected.

Some studies have been done about mixing common thermoplastics with biodegradable components to investigate the effect the biodegradable parts have on the plastics degradation speed. When the ratio of the thermoplastic and the bio-component is right, the added component can affect the crystallization level of the plastic and make the material more susceptible to micro-organisms and other degradation factors. Starch-based polymers are only materials that accelerate the degradation speed of the thermoplastics. Other bio-components tend not affect the plastics degradation speed [17].

Thermosets are a widely used polymer material group in composites. They are generally classified as non-biodegradable materials and often have to be disposed of by incineration or as landfill. Epoxy is a commonly used thermoset-type group of resins that has a high resistance to hydrolytic degradation. This means that it will take a considerable amount of time before epoxies begin to degrade due to environmental factors. There has been a study made that investigated degradation of epoxy in seawater with and without bacteria. Epoxy in seawater with bacteria began to degrade faster than in water without bacteria. Other studies have also suggested that epoxies can be disposed of with the help of micro-organisms [18].

Carbon fibres and glass fibres are common polymer composites' reinforcement materials. They do not essentially degrade in natural (outdoor) conditions and are turning into a problem when a product made with them is being disposed of. Both materials are recyclable to a degree but when comparing recycled materials and virgin materials by their mechanical properties and by price, the favour falls to virgin materials [19]. Finding bio-based materials with similar properties to those of glass fibres is a growing trend and multiple good candidates have already been found. Natural fibres such as cotton, flax, jute, hemp, and wool are researched as possible materials for biodegradable composites [20]. Animal and plant products are currently researched and their applicability and ability to replace traditional materials is something that many researchers are focusing on. Their environmental impact needs to be studied along with their applicability as it would be unwise to replace an existing product with a product that has a worse impact on the environment.

Plant-based reinforcement materials are more frequently studied than animal-based materials due to their easier accessibility and steadier supply. Studies have been made to investigate the effect plant fibres have on biodegradable plastics in 'bio-composites'. The study by of Bayerl et al [21] found that high fibre content accelerates the degradation of biodegradable plastic. It was assumed that the fibres work as channels for micro-organisms and other degradation processes causing the plastic to degrade from inside out.

Composites made of biodegradable materials can be composted in a reasonable time frame or they can be disposed of as energy. Due to their weakness, they are not yet suitable for challenging climates and under high mechanical stresses. They are suitable material for products that are designed to have a relatively short lifespan or light mechanical loading in applications. For example, protective panels, protective canvases for crops and similar applications. Biodegradable composites are a huge well of untapped potential.

1.3 Recycling of particulate filled plastics

Plastics made with special functionality in mind often have high demands and multiple overlapping requirements and have numerous additives and other filler materials added into them. Some of the additives affect how the plastic can be disposed of when the end of its lifespan is reached.

1.3.1 Plastics with additives

Polymers, either thermoplastic or thermoset plastics, that are intended for applications off electronic devices (wiring, switches and insulation) are strictly specified by various standards. They need to resist burning in different ways (e.g. ignition, flame retardancy), they must withstand relatively high temperatures, they must have proper electric resistance, they are required to have the mechanical properties to be used for a set time or uses, and they need to hold their designed shape even under stressful conditions, to mention a few. These requirements are so stringent that polymers or resins without fillers cannot fulfil the requirements. Electricity contact plastics must be with filled different kind of materials (e.g. fire retardants such as aluminium trihydrate (ATH) and magnesium hydroxide (MDH) to be safe to use. These plastics are a special group of polymer blends and they cannot be disposed of as easily as more common materials.

For thermoplastics, an ideal disposal scenario would be recycling of the plastic waste. The recycling process of thermoplastics is most effective when the collected waste batches are of the same polymer and have nearly the same additives (if any). This might allow the recycled plastic to be used in the same or similar application as the original product made of virgin material. However, often, the recycling of plastics in common binds leads to collection of various plastics [22]. Sometimes the product has requirements related to hygiene and purity and the recycled materials are not fit for such requirements. Most plastics in common usage can be mixed to a degree for reuse, but the applications for such materials are somewhat limited [23].

Due to the fillers and additives, the special application products (e.g. electricity contact plastics) have often quite different physical properties compared to common products even if the base polymer is the same. For certain fillers and additives, and related processing parameters, the mixing of them in a largescale recycling is impossible. The higher number of additives used, the greater is the amount of impurities in the recycled material. Special plastics must be recycled carefully to keep all the additives from contaminating the targeted type of recycled polymer. The plastics can then be separated by the base polymer and by additive composition. Recycled special plastics are recommended to be mixed with virgin plastics to create new products. The amount of recycled material should around 50% [24] of the entirety to affect physical properties positively. Incineration of special plastics is to be avoided because some of the fire-retardant additives do not burn well and emit carbon monoxide when incinerated.

Promising recycling results have been acquired by using multiple separation methods in a row. First, the targeted plastics are separated from the shredded Waste Electrical & Electronic Equipment (WEEE) material by density-based separation process. Material sorted by density can then be dissolved, for example, in a CreaSolv® solution and step by step the non-plastics and plastics material can be separated. The remaining plastic solution can be sorted into pure materials if there's need for a certain type of polymer. The processes will not completely remove all the additives, because some of them are in a state that makes it nearly impossible. The processes, however, remove a large number of harmful additives, making the materials composition remain within legal thresholds. The separated materials finally can have similar properties compared to those of virgin materials. Some differences can be attributed to the remaining impurities and traces of other plastics and degradation. The yields obtained by the multistep process are at least 70 %, making it a worthy endeavour [25].

1.3.2 Polymer composites

The recycling of reinforced polymer composites has become a reasonable objective and affect the requirements at the markets. Polymer matrix composites are challenging to recycle, because of the relatively small manufacturing quantities and because of the challenging processability of the materials. Numerous combinations of diverse matrix materials, reinforcement material structures and required additives ensure that composites cannot be recycled like materials from a single material phase [26]. Depending on the materials involved, different approaches of recycling should be utilized.

When the matrix is made of thermoset polymer resin, the composite is not fully recyclable. For thermosets, sensible disposal scenarios are still landfill and incineration. Depending on the reinforcement material used and possible recycling demands, thermoset matrix composites can be either ground or dissolved to use them as filler and support materials in other applications or to recover fibres etc. for reuse. Carbon fibre composites are recycled by grinding them into small particles and then mixing them with virgin materials and this process has great energy efficiency (15 MJ/kg) [27] This is due to the high energy consumption of virgin carbon fibre production (155 MJ/kg) [27] The cost efficiency and available technology often dictate the sensibleness of the recycling and re-use methods.

Thermoplastic matrixes are not so limited in terms of recycling and compared to thermosets. They can be re-granulated if the reinforcement material is small enough and will not get overly damaged in the re-processing. The recycled material often has poorer physical properties compared to the virgin material and has limited applicability [28]. If the reinforcement material is either carbon fibre or glass fibre, it is possible to incinerate the polymer matrix around the fibres and collect the fibres for reuse. This can be done for both thermoset and thermoplastic matrices. Recycled fibres have reduced quality compared to virgin materials [19]. However, the production costs of carbon fibre have increased the demand for reusing composites.

Finely ground fibre composites can be used as filler material in other applications as well. Depending on the amounts of virgin material and recycled material mixed, the composite filler product can have mechanical properties similar or better than a version made of only virgin materials [29]. In some products, ground fibre composites have slightly poorer mechanical properties compared to fully virgin materials due to the shortness of the ground fibres [30]. These results enforce the idea of blending recycled material with virgin material to achieve a minimal loss of mechanical properties and maximal recyclability of materials that are often regarded unrecyclable.

If the reinforcement material is bio-based, the recyclability of the composite is limited. Bio-based materials cannot be re-processed easily as they will heavily degrade in the process and create stains and impurities in the, re-used material. Separating bio-based reinforcement materials from the matrix is practically impossible because both components are likely to deteriorate before the separation can physically occur. This can only mean that the materials need to be disposed together. Incineration is common way of practise for natural fibre reinforced composites. If both matrix and reinforcement material are bio-degradable, industrial composting is a viable alternative. Perhaps, in the future, some composites can be composted and finally used as fertilizer for a new generation of bio-based materials from plants.

Few Studies have shown that bio-based composites can be recycled when processed properly. When the composites are mechanically recycled and, during the process, treated with thermal stabilizers, their mechanical properties are affected only a little. The recycled material is mixed with virgin material to achieve optimal target properties. The mechanical properties of the recycled materials are presumed to be poorer due to the shorter fibres in the material [31]. The grinding of materials is basically a mandatory step of the entire process and, therefore, the shortness of fibres and their effect on the properties of the product should be considered when using the material.

2. THE EXPERIMENTAL CASE STUDY

The target of this thesis is to investigate the environmental impacts of material selection in a defined, case product. Three completely different but rational versions of the product, each made of different materials, are being compared. The three versions are 1) a metallic reference version; 2) a pure plastic version and a 3) reinforced composite version. The overall environmental effects of the different versions are examined and used to improve the product design. The product is a protective panel of a 5G smart pole with transmitting-receiving radios and many other electronic devices. The panel is exposed to outdoor environment but is not under heavy mechanical stresses. It can bear a certain level of deterioration before being permanently damaged [32]. The expected lifespan of the product is 5 to 10 years depending on the durability of the panel. The product is part of the LuxTurrim5G+ smart city concept [33] and its various infrastructure technologies. A low weight (mass) can be an advantage due to lower sway of the smart pole.

2.1 Product definition

The product is shaped like a cylinder shell. Its dimensions are 250 mm (length) x 169 mm (outer diameter) x 3 mm (thickness) (see figure 2). The inner diameter, is in this case, is 163 mm. For calculative purposes, the product profile is assumed to be a perfect half-circle.

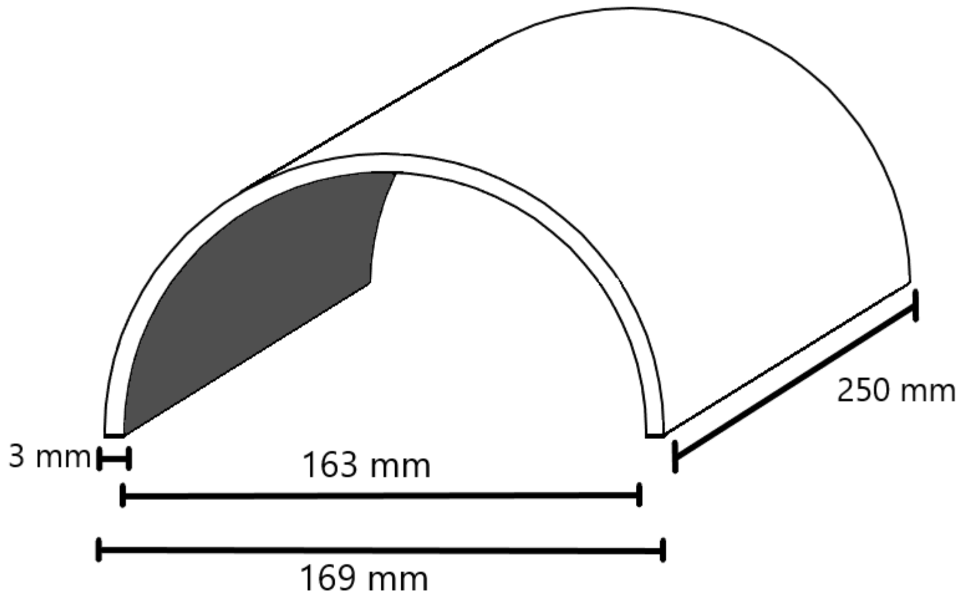

Figure 2. Dimensions of the protective panel

The volume of the product is acquired by first calculating the volume of a full cylinder with outer diameter dimensions and a volume of another cylinder with the inner diameter dimensions. Then, the smaller cylinder volume is subtracted from the bigger cylinder volume. The remaining shell geometry is halved to get the product volume. Finally, the volume is:

$$V = \pi * r^2 * h$$

Table 1. The volume of the product

	mm^3	cm^3
Outer cylinder	5607939,24	5607,94
Inner cylinder	5216810,95	5216,81
Difference	391128,29	391,13
Product	195564,14	195,56

The product could be used to protect 5G radio units at 5G frequency range(s). This ensures that it should be in use for several years before 6G becomes the rival technology. If the same radio units, containing radios in general, the panel could be used for 6G technology, then, the expected lifetime of the product is longer. If this is not the case in the future, then the expected lifetime of the product is approximately from five (5) to ten (10) years. Relatively short operation time means that the product will not be required to be as durable as it would need to be with a longer lifespan. In practice, metallic cover cannot be used (without signal windows) for radios, but it works as a traditional material reference. For shorter operation, the metallic version needs less protection, and plastic or composite will not need strong weather and UV protection. With lesser required performance, the products have a smaller amount of added specialty chemicals in them making their re-use or other disposal process or treatment simpler and less energy consuming.

2.1.1 The metallic version

The metallic version of the product is made of low carbon steel. Steel is the most used material in similar infrastructure applications, thus, steel is suitable reference material for the other versions. The metallic version will be manufactured by bending (cold forming) a steel sheet into the product shape. The panel will be then sand blown and coated with epoxy paint. The steel version of the product has an expected lifetime (in operation) of ten years with the epoxy paint. The mass off the metallic panel: 1554.7g

2.1.2 The plastic version

The purely plastic version of the product is made of polyamide (PA). PA, or in detail Nylon 6-6, is a polymer with great physical properties and resistances and is here a suitable material for the protective panel. The plastic product will be injection moulded. The plastic version should be recyclable for material reuse and, if that is not possible, then the product can be incinerated. The expected lifetime (in operation) of the product is five years. The mass of the panel: 222.9g

2.1.3 The composite version

The composite version of the product is made of pre-preg containing epoxy matrix and natural fibre reinforcement. The composite panel is laminated by using Automated Fibre Placement (AFP). For this, a male mould is made, and the robot will place the composite tape in chosen order (lay-up) and shape on the mould surface. Once the layup is finished and the panel cured, the product can be detached from the mould and finishing touches applied.

A female mould would be better for the actual product because the mould side of the product will have a better surface but makes lamination more difficult. In use, the product would gain an advantage (better look) from having a smooth surface and having a female mould would make acquiring that feature easier. The product is relatively small compared to the robot arm and a female mould would limit freedom of robot movement considerably. Therefore, the panel would not be laminated optimally, due to the limited movement range of the arm. Therefore, a male mould is used here.

The composite panel will be disposed of by incineration because other scenarios are not reasonable. (The assumptions in this thesis are based on the current information and will not surmise how the composite recycling will advance in the coming years.) The composition of the tape used is 40% (w/w) matrix material and reinforcement material (60%) (w/w). The expected lifetime (in operation) of the panel is five years. Recent research tries to give the panel a longer lifespan with the possibility for it to remain biodegradable [34]. The mass of the composite panel is approximately 262.1g

In this thesis, a test panel will be made using epoxy/carbon pre-preg for process. The current availability of epoxy/flax pre-pregs is limited. The carbon reinforced panel is analysed (LCA) only as an additional data for discussion. In reality, there are no design requirements supporting carbon fibre reinforcement. However, out of curiosity and to give more variety to the comparison, the environmental impact of the carbon fibre version was included in the analytical part, discussions. The manufacturing details and methods are given in Chapter 3 (power measurement).

2.2 Initialization for comparisons

The comparisons between the different versions of the panel are done based on results from a commercial LCA software. Data is partly based on project partners and measurements – these are specific to the thesis. For a large amount of data, the values are rough estimates and rely on the information the software database provides. In reality, there could be some additional processes, similar for each version (e.g. polishing of edges, or storing or packaging) and, therefore, are ignored in the comparison.

It shall be noted that perfect match cannot be found for materials and processes intended for the panel versions, and closest alternatives will be chosen. The effect will be discussed and considered.

2.2.1 The selected LCA tool

SimaPro 7.5 is a life cycle assessment software that is acknowledged as a trusted data provider. It has an extensive database library with information from over 80 countries. SimaPro has multiple databases and the ones chosen for this thesis are: Ecoinvent 3 (allocation at point of substitution - system), ELCD, Industry data 2.0 and Methods. Multiple databases were chosen for their relevance and to ensure better coverage. It is known that some of these databases have not been updated recently or have been discontinued but the data is here considered relevant.

2.3 The LuxTurrim5G+ Smart city concept

LuxTurrim5G is a Finnish smart city ecosystem that focuses on integrating wireless technologies with public everyday activities, needs, services and urban infrastructure. The general idea is to give the populace digital services to ensure public safety and well-being along with basic data needs. For example, the smart city sensors can be programmed to recognise when a certain part of the park or street is not in use and turn of lighting on that area. This will save energy and minimize light pollution. Other applications include, yet are not limited to, surveillance drones that can be used to witness various occurrences and to guide both citizens and emergency staff. Also, information touch screens that work as a user interface to the related technology and powerful 5G radio network that ensures that data is moving at top speed within the city area.

The Luxturrim5G and the Neutral Host form an ecosystem as collaboration between multiple companies, public institutes, and cities. One of the physical outcomes of the ecosystem is a 5G smart pole – a protective and aesthetic panel is the focus of this thesis. The smart pole can provide for various services, devices and, therefore, could be harnessed with specialized protective panels, radomes and radio units (so called CRUs). The LCA of the products- like the panels, is seen as an important part of the product design because minimizing the environmental impact or possibly reaching carbon neutrality is part of the responsible actions – also in the Luxturrim5G entity.

2.3.1 5G radios, devices and outdoor protection

5G is a name given to the fifth generation of cellular technology. It operates on a different frequency range than previous generations. The 5G has three frequency bands called low (600-700 MHz), medium (2,5-3,7 MHz) and high (25-39 MHz) [35]. As the frequency increases, the potential to high data rate increases as well. The increase in frequency tend to affect the 'service range' as well. The expected 5G radio operation (radius) for a wide range of services require so-called small cell platform with radio separation only tens or at maximum hundred meters. When compared to the previous mobile data generations, a full working 5G network is going to need even thousands of more radios (small cell platform). More transmitters mean increasing material, labour and transport costs and emissions related to the producing of physical devices. Switching to new technology should be done responsibly and this includes designing the processes sustainably.

The signal spectrum of 5G is in general sensitive to attenuation (abating of signal strength) and its transmitter locations must be designed with this feature in mind. Building walls, in general any material with good thickness, cause difficulties to send and receive the signals. As there are already many obstacles the 5G signal provider cannot affect, it is important to minimize the interferences from the sources they can affect. This means optimizing radomes and device walls and shapes by choosing the most suitable materials and by improving the shape of the radome.

For the current designs in Luxturrim5G, the radios and radomes are mostly located outside the main pole beam. This means that the actual technology is exposed to varying weather conditions. Even in the optimistic scenarios, there'll be some restless individuals who could end up causing injuries to common city infrastructure, typically called vandalism. Thus, some devices located low need a certain amount of mechanical protection.

The most straightforward increase in mechanical protection is achieved by thick protective panels or radomes, but unfortunately, thick walls affect the 5G signal. This problem can be circumvented by cutting small windows at the exact spot where the signal is sent from or by using multiple small panels to create a protective yet airy cocoon for the transmitters. In this thesis, the represent panel is an 'intermediate' size of a protective panel. Several materials (metallic, plastic, composite) also basically allow different design targets, e.g. for different devices or different locations in the smart pole. It has been found that smart poles are often tailored per site or even per pole.

3. POWER MEASUREMENT

The comparison of the different versions of the defined product is the main target of this thesis. The metallic version of the panel is used as reference version because similar products are usually made of steel or other metals. The plastic version is the most generally used alternative and is included because of its potential. Both versions will get all their LCA data from the databases because the used manufacturing processes are simple enough to simulate the intended product in this thesis. The composite version is manufactured using more unconventional methods and, thus, database material is not suitable for comparative purposes. The energy consumption during lamination is highly part-dependent and will be measured by manufacturing a prototype panel and measuring momentary total power.

3.1 Setup

The power measurement process begins by defining the size and material of the prototype panel. The panel is made of carbon fibre and epoxy pre-preg tape by layering the tape on a mould and then curing the layered part in an oven. The layering is done by a robot (KUKA KR 20R1810). The robot arm has limited mobility and needs space to operate. This restricts the mould shape. For the curved shape of the product, a male mould is chosen to be most suitable. The mould is made of halved glass fibre and epoxy composite pipe, a steel support clamp and concrete basis (for stability). Then a mould model with similar dimensions is made in a CAD program (AutoCAD 2020) (Figure 4). The 3D model is needed to teach the robot the movements in a path marking simulation (Rhino 3D, RoboDK). The robot and the automated fiber placement (AFP) tool (AFP-XS, Addcomposites) are taught the movement directions and dimensions, how to place and cut the tape (by the AFP tool), and how to move the most optimal way in terms of lowest energy consumption.

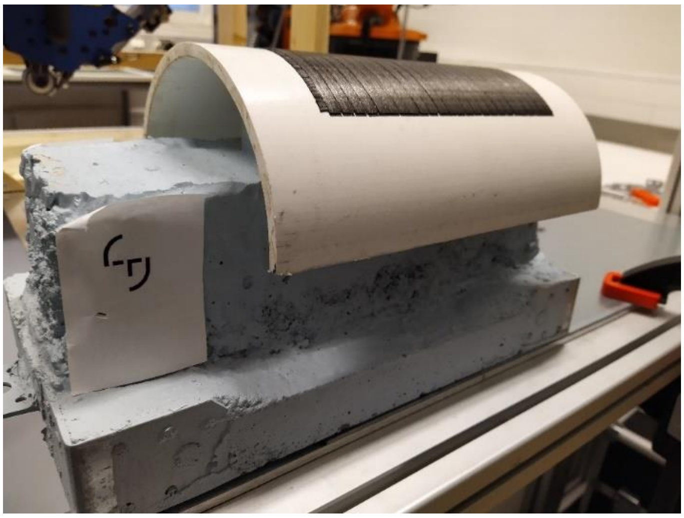

Figure 3 The prototype mould and layers of pre-preg tape on it

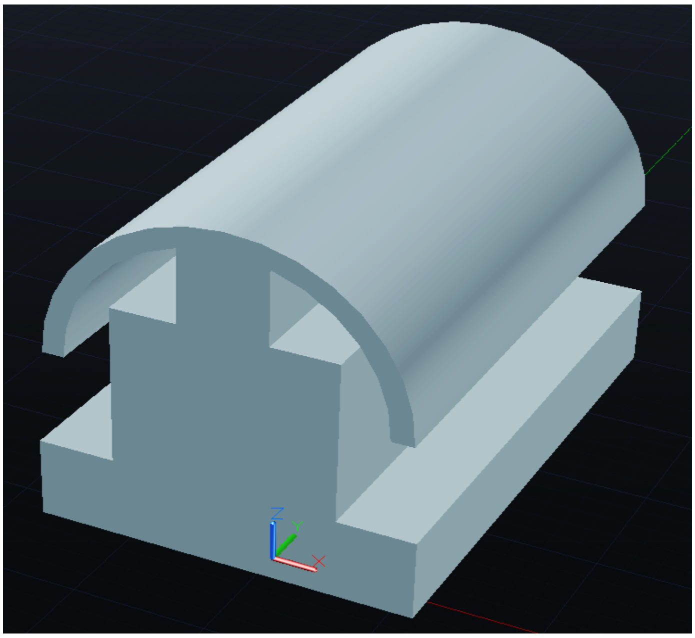

Figure 4 The 3D model (AutoCAD) of the mould

The power measurement is done by using a measurement tool called Fluke Norma 4000 Power Analyzer (Fluke) between the robot and its power plug (see Figure 5). A dedicated program (in house coded by Aalto University, Espoo) will measure the alternating current (AC) parameters at given sampling rate. The measurements are done for one (1) panel made as well as simulated robot movement (without pre-preg) beforehand. The necessary parameter is the true electrical power and the time per each measurement (integration) point. The system measures other parameters as well, but they are irrelevant for this study and are thus ignored.

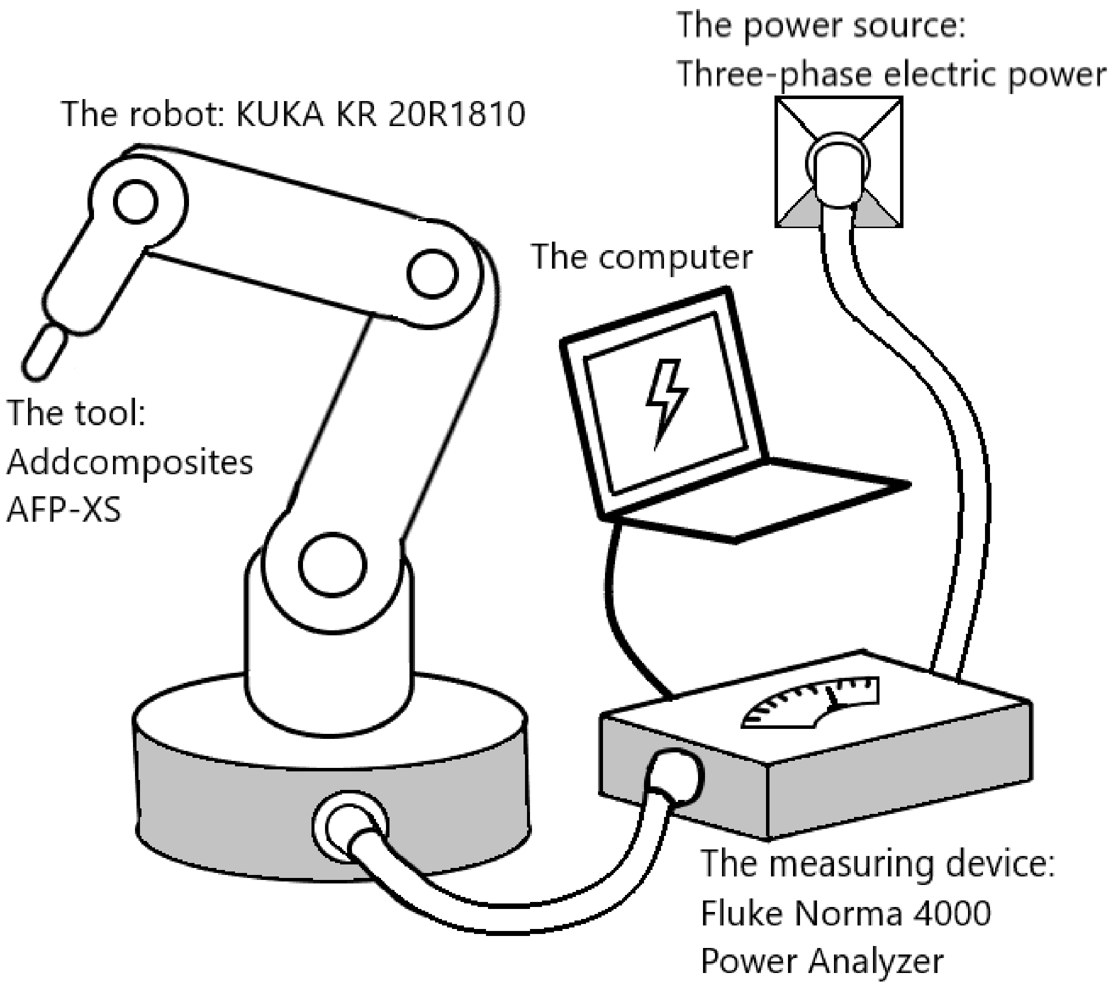

Figure 5 The power measuring setup

The robot is set to move in certain direction to form the targeted lay-up, in this case in a 90-degree angle and 0-degree angle to the mould setup. The layers are done in target stacking sequence, in the panel that sequence is 90/0/0/90. The layers are added until the desired part thickness is achieved. After the laminating is done, the mould is taken to a digitally controlled oven (Termaks TS8136) to cure the epoxy matrix. In Figure 6 the lay-up is visualized to clarify the lamination. The part titled “90” represents the first layer of the product. The part titled “90/0” represents the second layer of the product. The part titled “90/0/0” represents the third layer, and the final part titled “90/0/0/90” is the fourth. When the composite panel is made of layers laid in different directions it will have better multiaxial strength.

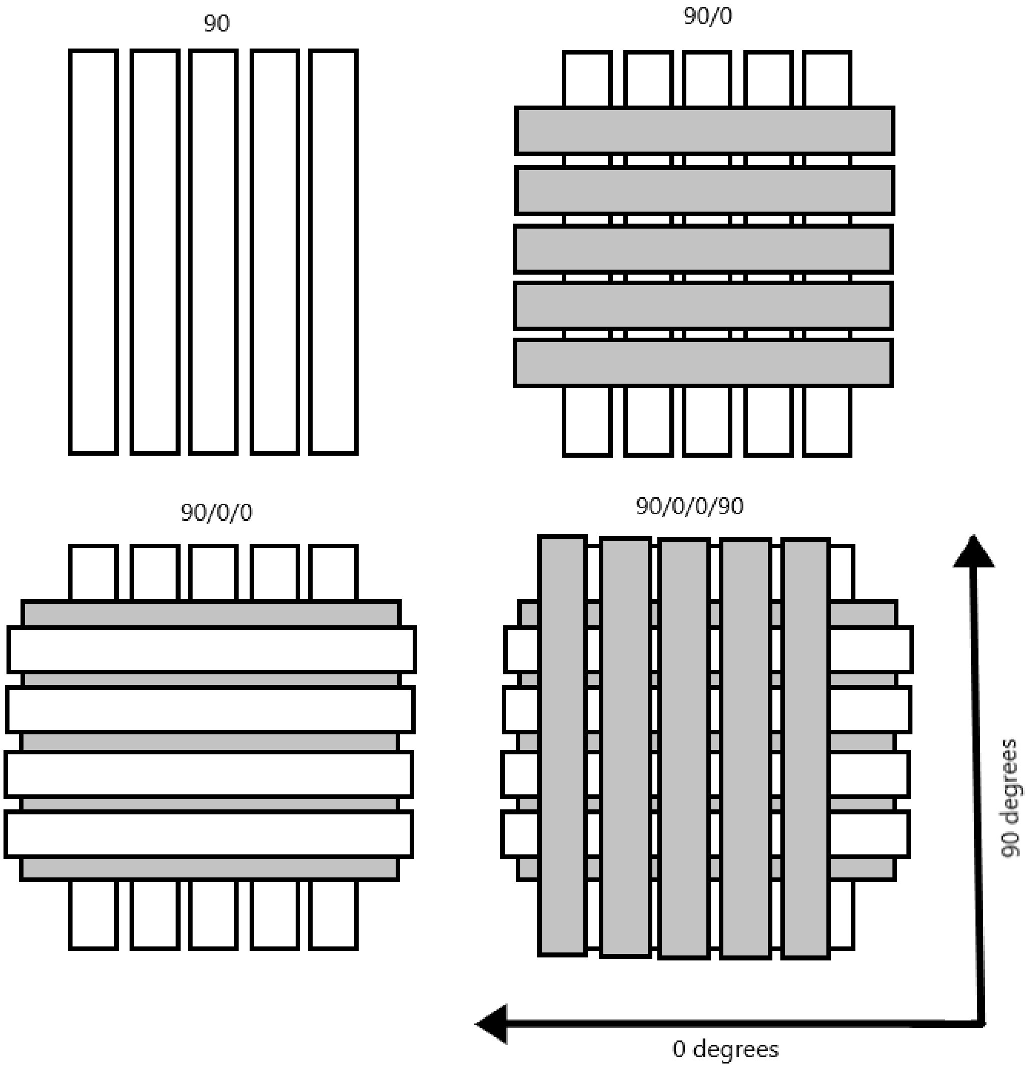

Figure 6. Layer order and directions in the prototype panel of the thesis

3.2 Numerical results

The total time it took to make the laminate was 2222 seconds (37 minutes). During that time, 1533 data points were acquired by the code. These data points show how the timely robot movement affects, and energy consumption, as shown in Figure 7. It takes more energy and more time for the robot to move in a certain direction, in this case, the direction that requires upward movement (change in robot arms potential energy). The robot has to do more elaborate movements to apply the tape and when it returns to a neutral position, especially at corners and cutting tape for new layer.

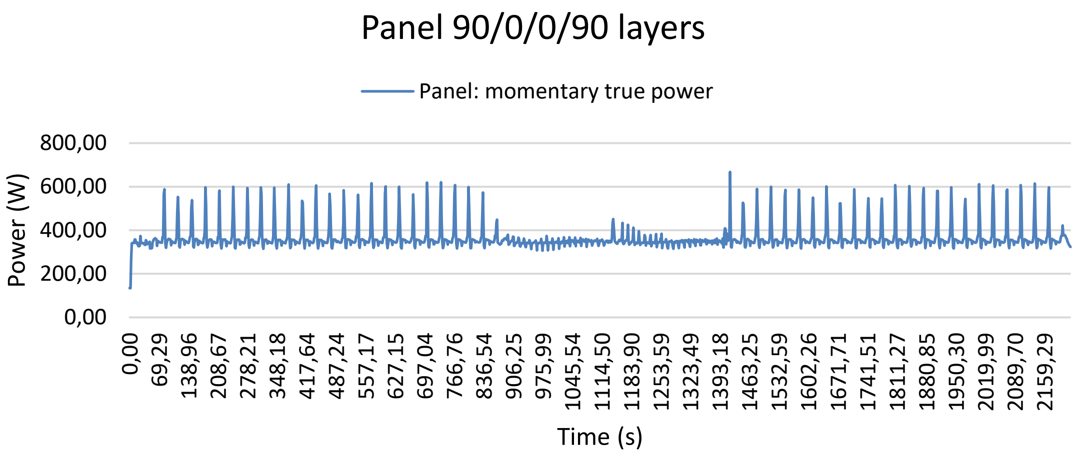

Figure 7. Panel: momentary true power

The energy consumption during the prototype panel lamination is calculated by integrating the discrete time-power data. Here, the Riemann sum-type integration is applied:

$$\sum_{i=0}^{n-1} f(t_i)(x_{i-1} - x_i)$$

The approximation of the energy consumption is acquired by multiplying the size (length) of the time step (x-axis) by the momentary power (y-axis) matching the time step (initial value) and, finally, computing the accumulating sum over the integration range. Here, MS Excel was used to handle the large amount of data points.

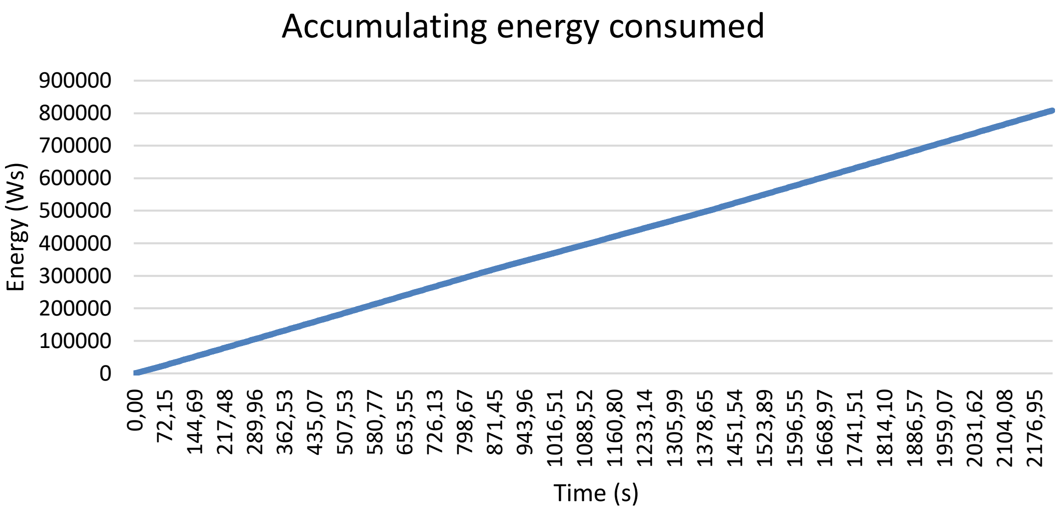

Figure 8. The cumulative energy by integration of true power during the robot operation when laminating the prototype panel.

The total energy consumption of the prototype panel laminating was 808236,474 Ws or 224,51 Wh = 0,225 kWh, as seen in Figure 8.

3.3 The scaling of the results for design size of the panel

The prototype panel dimensions were not the same as those of the design panel definition. The prototype panel is smaller and thinner than the full-sized panel, thus the energy consumption calculated previously needs to be scaled accordingly.

3.3.1 Area-based scaling

The design panel panel has the dimensions: length (l) 250 mm and diameter (d) 169 mm. The length of the arc (a) of the panel is:

$a = \frac{\pi d}{2} = \frac{\pi \times 169}{2} = 265\ mm$

The prototype panel has the dimensions: length (l) 178 mm and arc (a) length 139 mm.

These measurements give the panels the following areas:

Full-sized, design panel: $250 \times 265{,}5 = 66375$ mm^2

Prototype panel: $178 \times 139 = 24742$ mm^2

It follows that the design panel is

$$\frac{(66375 - 24742)}{24742} \times 100\% = 168{,}23\ \%$$

larger than the prototype panel.

The prototype panel's results must be multiplied by the factor of 2,68 to have the energy consumption of lamination for the design panel based on the area-based scaling.

3.3.2 Thickness-based scaling

The target thickness of the design panel is 3 mm. This equals approximately 16 layers of the pre-preg tape: the tape thickness has an approximate thickness of 0.2 mm.

The thickness of the prototype panel is four layers or approximately 0,8 mm.

Therefore, the design panel is four (4) times thicker than the prototype.

3.4 Energy consumption for the design composite panel

The scaling based on area and thickness gives the full-sized design panel laminating the energy consumption of:

0,225 kWh × 2,6853 (the area difference) × 4 (thickness difference) = 2,409 kWh

In addition to the automated lamination by the robot, the epoxy resin of the pre-preg requires to be cured to reach its physical properties. The curing is done in a digitally controlled oven (model TS8136, Termaks). The curing temperature is 180 degrees Celsius. The heating-up phase, in addition to the dwell time, is necessary to be analyzed. Here, the energy computation is made for one test panel. In reality, the consumed energy is not exactly fair for mass-production products (the oven itself heats up considerably). It is assumed that the oven is working perfectly and at the heating (maximum) power mentioned in its datasheet. The composite is recommended to be cured in a vacuum for some applications, but for the function of this panel, vacuum curing was chosen to be unnecessary in terms of curing energy consumption.

The heating of the oven from 26 degrees Celsius to 180 degrees Celsius took approximately 47 minutes and 35 seconds. The nominal true power of the oven is 1430 W. This results for the oven to consume approximately the following amount of electrical energy:

$$2855{,}23\ s \times 1430\ W = 4082979\ Ws = 1134\ Wh = 1{,}134\ kWh$$

The laminating and oven cure as energy consuming processes are summed up to gain the energy it takes to laminate and cure one composite panel. Here, the estimated energy consumption of the full-sized, design panel is:

$$2{,}409\ kWh + 1{,}134\ kWh = 3{,}543\ kWh$$

4. THE LCA PROCESS

The process in this thesis will follow LCA and the phases stated in the ISO-14040 standard. The phases are: the goal and scope definition phase, inventory analysis phase, impact assessment phase and the interpretation phase.

4.1 Goal and scope of the study

The goal of the study in thesis is to justify and encourage certain material choices regarding the product. The comparison will be analysed to show the environmental effects of the selected materials and prove the possible superiority of the preferred materials when environmental values are considered. This work shall provide evidence to designers and other decision-makers and act as a reference.

The results in detail are here somewhat approximate due to second-hand data and database reliant inputs. The focus is on the manufacturing phase and end-of-life phase because these phases are possible to be altered by design criteria to mitigate the environmental impact of the product. Raw material acquisition is less accurately considered because it can be affected only minimally by the (Luxturrim5G) project and lack of first-hand data. The using (operation) phase is generally ignored due to the passive nature of the product. The panel is not ought to need maintenance or other actions - it is left on its place through the operation phase. This means that repairs and maintenances are ignored in this study.

4.2 The system boundary in the study

All of the versions of the product are assessed from cradle-to-gate, meaning that their impact on the environment is studied for their entire lifespan. As mentioned before, this study uses mostly second-hand data and thus only selected phases are analysed by using first-hand data. The key phases that are addressed in the following are: raw material acquisition, raw material refinement, product manufacturing, using phase, and end-of-life scenarios. These are all unique for all of the versions.

Figure 9 shows the rudimentary lifecycle of the metallic panel. It begins with the ore mining and refinement and from there it proceeds to the product-specific phases. In this case, the panel manufacturing includes the shaping of the steel sheet, cutting and shaping the panel, and finishing the panel with coating etc. Then, there is the use phase. For this product the use phase is passive and only some steps are included. After the product has fulfilled its function (operation), it must be disposed of. The product can be reused in the same or similar application it was designed for, but due to the specificity of the product, that is not likely. The product is possible to be recycled into raw-materials and be used for other products. The last, least preferred, option is to leave the product at a landfill site or other permanent disposal option. This happens, if the product has begun to rust (oxidize significantly) and the amount of salvageable material is low.

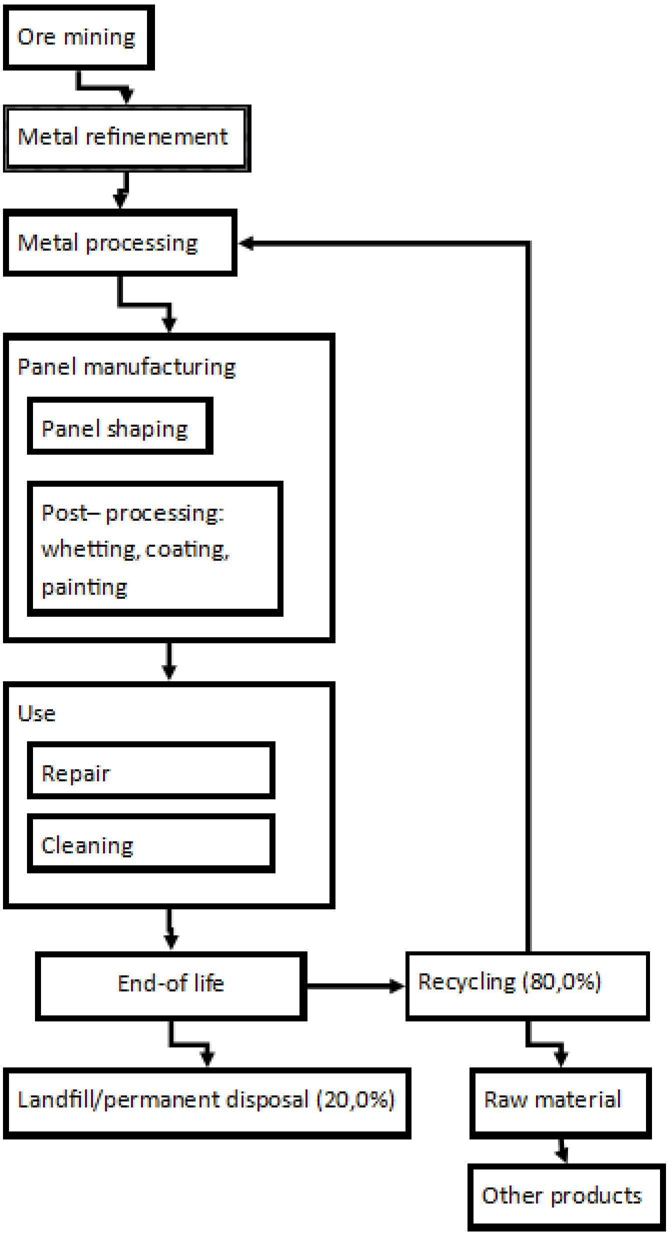

Figure 9. The system boundary of the metallic panel

The plastic panel in terms of its lifecycle is shown in Figure 10. It starts with the oil refinery and polymer refining and continues to the plastics manufacturing. From there it proceeds to the product-specific phases. For this product, the specific processes are material mixing, injection moulding and finishing touches and possible additives. Likewise, the metallic panel, the plastic panel has a passive use phase and it has little impact on the results. The disposal of the plastic panel can be performed multiple ways. It can be reused in the same or similar application, but that is unlikely scenario. Some of the used products can be recycled into raw-materials and be used in other applications depending on how pure the collected material is. With the current know-how, most of the used products will be disposed of as energy. The last, least preferred, option with the plastic version is the landfill site. The material might have suffered some permanent damage and is unsuitable for recycling or is located too far from a power plant so that it is more likely to be dumped at a landfill site.

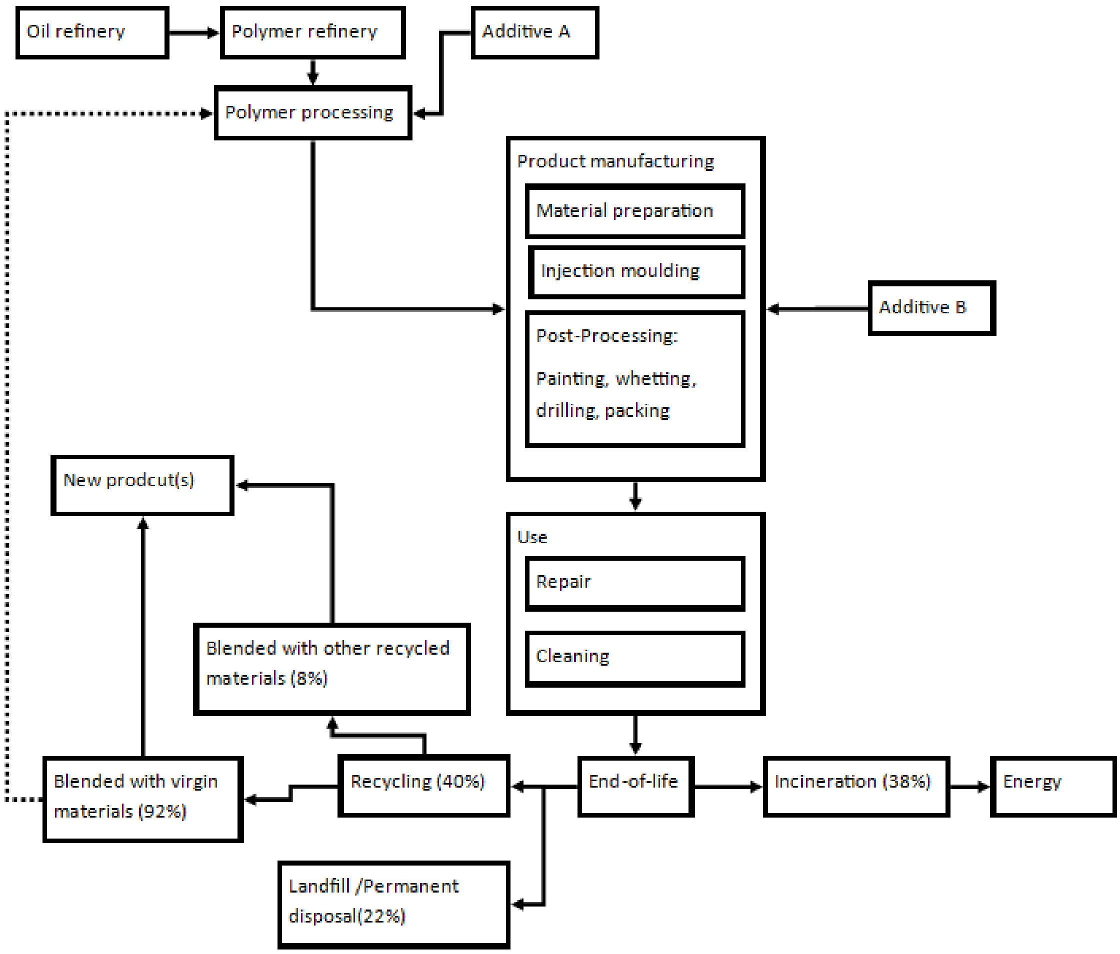

Figure 10 The lifecycle and the system boundary of the plastic panel.

Figure 11 shows the lifecycle and system boundary of the composite panel version. The cycle begins at raw material refining for both matrix and reinforcement materials. Both materials are processed and then combined into one. The product-specific steps occur afterward. These steps include lamination of the product and finishing touches etc. adding a protective coating. Like the metallic and plastic panel versions, the use phase of the composite is passive and has little effect on the overall results. The disposal of the composite panel can happen in different ways. Reusing is an unlikely, but possible scenario. Recycling is currently an unusual choice but may gain more popularity in the future for composite parts. The bio-composite version is mostly going to be disposed of as energy because the other options are ill-fitting. Some pieces will end up in landfills due to some parts being unsuitable for recycling or due to the unavailability of the energy transforming processes locally.

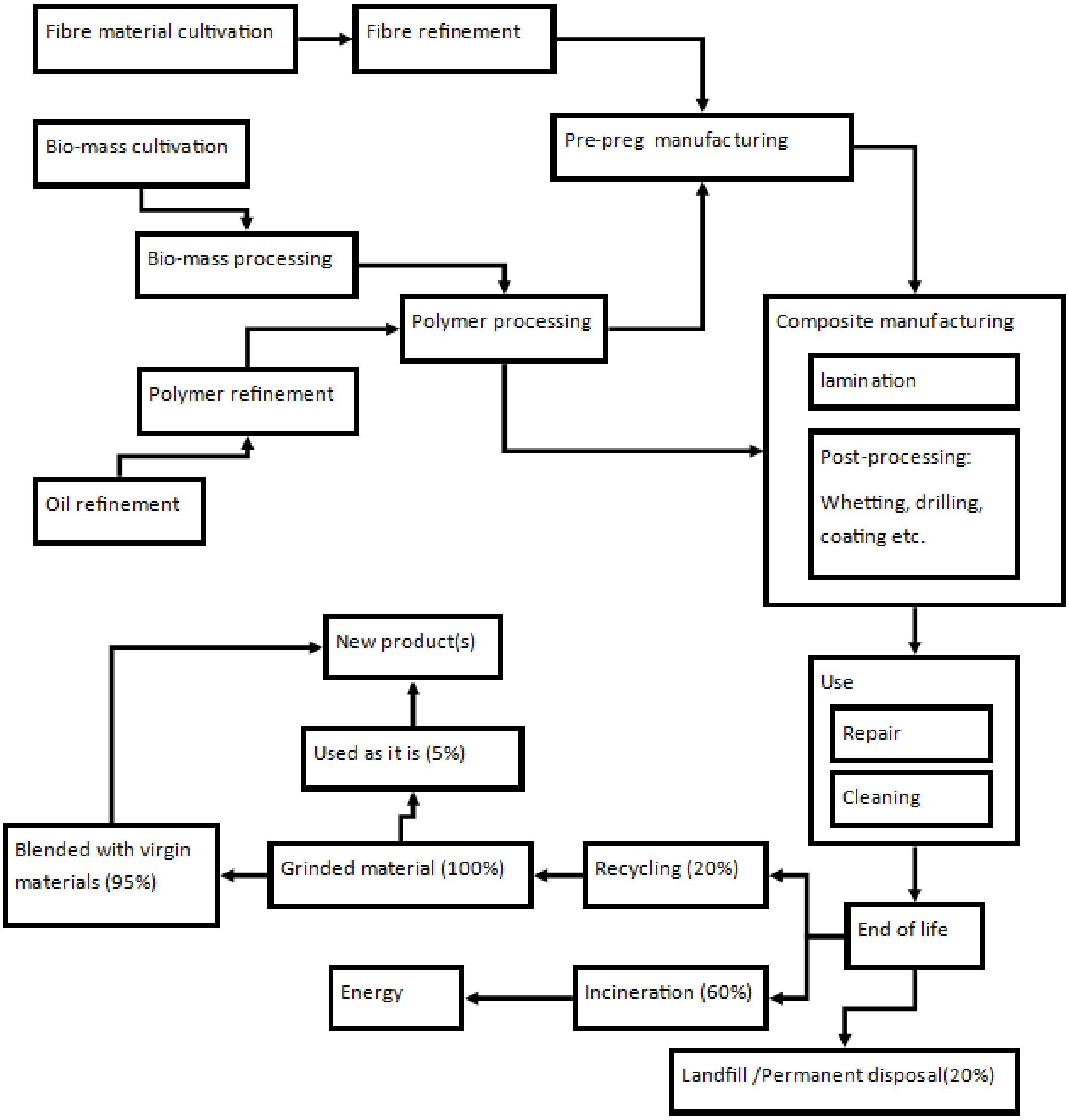

Figure 11 The system boundary of the composite panel.

All the three versions of the product have their phases, but they also share similarities. These lifecycles mostly use virgin materials, but recycled material is used in increasing fashion for products like the panel in this thesis. The overall environmental impact of material is more difficult to calculate when the material has been recycled multiple times. The only certainty is, that the material has a smaller environmental impact than virgin material because certain processes are no longer needed to prepare and/or refine the materials for manufacturing.

The applied material(s), the manufacturing process and the product end-of-life have the highest impact on the results. The system boundary was set to be more focused and some phases were finally determined to be ignored. Some processes and materials in

SimaPro include earlier processes and there was no need to give them a separate title. The Figures 12, 13 and 14 show the system boundaries used in the comparison of the panel versions in this thesis.

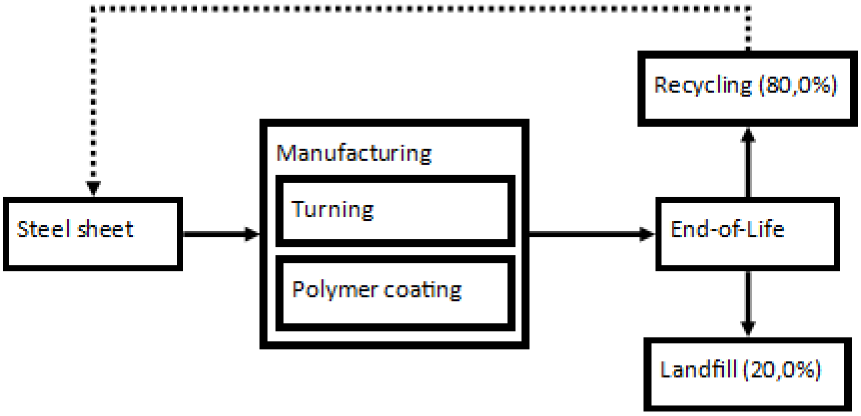

Figure 12 The applied system boundary of the metallic panel.

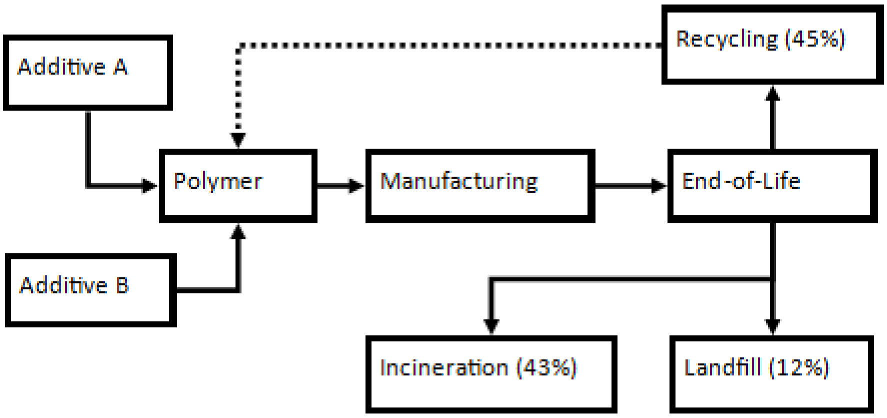

Figure 13 The applied system boundary for the plastic panel.

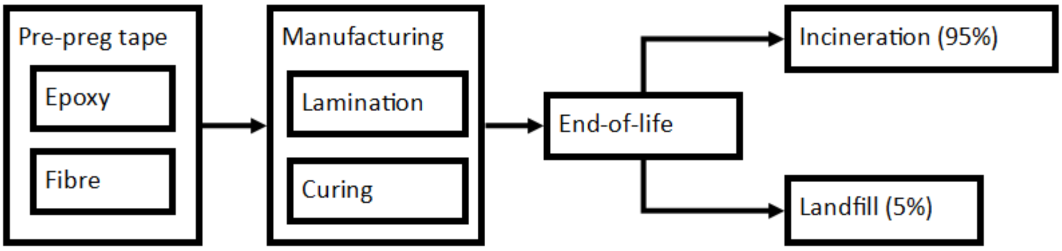

Figure 14 The applied system boundary for the composite panel.

The system boundaries were cropped to make the version comparison more straightforward. Also, the author's knowledge of the manufacturing processes and material details was not the same for each panel version. by adding all the thinkable details to one version but then only using rough estimates for other versions would create an imbalance that would disfavour one version over others. Therefore, cropped system boundaries were used for each version. It is acknowledged that dismissing some processes from every product version could affect the results of the final analysis. These effects will be finally estimated and discussed within interpretation.

4.3 The inventory analysis

Here is listed the variables and other factors that affect the results.

4.3.1 Transportations of goods and materials

The materials for each panel version come from around the world and the transportation emission is sorted for each version accordingly. It is here assumed that the materials are transported in large quantities and, therefore, ground- and water-based transportation methods are preferred. The vehicles are cargo ships, freight trains and trucks. Some materials travel via other existing infrastructure (e.g. oil pipes).

The theoretical factory for the final product manufacture is situated in Tampere, Finland. All distances are rough estimates based on data acquired from online map services.

4.3.1.1 The metallic panel: transportation

The iron is mined and refined to steel in China. From there, it is transported by a cargo ship to Greece (16300 km). From Greece, the material will travel by a freight train (1450 km) and truck (950 km) to Finland.

4.3.1.2 The plastic panel: transportation

The oil for the plastic comes from Russia. The oil travels via pipelines most of the journey (1500 km). The distance from Russia to Finland (200 km) is transported by an oil tanker. The refined material is transported to Tampere by a truck (175 km).

4.3.1.3 The composite panel: transportation

The flax for the composite is cultivated in France. It is transported by a freight train and trucks (1260km + 1100km) to Finland. The oil for the plastic comes from Russia and is transported similarly to the plastic version (1500 km + 200 km +175 km).

4.3.2 Materials inventory

In the following, the presumed origins of all the materials are defined for the product in this thesis.

4.3.2.1 Metallic panel: materials

Iron ore is mined and refined in China. Part of steel used in the product is recycled material. The iron is cast into steel sheets in China and the sheets are transported overseas. The protective surface coating (0,8 wt% of the whole panel) is made of epoxy resin (paint) and has small amounts of additives, such as pigments.

4.3.2.2 Plastic panel: materials

Oil is acquired from Russia and refined in a local refinery. The plastic is polyamide 66 filled with glass fibre fluff. Additives included are fire retardant ($Al(OH)_3$, 2,9 wt%), fillers (glass fibre fluff) and colouring materials (TiO_2, 2,9 wt%).

4.3.2.3 Composite panel: materials

The matrix is made of epoxy resin (36 wt%) and the reinforcement material is a natural fibre (64 wt%). The natural fibre of the product was initially to be flax in the early drafts. However, in the databases chosen, flax is not available material and had to be replaced. Kenaf fibre was chosen to be close enough match for flax fibre. The main difference between them is the cultivation location. Kenaf fibre is mostly produced in India while flax is cultivated in Europe. It is assumed that the composite version is made of flax, if produced, and thus the transportations for the fibre are based on France in the LCA of this thesis.

4.3.3 Product manufacturing

All the panel versions are manufactured by different methods. The metallic and plastics versions are given processing values from the database directly but the data for the composite version is from first-hand measurements.

4.3.3.1 Metallic panel: processing

The steel sheet is stamped and bend to correct shape. Connection holes and other finishing touches are added, and protective coating applied finally.

4.3.3.2 Plastic panel: processing

The product is injection-moulded and finishing touches are added (drilling of connection holes, removal of possible fillets).

4.3.3.3 Composite panel: processing

The panel is robot-laminated and oven-cured. Finishing touches are done (drilling, reaming).

4.3.4 The use phase: operation

The product is generally presumed to stay in passive operation as a protective panel. There is, however, the possibility that the panel needs to be cleaned or repaired. The repair could be necessary action due to hit by falling tree or other mechanical impact. The occurrence of these random scenarios differs for each version. The use phase is left out of the comparison due to its insignificance. The possible needs are, however, mentioned for reference purposes.

4.3.4.1 Metallic panel: operation

Even if the material is coated steel, rust can occur. Rust affects the aesthetics of the panel and entire smart pole and, thus, large amounts of rust should be removed. The coating should prevent the growth of algae, but it might get damaged. There is a possibility that the panel gets dirty due to natural causes or alternatively due to vandalism. The panels might be needed to be taken down and cleaned.

4.3.4.2 Plastic panel: operation

The plastic version can get damaged from long exposure to ultraviolet (UV) light and high humidity. Possible oxidization on non-painted surfaces can be removed by polishing. The plastic panel might function as a platform for organisms and might get dirty due to algae growth or dust, likewise the metallic panel.

4.3.4.3 Composite panel: operation

The composite panel has similar characteristics than the plastic panel. It has better resistance against mechanical damage but is more susceptible to micro-organism induced damage due to natural fibres. The growth of organisms is harder to prevent as efficient measures are toxic. The application of a coating (paint or gelcoat) is a possibility if the environment so requires.

4.3.5 End-of-life phase

This phase determines how the product is handled after its operation has ended. Usual outcomes are as follows. 1) Recycling: the product is returned to use as raw materials. 2) Reuse: the product is used as it is in other or similar application. 3) Energy production:

the product is processed and used as fuel. 4) Landfill or another permanent disposal: the product is stored away with other disposed items.

4.3.5.1 Metallic panel: disposal

Steel is an expensive material in multiple measures. Therefore, it is presumed that most of the panels are recycled for raw materials. Some panels are likely to end up in permanent disposal due to their poor condition (significant rust) or unavailable recycling options locally.

4.3.5.2 Plastic panel: disposal

The plastic panels should be recyclable if oxidization has not affected them significantly. Some panels will likely end in landfill, depending on the number of panels available at the site and closeness of recycling facilities. Some panels will be incinerated due to lack of recycling options locally. Some panels can be ground (particles) and used with virgin material to create new products.

4.3.5.3 Composite panel: disposal

There is a possibility that the material could be recycled, but those applications are very few for natural fibres currently. Most likely the composite panel will be incinerated for energy. Some panels might end in landfill or possibly in other reuse applications.

4.4 Impact assessment

The LCIA method dictates the impact categories inspected and what kind of results are of interest. The methods are developed either by private parties or by public organizations. Some methods are developed to focus on certain countries or certain areas of interest. The LCIA methods focus only on one type of emissions or have multiple categories and inspect emissions in their entirety. Most of the multicategory impact assessment methods share similar or the same categories, but their effect is calculated by different means.

The results can be presented in multiple ways. They can be shown as they are or by given factors based on the practitioner's values. The common displays are characterization, normalization and weighting. The characterization shows the results in the standard unit system and is a mandatory part of displaying the results. Normalization and weighting both give the results certain factors based on the desired outcome and value choices. For example, if the ethical aspects of the product lifespan are more important than e.g. environmental aspects, human health affecting results can be given more weight. The weighting factors and the reasoning behind should be explained when the weighted results are shown. In this thesis, only characterization is used when displaying the results.

The impact assessment method chosen for this thesis was The International Reference Life Cycle Data System recommendations (ILCD) for LCIA in the European context. It is developed by the European Commission and is based on several methodologies to ensure proper results [36]. The ILCD was chosen as the most suitable method due to it being developed and updated by a public organization and thus the data quality and availability are guaranteed. The initial production of the product is presumed to take place in Europe and ILCD being European made ILCD the method off this thesis.

The ILCD impact assessment method focuses on midpoint effects. They are the emissions or other measurable units of environmental effects. Midpoint categories generally have a determining unit in which the results are reported, for example, climate change is reported as how many kilograms the subject emits carbon dioxide and other gases shown as CO_2 equivalent. There are also endpoint categories that are applied when the general impact on a certain group is more interesting than specific emissions. The endpoint categories are human health, natural environment and natural resources. The impact categories can be included in more than one endpoint category (Figure 15).

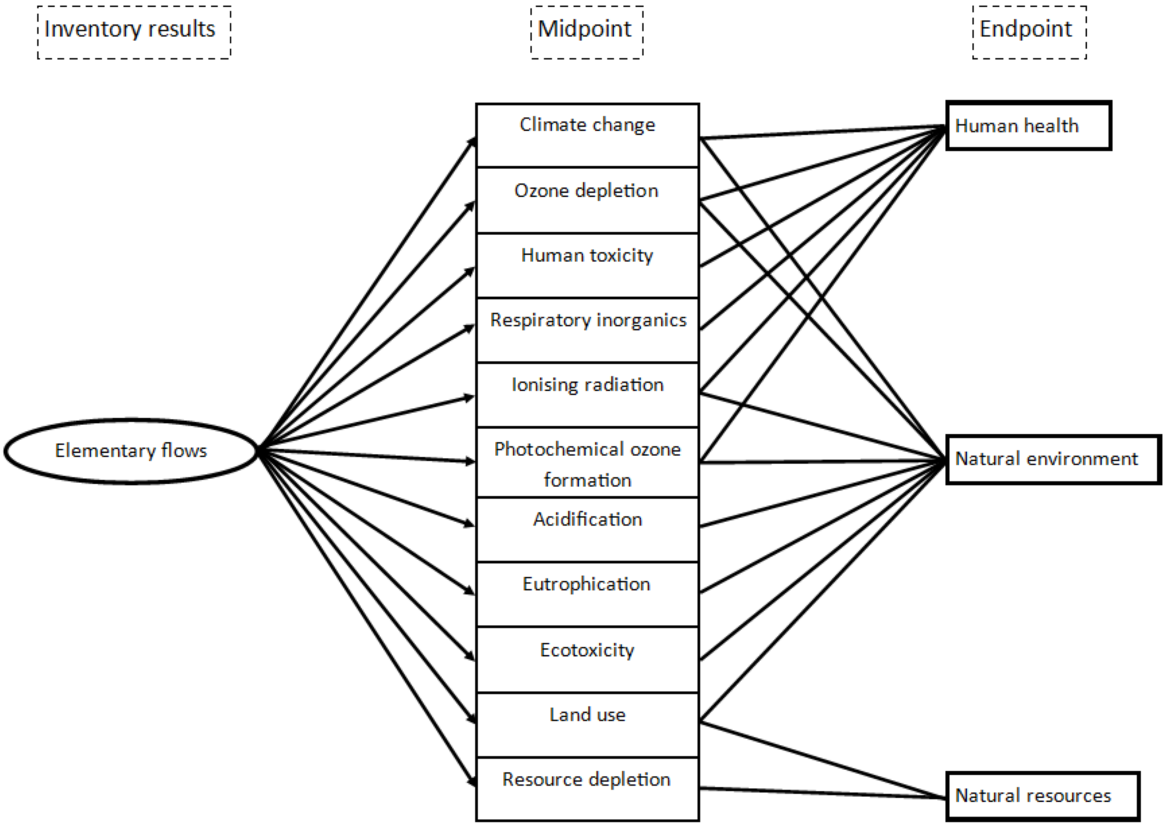

Figure 15 Midpoint and Endpoint relations presented as a graphical schematic

ILCD impact assessment categories are listed in Table 2 (Appendix) with their recommended LCIA method, indicator and classification. Classification levels indicate the reliability of the data and how much the category still needs adjusting. To ensure the most reliable results for the case in this thesis, only level I categories are compared seriously. Other categories are used either to enforce or question the reliability of the results. Level I impact assessment categories are climate change, ozone depletion and particulate matter/ respiratory inorganics.

The recommended default LCIA method for climate change is the Baseline model of 100 years of the Intergovernmental Panel on Climate Change (IPCC). It is a prediction based on median climate data and tells what will happen in 100 years if the current environmental impact progress continues [5]. ILCD recommends Steady-state ODPs 1999 as in WMO assessment as default LCIA method for ozone depletion. It is the World Meteorological Organization (WMO) that issued the references for ODPs. It lists known ozone layer affecters and their longevity and effect on the environment [37]. The recommended LCIA default method for particulate matter/ respiratory inorganics is a RiskPoll model [38, 39]. RiskPoll is a risk assessment program that can be used to calculate possible health and environmental impacts from particulate matter (PM_{10}) and common emissions

(SO_2, NO_X, CO etc.). It follows the methodology developed by the ExternE Project of the European Commission [40].

4.5 Interpretation of the results for panel versions

The interpretation phase of the life cycle assessment is where the results acquired from earlier phases are analysed and decisions to act based on the results are made. The results are compared in the characterization. The characterization provides clearly comparable results with concrete units. The only impact categories with the classification of level I are climate change, ozone depletion and particulate matter/ respiratory inorganics, and for that reason they are used as a basis for decision making in this thesis. Other results are shown in Appendix, in case they are referenced. These results show the environmental impact of one (1) panel manufactured.

The climate change effect is measured in kilograms of carbon dioxide equivalent. This means that other emissions are converted into CO_2 emission equivalents by using a factor based on their environmental impact. Then, all the emissions can be summed up for the overall impact on climate change.

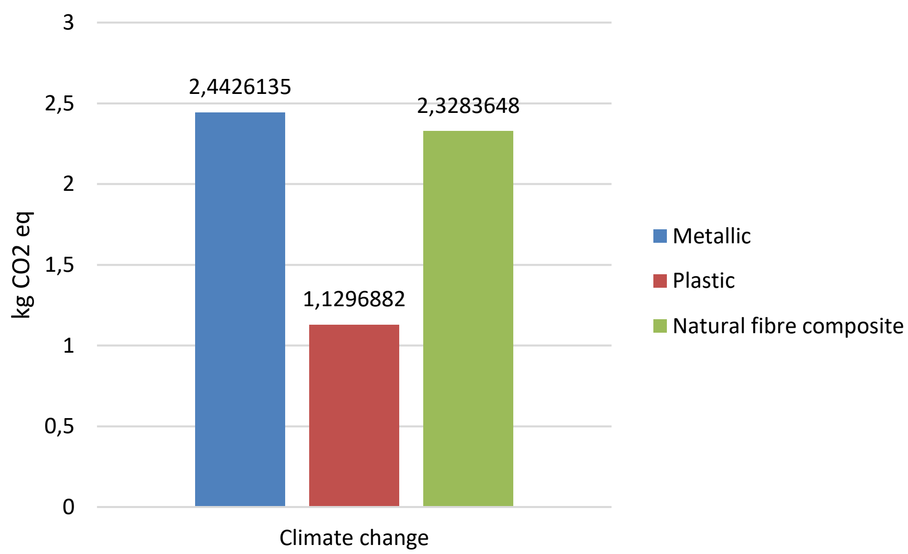

Figure 16 Climate change impact for all three panel versions

The plastic panel version has the least impact on climate change compared to the other versions. The impact is approximately half of the impact of other versions. The metallic panel version and composite version have a similar impact yet the metallic version has a slightly larger effect (see Figure 16). Plastic materials in general require less energy during manufacturing and processing. Steel manufacturing is energy consuming and raw materials have to travel before they can be utilized. Natural fibre composites raw materials consume natural resources and their end-of-life options are limited.

The ozone depletion potential is measured in kilograms of CFC-11 equivalent. CFC-11 has been chosen as a basis of comparison because it has the highest ozone layer depletion potential of ozone layer degrading compounds. All other ozone layers-depleting emissions are converted into CFC-11 equivalents by using an individual factor and the results are summed up to gain the overall impact.

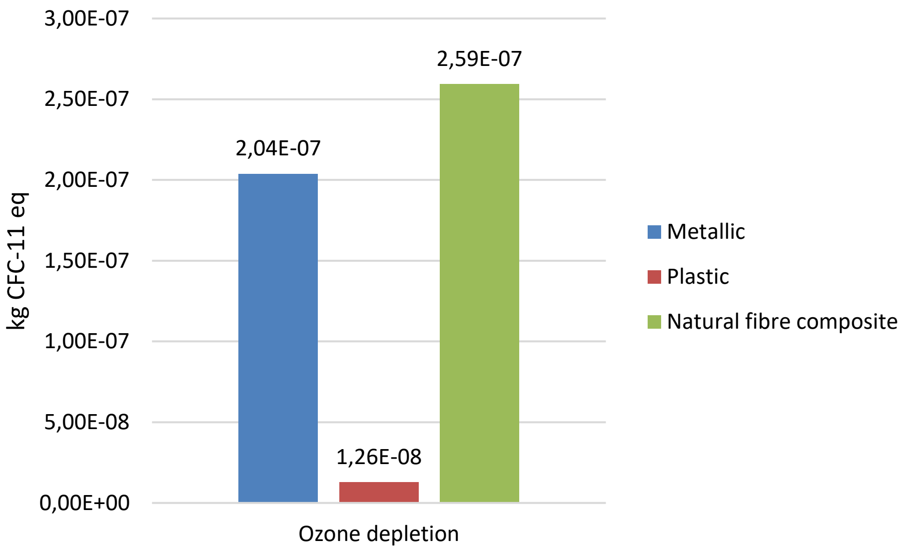

Figure 17 Ozone depletion potential for all the three panel versions

All the panel versions only emit trace-level amounts of ozone-depleting emissions, but, anyway, the plastic version emits the least. The metallic version and the composite version emit roughly the same amount (metallic version slightly less) (see Figure 17).

The particulate matter is displayed as kilograms $PM_{2.5}$ equivalent. $PM_{2.5}$ is particulate matter with a diameter of 2,5 µm or less. Small particles are a serious health hazard and cause premature deaths around the world. All particulate emissions are transformed into $PM_{2.5}$ equivalents by using their factors.

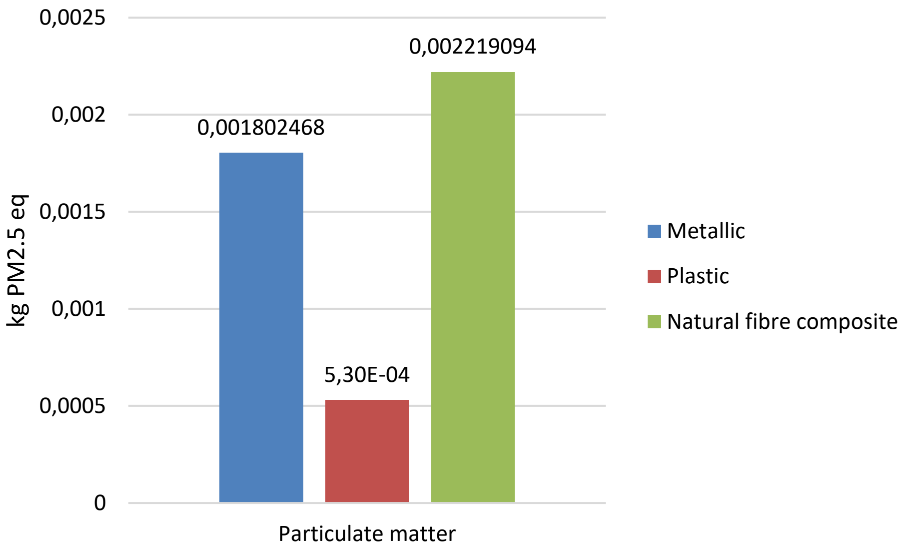

Figure 18 Particulate matter emissions for all the three panel versions

All the panel versions emit particulate matter in small amounts, and, in this impact category, the plastic version has the smallest emissions. The metallic version and the composite version have again roughly similar emissions (the composite having larger emissions) (see Figure 18).

The effect of these results and actions to be made based on these results are discussed in Chapter 5. (Synopsis).

5. SYNOPSIS

The conclusions of the thesis are based on the LCA results and other factors to be discussed. Even if the data points to a certain outcome, some variables must be assessed before the conclusions can be truly given. Some factors that have not been addressed before will be addressed here. The carbon fibre version is included in the discussion out of curiosity and to provide a better comparison for composite systems, like the natural fibre composite. Carbon fibre was the reinforcement material used in the lamination and cure process measurements for energy and is included to give a better understanding of the materials general environmental impact. All the results shown and mentioned in this chapter have been balanced by a design “lifespan factor”. In this case, the plastic and natural fibre composite versions are given lifespans of five (5) years in operation but the metallic and carbon fibre composite versions of the panel are given lifespan of ten (10) years. This leads to two panels manufactured in the selection of plastic and natural fibre composite panels during the lifespan of metallic and carbon fibre versions. All the results for plastic and natural fibre composite panels in the following text are multiplied by two (2) to gain more realistic results and to account for durability differences of the material systems.

5.1 The panel version comparison

When the environmental effect is the only ruling measure, the plastic version is the best compared to the other panel versions. It has the smallest impact on climate change and has the least emissions (see Figure 19). This can be explained by the plastics-related raw material origin and manufacturing process. Plastic-related raw materials are commonly petrochemistry outcomes and due to the massive proportions of the oil industry, the plastic-related raw materials have a steady supply. There is no need to establish mines or cultivate land to obtain their raw material. Their processing is also less energy-consuming compared to other materials due to the mature technology in processes and the low temperatures (of melting and refining).

The next best version based on environmental values is the metallic panel. This can be attributed to the material’s high recyclability and expected long lifespan in operation. The composite versions have the biggest environmental impacts mostly due to the long (multi-step) processing and manufacturing phases. They also have a larger impact due to their limited recyclability.

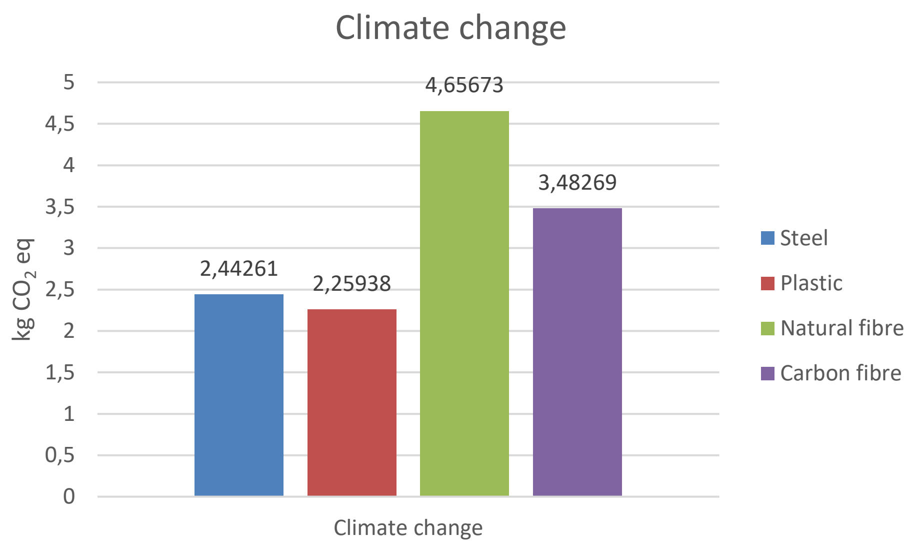

Figure 19 Balanced climate change effect for all the panel versions

The ozone depletion clearly divides the panels per material selections. The plastic version has the least emissions, only a fraction compared to the others (see Figure 20). The relatively light processing of the material can be pointed as the reason for these results. Steel manufacturing consumes energy, but as the processes mainly consist of heating and mechanical treatments, the metallic version has less emissions than treatments, the metallic version has less emissions than the composites. The composite panels emit more ozone-depleting particles because they require more chemicals and more intensive processing. The carbon fibre processing requires more energy than the other materials and emits more ozone-depleting particles [41] which explain the great difference between the carbon fibre composite version and the other versions.

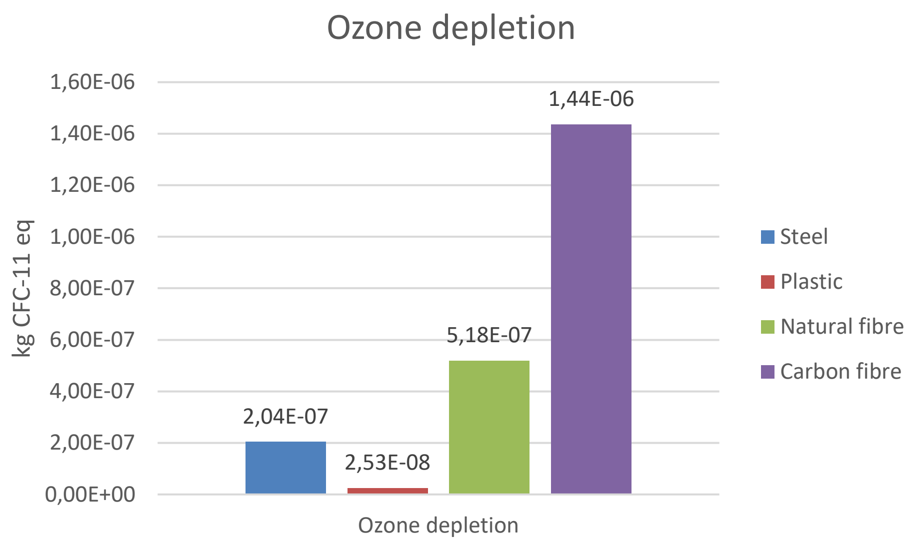

Figure 20 Balanced ozone depletion for all the panel versions

The particulate matter emissions are the least for the plastic panel version again. Like before, the plastics processing is simple compared to other materials and the processes emit particulate matter less than the other versions (see Figure 21). The most significant emissions are produced by the natural fibre composite, because of the manufacturing processes of the plant matter and soil usage.

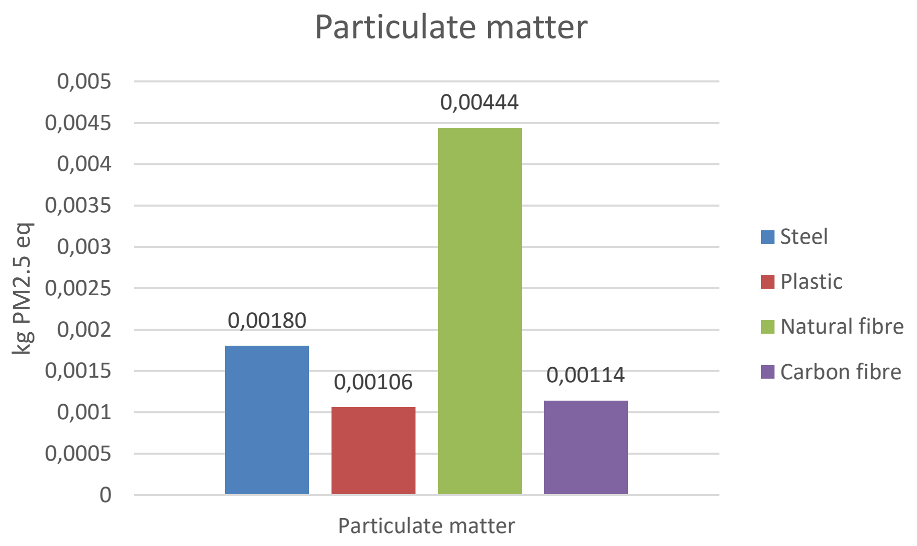

Figure 21 Balanced particulate matter emissions for all the panel versions

It needs to be notified, that even when there is a noticeable difference between (some) the results, they are all quite small overall. The ozone depletion and particulate matter emissions are measured in grams or less. Of course, the product is expected to be manufactured in batches of thousands or tens of thousands, so that all emissions add to greater numbers quickly. Even small emissions can have a great environmental impact if they are toxic enough, so dismissing the results for small amounts is irresponsible. Some results might be less significant when scaled up to larger manufacturing quantities, but that is left out of the results for now. For example, a processing effects per panel can be decreased when mass production techniques are applied.

The extrusion of the plastic pipe and bending the steel sheet are fast processes compared to the lamination and curing of the composite. It is possible to produce multiple steel and plastic products in the time it takes to make one composite product. Based on the time it took to make the prototype panel, a full-sized composite panel would take approximately eight (8) hours to be laminated by single robot and cured. Keeping up with the faster pace of the other versions production would require investing in more robots or to completely redesign the composite production method.

The environmental impact of building new infrastructure has its effect on the results as well. The steel processing and manufacturing are relatively old technologies. This means that there are already existing production plants and processing machinery that can be utilized for panel production. In theory, there is no need to use resources and create a greater environmental burden by creating new machinery for specifically the panel production. The issue with using old machinery is that not all of the old machines are up to modern standards. It is common to see fifty (50) year old machines still in use today. The laws, requirements and technology have evolved since that machinery was new and by the current standards, the old machinery might be inefficient, polluting or dangerous to use. Newer machinery is more efficient and environment and human friendly, but it might take decades before the environmental impact of newly acquired machinery is compensated for. The plastics manufacturing is a little younger industry, but due to the ease of plastic melt applications, the machinery is relatively similar for all production. There is no need to build new infrastructure for the plastic panel version, perhaps only acquiring the mould would be enough. The composite industry is fairly new, which means there are only a handful of existing composite manufacturers. There is a high possibility that a new manufacturing plant would have to be built for panel manufacturing, which would increase the environmental load of the composite panel version even more.

The panel is imagined as a part of the smart light pole could also be used in other radioprotective applications. The actual number of panels has not been addressed, but it is presumed that it would be at least two (2) per pole. The metallic panel weights multiple times more than the other versions and would thus require a sturdier pole connection and possibly more fasteners. The effect of added elements increases with the number of panels in the pole. Lifting and moving the heaviest panel around consumes more energy and fuel than during assembly of pole with other panel versions. Due to the possible weight limits, the metallic panels might be needed to be moved in multiple batches while the other versions could be carried in fewer.

The lifespan of the product greatly affects the results. The plastic and natural fibre composite panels are given here shorter lifespans because their outdoor degradation is typically more severe than for (thick) metallic part. Long exposure to the outdoor environment can cause unanticipated damages and for this reason, these panel versions are given shorter lifespan for operation. This assumption is tightly related to the climate the product is used at. In a milder climate in which the temperature changes are less extreme and the weather conditions are easier to forecast, it is easier to optimize the product qualities, like protective paints and painting techniques. The optimization could lead to a possibly longer lifespan and smaller environmental impact.

The products end-of-life phase affects the results significantly. The metallic version is expected to be mostly if not fully recycled. The material has a high demand and even after being recycled multiple times the material properties remain similar to those of the virgin materials. Plastics are relatively inexpensive materials, so the material cost is often an ineffective stimulant to encourage plastics recycling. The plastic panel is expected to be recycled at least partly, because the plastic it is made out of, is not cheap enough to be fully dismissed. The additives in the plastic affect recycling efficacy. The additives are costly if not impossible to remove and they limit the usage of the recycled material to a similar application as the original product had. This results in plastics recycling are less effective compared to steel recycling. The plastic version is expected to be incinerated for energy because it is an easy way to gain something from a product that has otherwise fulfilled its purpose. The composite versions are assumed to be fully incinerated due to the difficulty of composite recycling. The carbon fibres can be harvested for reuse after the polymer matrix has been incinerated, but that possibility is left out of this one lifespan centered study. A number of panels for all the versions is expected to end up in landfill due to the material being not recyclable anymore or there is no suitable infrastructure in that part of the world where the panel has been used.

The impact categories that are given lower classification than I (one) should not be used as a basis for serious interpretation, due to their results can be unreliable. They can be used to get a general understanding of the differences between different product versions. In this thesis, the metallic version has notably higher human toxicity emissions than the other versions (Appendix, Figure 22, Figure 23). This is likely due to the particulates and chemicals released in steel refining. The composite material systems have higher ionizing radiation emissions than the other versions (Appendix, Figure 24, Figure 25). The carbon fibre results in the highest emissions. Plants and soil have relatively high radioactivity and so does carbon-related production. All the panel versions have notable photochemical ozone formation, but natural fibre has the highest (Appendix, Figure 26). These volatile organic compounds (VOCs) are oxidized by sunlight, so it is assumed that plant matter is more likely to contain them. Acidification impact among all the panel versions is similar to the photochemical ozone formation (Appendix, Figure 27). Natural fibre composite has the highest effect, likely due to its relation to the natural carbon cycle. The natural fibre version has the highest impact in all eutrophication categories: terrestrial eutrophication (Appendix, Figure 28), freshwater eutrophication (Appendix, Figure 29) and marine eutrophication (Appendix, Figure 30). Other versions have varying results in these categories. The results for the natural fibre composite are likely due to the need to fertilize the crops. The high impact of steel on freshwater eutrophication could be explained by steel refining processes. The metallic and natural fibre composite panel versions have a higher impact on freshwater ecotoxicity than other versions (Appendix, Figure 31). Steel refinement and processing uses and pollutes water, whereas natural fibre requires water use and chemicals for raw materials (flax, kenaf). The natural fibre composite version uses more land and water resources than the other versions (Appendix, Figure 32, Figure 33). This can be credited for the raw material crops. The metallic version uses more land than the plastic and carbon fibre composite versions, that is likely due to its raw material acquisition and refining processes. The metallic version uses notably more mineral, fossil and renewable resources than the other versions (Appendix, Figure 34). The steel material requires more resources due to how it is produced. Like with the classification I impact categories, some of the aforementioned impacts in terms of emissions are relatively low (per panel). Even if there is a big difference between the versions, the overall impact can be hardly noticeable in terms of absolute values (per panel).

5.2 Possible error sources and other issues

It was noted before, in actions of chapters for calculations and measurements, that there are many phases were humane and unexpected mistakes can occur. Most common missteps were tried to be anticipated, to either avoid them or to ensure that their effects on the results were known. Some data omitting was made as decision to smooth out certain processes. The decisions of neglecting phases affected the results, but that impact was minimized by proper planning (e.g. of measurements). The different versions of the product were not treated perfectly equal and that has effects, yet this has been discussed.

The system boundaries affect the results the most. Setting the system boundary to be comprehensive but ignoring process phases and details leads to unbalanced results. In this case, the author’s previous knowledge on certain processes and material type likely caused the less familiar materials to miss some early process phases that could have affected the calculations. to miss some early process phases that could have affected the calculations. The quality of the used databases affected the results naturally. Some exact material systems originally planned for the product could not be found from the databases and had to be replaced with the closest alternative. Some processes did not have an alternative and had to be left out altogether (for example polishing and other processes related to product finishing). Some materials appeared only by their trade name or had to be crafted from raw materials. There were no proper choices for material recycling in the libraries used. The recycling phase was substituted with a reuse option with a similar product being the target for the reused material. This probably leads to results where the metallic and plastic versions appear better than they should have. The number of production phases was limited by the product version with the least applicable phases. This was done to keep the results at relatively similar accuracy.

The assumptions made of the version manufacturing locations, methods and materials are educated estimations at best. Most decisions made for the calculations are cost-based because costs are a common purchase decision factor in real commercial industry. Other factors such as environmental impact, ethics and accessibility were given less weight in calculations, because they rarely are used as a basis for final decision making in the information and communications industry sector. The transportation methods and distances are rough estimates based on general knowledge about regional infrastructure. When observing that the transportations have only a minimal effect on the results their inaccuracies can probably be overlooked (Appendix, Figure 35).

The product versions are given lifespans of five (5) or ten (10) years. These estimates are based on the expected maximum lifespan of the 5G technology and degradation in plastic/composite materials. If the technology advances faster than anticipated and the 5G becomes obsolete earlier, then the panels environmental impact is larger than calculated. There is the possibility that 5G technology is in use longer than predicted and that affects the relationship between the results of the different panel versions. Same panels could be utilized for the newer (6G) technology or repurposed in a way that could not be currently foreseen. Trying to guess how future unfolds, adds its challenges toto the interpretation and analysis. The recycling of composites and plastics may advance unpredictably in near future and any calculations based on current knowledge shall always be re-analyzed in the future. Raw material acquisition is affected by the unstable political climate and if there are issues with dominating (close to monopoly) providers, it affects the entire industry. Some materials can become expensive if not impossible to acquire and recycle, and that would re-guide the material selection in the future.

The movement of the robot and tool used in the composite panel's energy consumption measurement was left unoptimized due to the strict schedule. The movement speed could be increased if the 3D model mould had been more accurate and the robot movement software wouldn’t need to calculate the actual spatial differences. The material (pre-preg) selection also affects the speed. Some materials require less time to attach to the mould and previous layers and are more easily cut. If the other properties and price are agreeable it would be better to switch to that kind of material. The layup setup was limited due to the tool movement range. With the setup used in the energy measurements, the robot could only apply the tape from a certain direction. This leads to a relatively large portion of the manufacturing time being spent on tool rotation. The tool design or movement speed should be revised for mass production calculations.

The final manufacturing location of the panels is presumed to be in Finland and the end-of-life scenarios are performed in Finland as well. This means that the energy consumed in production is at least partly from renewable sources and the recycling processes are well organized. Should the product be manufactured somewhere else, these factors could differ notably. The energy production profiles, and material recycling and disposal possibilities vary greatly from one country to another. The electricity production method affects the results prominently as does the chosen method of disposal. The product is expected to be used in multiple countries of varying infrastructure and predicting the environmental effect in every possible location is a too vast task to perform in a short time window. The current results are for final manufacture in Finland and panel (smart light pole) operation in Finland.

The manufacturing calculations are done for one panel in theoretically ideal conditions. The background processes and activities are not included even if they would affect the results greatly. For example, machine heating times and inefficiencies are ignored and so are human-related energy consumptions e.g. lights, room heating, computers and other not directly to the panel manufacturing-related factors. Even relatively small increases in energy consumption affected the panel version’s environmental impact, so some versions may seem greener than they should be. The extra processes related to manufacturing are left out for all the panel versions, and this means that the results are equally exclusive.

5.3 Conclusions

Based on the results and the discussed factors and effects, the plastic panel version seems like the best option given the alternatives. The metallic version is a strong contender but has some seriously hindering qualities. The issue with the metallic panel is that no electromagnetic signal can pass through. Similarly, carbon fibre composite panel does not basically pass through any (5G) electromagnetic signal. Other better thought designs (e.g. with signal windows) or designs combining multiple materials could make the use of these two materials possible.

Based on environmental impact assessment results the plastic version is the better option out of the two suitable candidates (plastic and natural fibre composite). The plastic version is easier, faster and cheaper to produce with the current design. The design would have to be changed into something more complex for the composite version to become the more sensible option. The volume (thickness) of the product in this thesis was not optimized per material selection, e.g. based on mechanical strength. The results would have been better for natural fibre composite if the optimization had been done, but likely it would still have higher emissions than the plastic version. Surprisingly, the material that is generally regarded as the environmentally friendliest part of the composite, the natural fibre, is the part that makes it less environmentally friendly than the plastic panel version for a constant, predefined thickness.

LCA is a complex procedure and cutting any corners will make the results inaccurate in some regard. The LCA is, however, a useful tool to prove some persistent ignorant claims wrong and cause people to question things generally accepted as the truth. Every single thing ever produced should have an LCA done to give people some perspective about their (indirect) impact on the environment. LCA, however, is not a flawless tool. It considers the facts from one point of view, but by doing so it ignores other facts that affect the reasoning behind the choices made. It is a useful tool, nonetheless, but should be used with its limitations in mind.

Unfortunately, the current LCA tool availability is limited to expensive high-quality products and varying quality opensource products. The making of LCA on a budget is challenging at best and is a clear obstacle for companies interested in their environmental impact. As environmental issues are becoming a more pressing topic, the public authorities should ensure that the people and companies responsible for most of the impacts, emissions, have access to the tools that can be used measure and limit those emissions with accurate data.

It is only a matter of time before measuring the environmental impact of any produced goods becomes mandatory. It is advisable to familiarise oneself with LCA proceedings so that when the time comes, the data required for the calculations are easily acquirable. In case the LCA of a product will only be a recommended procedure, it is still useful to conduct. The data acquired from a study can be used to identify possible problems in the process chains or at least be used for marketing purposes.

REFERENCES

[1] Jozefat B. Climate change and all Evidences of Global Warming, Climate Change, 2015, Pages 62-63, 66-70

[2] IPCC 2006 Guidelines for National Greenhouse Gas Inventories, Volume 1, General Guidance and Reporting, 2006, chapter 1, page 1.5

[3] Bongaarts J. Human population growth and the demographic transition. Philosophical Transactions of the Royal Society B: Biological Sciences 2009; 364:2985–90. https://doi.org/10.1098/rstb.2009.0137. Chapter 2

[4] Moltensen A, Bjørn A, LCA and Sustainability, Life Cycle Assessment, 2018, Technical University of Denmark, Pages 48-50

[5] Edenhofer O, Sokona Y, Minx JC, Farahani E, Kadner S, Seyboth K, et al. Climate Change 2014 Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Edited by. 2014. Pages 9-11

[6] Tsao JY, Waide P. The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents. LEUKOS 2010; 6:259–81. https://doi.org/10.1582/LEUKOS.2010.06.04001. Page 278

[7] Garimella S v., Persoons T, Weibel J, Yeh LT. Technological drivers in data centers and telecom systems: Multiscale thermal, electrical, and energy management. Applied Energy 2013; 107:66–80. https://doi.org/10.1016/j.apenergy.2013.02.047. page 67

[8] Lange S, Pohi J, Santarius T. Digitalization and energy consumption. Does ICT reduce energy demand? Ecological economics volume 176; October 2020; 106760. https://doi.org/10.1016/j.ecolecon.2020.106760 page 8

[9] Emblemvåg J, Bras B. LCA Comparability and the Waste Index. The International Journaal of Lifee Cycle Assessment 4. 1999 page 282

[10] Biron M, Marichal O. Thermoplastics and Thermoplastic Composites. Plastics Design Library 2018 page 15

[11] Guo Q, Hamerton I, Mooring L. The use of thermosets in aerospace applications. Thermosets: Structure, Properties and Applications. 2012. Pages 192-193

[12] Baley C, Lan M, Bourmaud A, Le Duigoou A. Compressive and tensile behaviour of unidirectional composites reinforced by natural fibres: Influence of fibres (flax

and jute), matrix and fibre volume fraction. Materials Today Communications 16 (2008). https://doi.org/10.1016/j.mtcomm.2018.07.003 page 301

[13] Campbell F. C. Manufacturing processes for Advanced Composites. Introduction to Composite materials and Processes: Unique Materials that Require Unique Processes. https://doi.org/10.1016/B978-1-85617-415-2.X5000-X 2003. page 3

[14] Goodship V. Management, recycling and reuse of waste composites. An introduction to composites recycling. 2014. page 19

[15] Farah S, Anderson D G, Langer R. Physical and mechanical properties of PLA, and their functions in widespread applications – A comprehensive review. Advanced Drug Delivery Reviews. https://doi.org/10.1016/j.addr.2016.06.012 2016 page 368

[16] Madival S, Auras R, Singh S P, Narayan R. Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2009.03.015 page 1188

[17] Vieyra Ruiz H, Martínez ESM, Méndez MÃA. Biodegradability of polyethylene-starch blends prepared by extrusion and molded by injection: Evaluated by response surface methodology. Starch/Staerke 2011; 63:42–51. https://doi.org/10.1002/star.201000075. Page 52

[18] Eliaz N, Ron EZ, Gozin M, Younger S, Biran D, Tal N. materials Microbial Degradation of Epoxy 2018. https://doi.org/10.3390/ma11112123. Page 13

[19] Jiang G, Pickering S J. Structure-property relationship of recycled carbon fibres revealed by pyrolysis recycling process, Journal of Materials Science. DOI:10.1007/s10853-015-9502-2. 2016. pages 1955-1956

[20] Bismarck A, Mishra S, Lampke T. Plant Fibers as reinforcement for Green Composites, Natural Fibers, Biopolymers, and Biocomposites. https://doi-org.libproxy.tuni.fi/10.1201/9780203508206. 2005 pages 37-39

[21] Bayerl T, Geith M, … AS-I, 2014 undefined. Influence of fibre architecture on the biodegradability of FLAX/PLA composites. Elsevier n.d. page 21

[22] Fråne A, Stenmarck Å, Gíslason S, Lyng K-A. Collectiopn & recycling of plastic waste: Improvements inexisting collection and recycling systems in the Nordic countries. DOI: 10.6027/TN2014-543. 2019. pages 85-86

[23] Tarantili P A, Mitsakaki A N, Petoussi M A. Processing and properties of engineering plastics recycled from waste electrical and electronic equipment (WEEE). Polymer Degradation and Stability https://doi.org/10.1016/j.polymdegradstab.2009.11.029. 2010 pages 409-410

[24] Yin S, Tuladhar R, Combe M, Collister T, Jacob M, Shanks R A. Mechanical properties of recycled plastic fibres for reinforcing concrete. Fibre concrete 2013. page 5

[25] Schlummer M, Mäurer A, Leitner T, Spruzina W. Report: Recycling of flame-retarded plastics from waste electric and electronic equipment (WEEE). Waste Management and Research 2006; 24:573–83. https://doi.org/10.1177/0734242X06068520. Page 578

[26] Asmatulu E, Twomey J, Overcash M. Recycling of fiber-reinforced composites and direct structural composite recycling concept. Journal of Composite Materials 2014; 48:593–608. https://doi.org/10.1177/0021998313476325. Page 594

[27] Suzuki T, Takahashi J. The Ninth Japan International SAMPE symposium PREDICTION OF ENERGY INTENSITY OF CARBON FIBER REINFORCED PLASTICS FOR MASS-PRODUCED PASSENGER CARS. n.d. 2005, Page 15

[28] Oliveux G, Dandy L O, Leeke G A. Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties. Progress in Materials Scinece. https://doi.org/10.1016/j.pmatsci.2015.01.004. 2015. pages 94-95

[29] Kouparitsas CE, Kartalis CN, Varelidis PC, Tsenoglou CJ, Papaspyrides CD. Recycling of the fibrous fraction of reinforced thermoset composites. Polymer Composites 2002; 23:682–9. https://doi.org/10.1002/pc.10468. Pages 687-688

[30] Bernasconi A, Rossin D, mechanics CA-E fracture, 2007 undefined. Analysis of the effect of mechanical recycling upon tensile strength of a short glass fibre reinforced polyamide 6, 6. Elsevier n.d. Pages 636-639

[31] Leão RM, da Luz SM, Araujo JA, Christoforo AL. The recycling of sugarcane Fiber/Polypropylene composites. Materials Research 2015; 18:690–7. https://doi.org/10.1590/1516-1439.321314. Page 692

[32] di Vito D. OSCAR RODERA GARCIA DAMAGE ONSET MODELLING OF CURVED COMPOSITE LAMINATES. n.d. Pages 64-68

[33] https://www.luxturrim5g.com/https://www.luxturrim5g.com/

[34] Jutila L. THE RE-DESIGN OF A SUSTAINABLE MONOCOQUE SHELL FOR ULTRA HIGH FREQUENCY TRANSMITTING RADIOS. n.d. Page 88

[35] 5G Spectrum. GSMA Public Policy Position. 2020. page 2

[36] ILCD handbook – International Reference Life Cycle Data System. General guide for Life Cycle Assessment – Detailed guidance. JRC European Commission. 2010. pages 1-2

[37] World Meteorological Organization Global Ozone Research and Monitoring Project-Report No. 44. National Oceanic and Atmospheric Administration National Aeronautics and Space Administration United Nations Environment Programme World Meteorological Organization European Commission. n.d. Page 1.41

[38] Methodology | Ari Rabl and Joseph V. Spadaro | Ari Rabl n.d. http://arirabl.org/untitled/ (accessed December 11, 2020).

[39] Cocchi D, Greco F, Trivisano C. Hierarchical space-time modelling of PM10 pollution. Atmospheric Environment 2007; 41:532–42. https://doi.org/10.1016/j.atmosenv.2006.08.032. page 532

[40] ExternE - externalities of energy - methodology 2005 update (Technical Report) | ETDEWEB n.d. https://www.osti.gov/etdeweb/biblio/20712289 (accessed December 11, 2020).

[41] Tapper RJ, Longana ML, Norton A, Potter KD, Hamerton I. An evaluation of life cycle assessment and its application to the closed-loop recycling of carbon fibre reinforced polymers. Composites Part B: Engineering 2020; 184:107665. https://doi.org/10.1016/j.compositesb.2019.107665. Page 3

[42] Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods Database and supporting information n.d. https://doi.org/10.2788/60825. Pages 29-30

APPENDIX

Impact category	Recommended default LCIA method	Indicator	Classification
Climate change	Baseline model of 100 years of the IPCC	Radiative forcing as Global Warming Potential (GWP100)	I
Ozone depletion	Steady-state ODPs 1999 as in WMO assessment	Ozone Depletion Potential (ODP)	I
Human toxicity, cancer effects	USEtox model (Rosenbaum et al, 2008)	Comparative Toxic Unit for humans (CTUh)	II/III
Human toxicity, non-cancer effects	USEtox model (Rosenbaum et al, 2008)	Comparative Toxic Unit for humans (CTUh)	II/III
Particulate matter/ Respiratory inorganics	RiskPoll model (Rabl and Spadaro, 2004) and Greco et al 2007	Intake fraction for fine particles (kg PM2.5-eq/kg)	I
Ionising radiation, human health	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	Human exposure efficiency relative to U235	II
Ionising radiation, ecosystems	No methods recommended		
Photochemical ozone formation	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe	Tropospheric ozone concentration increase	II
Acidification	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)	II
Eutrophication, terrestrial	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)	II
Eutrophication, aquatic	EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe	Fraction of nutrients reaching freshwater end compartment (P)/ marine end compartment (N)	II
Ecotoxicity (freshwater)	USEtox model, (Rosenbaum et al, 2008)	Comparative Toxic Unit for ecosystems (CTUe)	II/III
Ecotoxicity (terrestrial and marine)	No methods recommended		
Land use	Model based on Soil Organic Matter (SOM) (Milà i Canals et al, 2007b)	Soil Organic Matter	III
Resource depletion, water	Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al, 2008)	Water use related to local scarcity of water	III
Resource depletion, mineral, fossil and renewable	CML 2002 (Guinée et al., 2002)	Scarcity	II

***Table 2 ILCD categories and classifications* [42]**

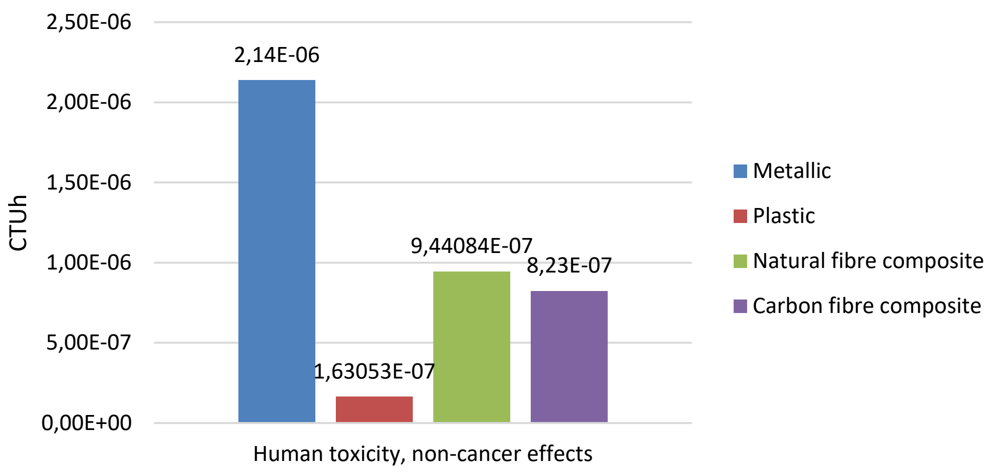

Figure 22 balanced human toxicity emissions

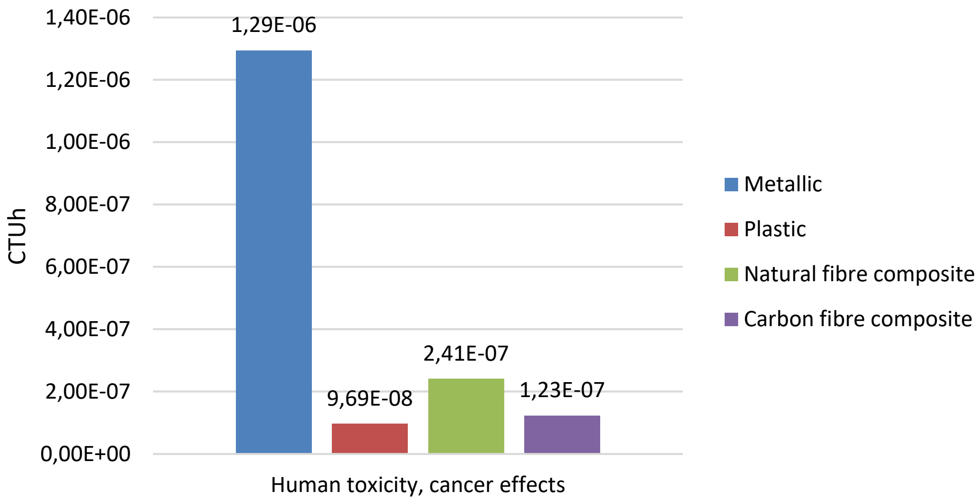

Figure 23 balanced cancerous human toxicity emissions

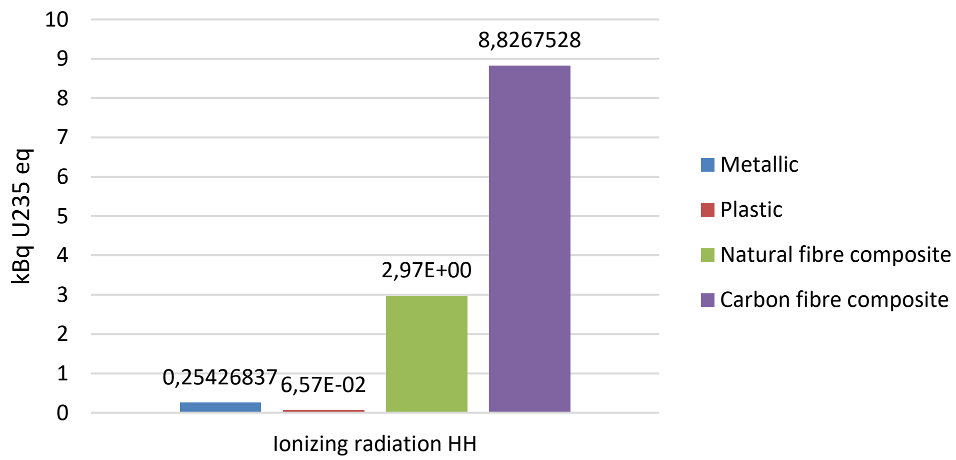

Figure 24 balanced Ionizing radiation results on human health

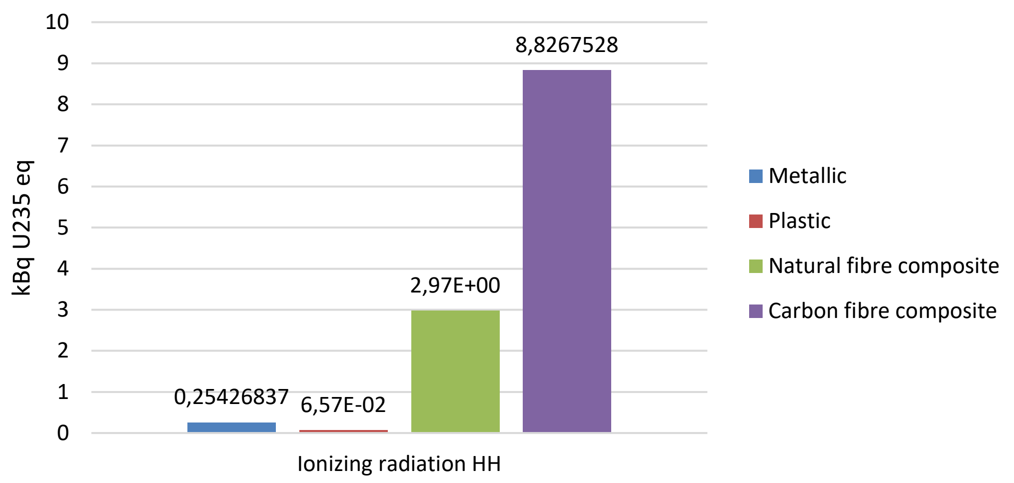

Figure 25 Balanced Ionizing radiation emissions

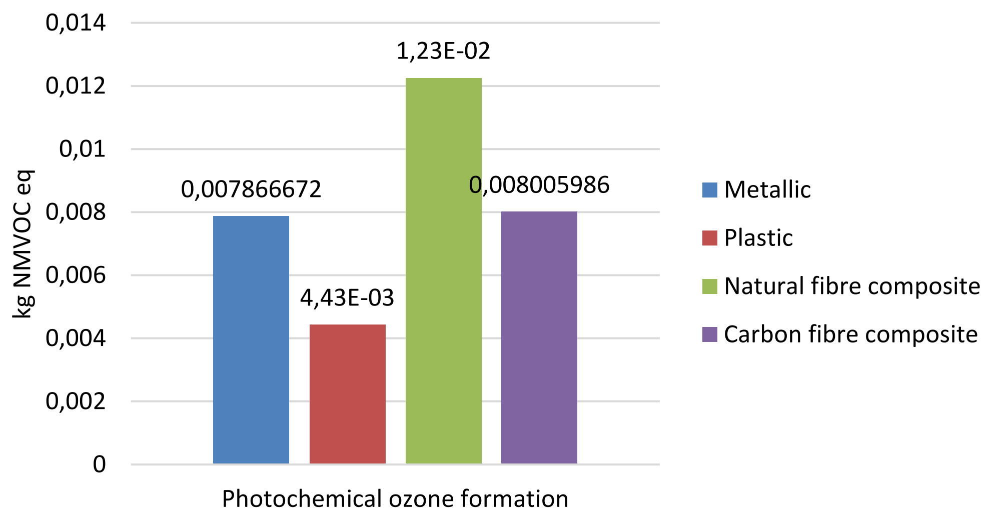

Figure 26 Balanced photochemical ozone formation results

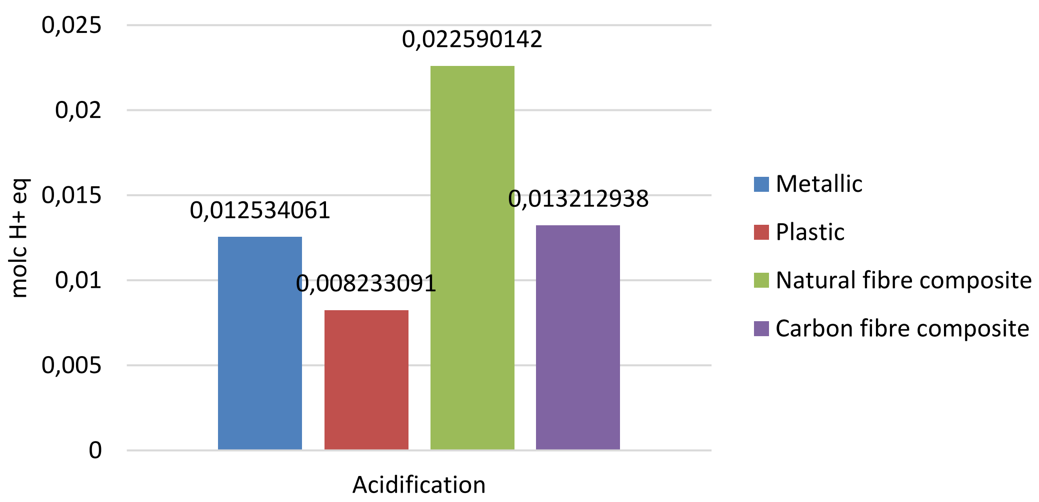

Figure 27 Balanced acidification results

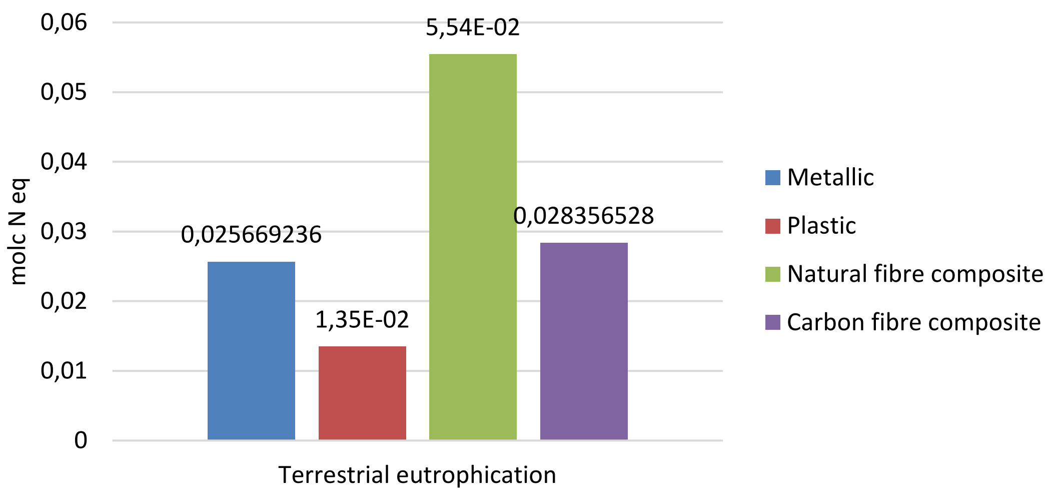

Figure 28 Balanced terrestrial eutrophication results

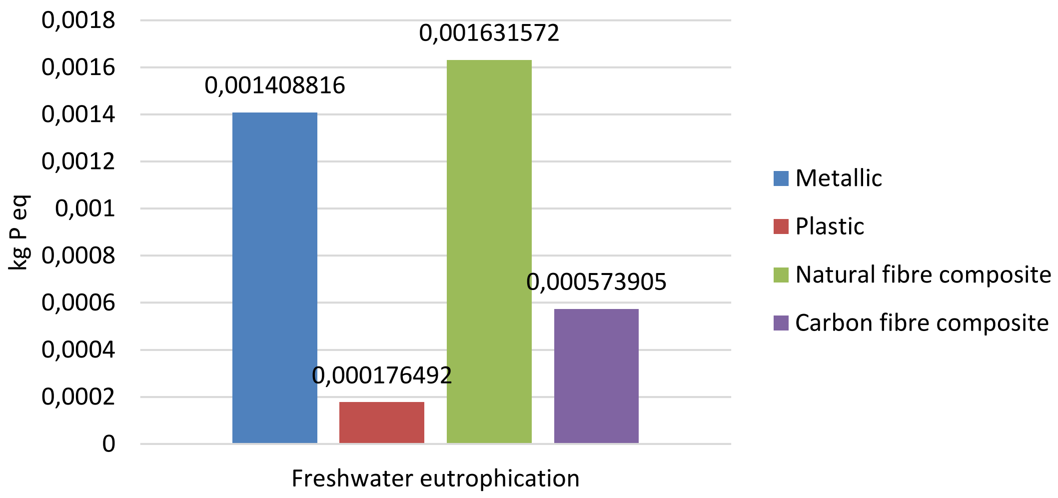

Figure 29 Balanced freshwater eutrophication results

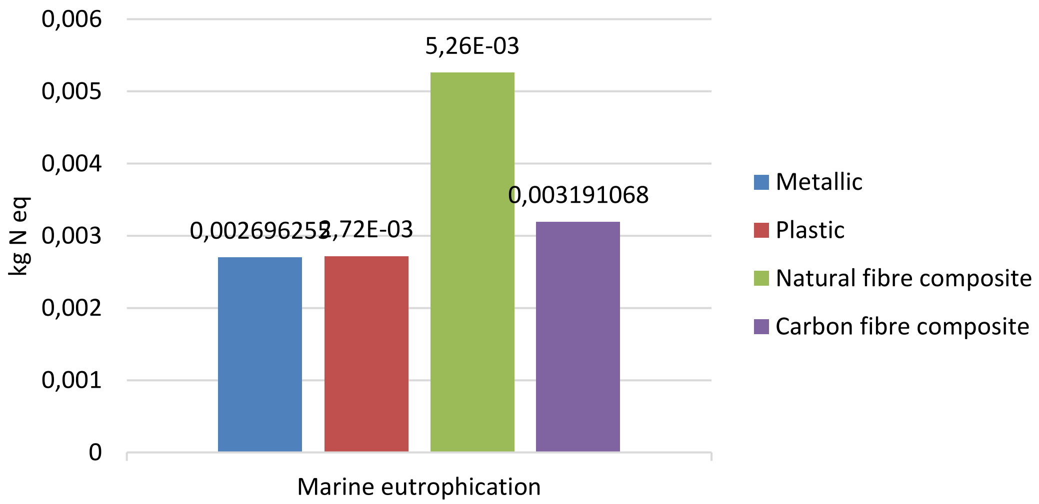

Figure 30 Balanced marine eutrophication results

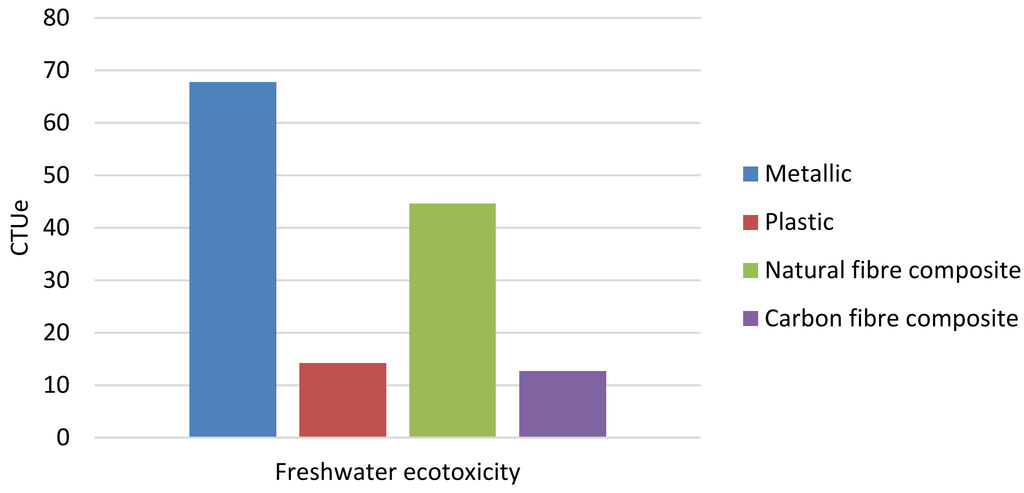

Figure 31 Balanced freshwater ecotoxicity results

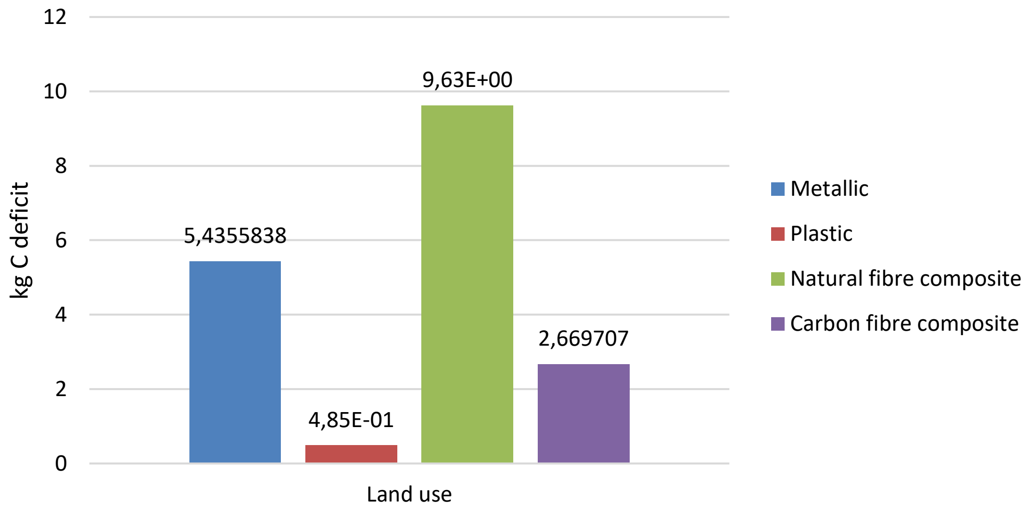

Figure 32 Balanced land use results

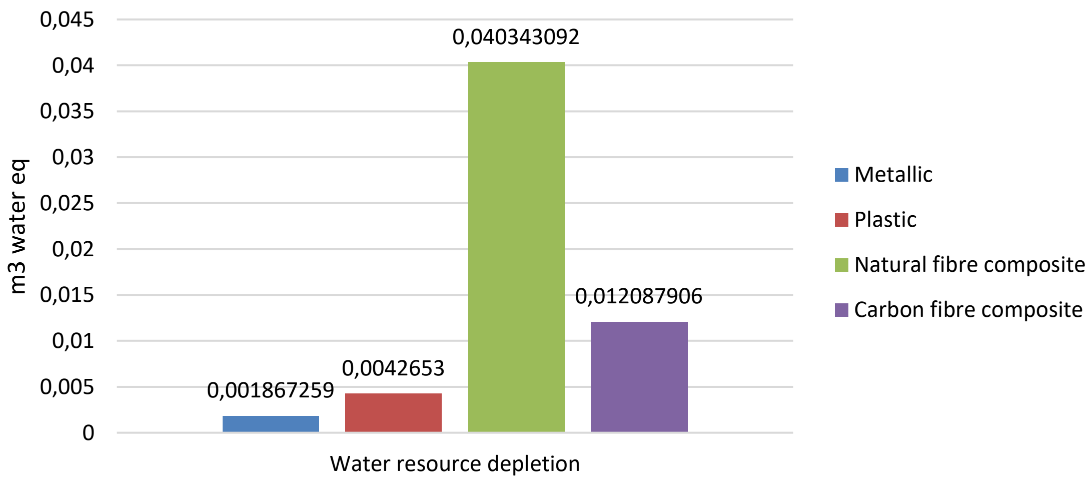

Figure 33 Balanced water source depletion results

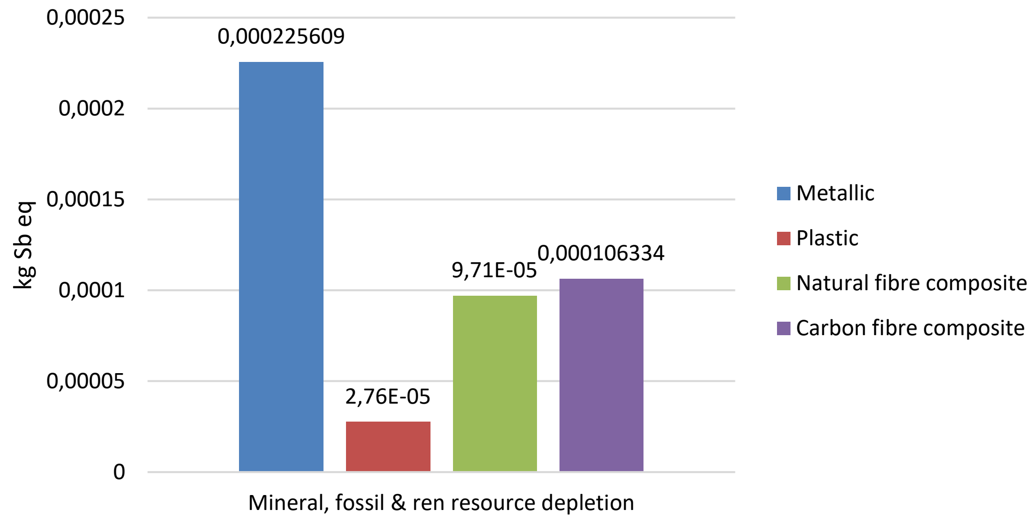

Figure 34 Balanced resource depletion results

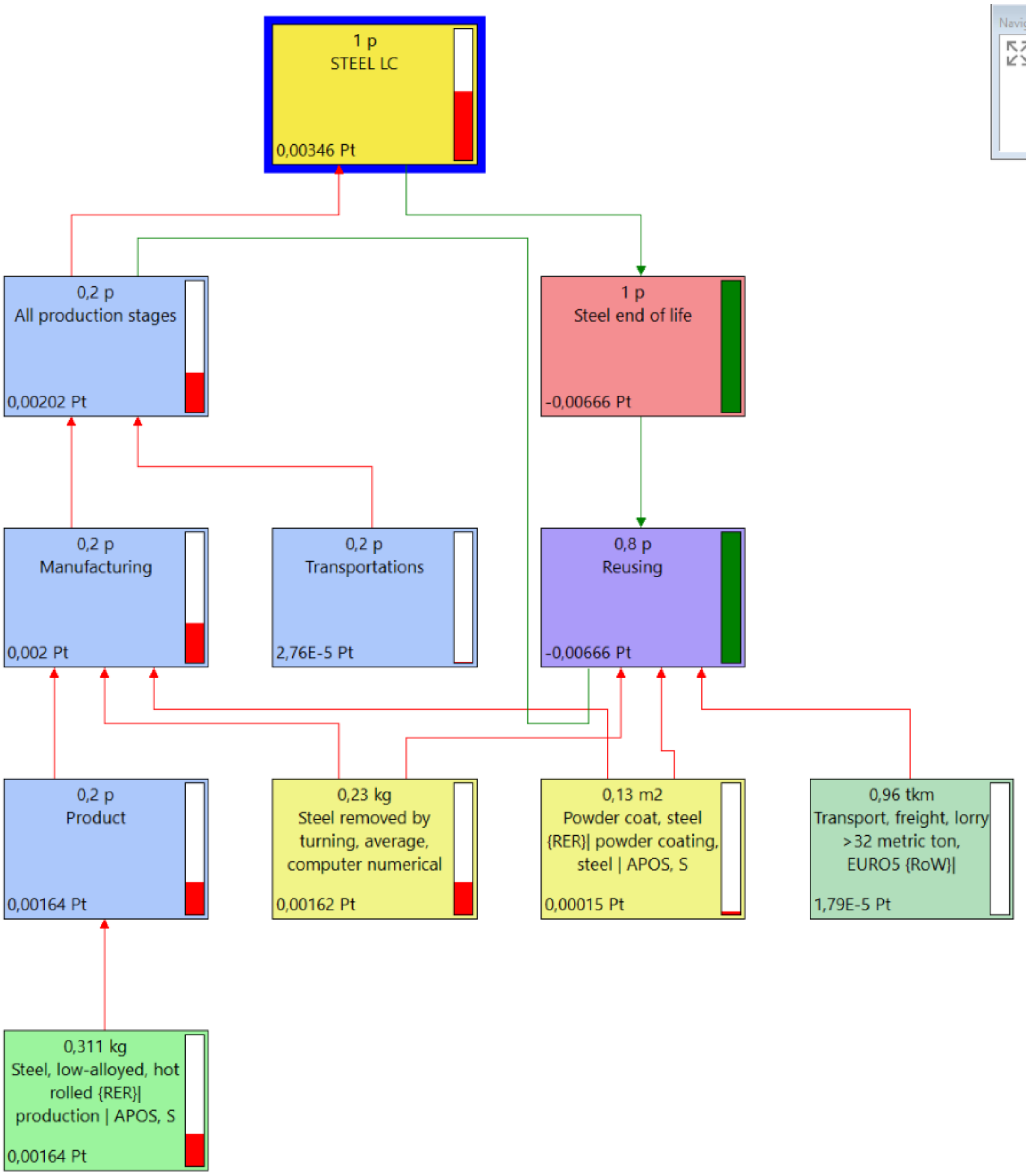

Figure 35 The environmental impact tree of the steel version as an example.