Evaluation of alternative, sustainable polymer materials in regard to mechanical properties and sustainability

Hanna Axelsson, Joaquin Rudervall

MASTER'S THESIS

Faculty of Engineering LTH at Lund University
June 16, 2021

Abstract

We live in a world where products are consumed at an ever increasing rate, and where responsibility for the waste created is seldom taken. Plastics are in many ways wondrous materials, but they put a big strain on the environment, both in production and as waste. Alternatives to the conventional, virgin fossil-based plastics have been available and emerging for some time now, for example seen in the recycling of PET bottles. The industry has been hesitant to implement them in engineering applications though, fearing they might not be up to standard. In this project, biobased and recycled plastics, both normal and fiber-reinforced, have been compared to the currently used plastics in a small IT product. The plastics have been compared through mechanical compression tests and standardized impact tests, thermal aging and exposure to detrimental environments. The study was also complemented with a comparative Life-cycle assessment considering both energy consumption and carbon footprint. The result has been that the recycled plastics not only out-performed the biobased and conventional plastics in the tests, but also had the lowest environmental impact of the three categories. The biobased plastic performed worse than the other in the tests, but was still above the normal requirements for what was acceptable in the products, and a close second in environmental impact.

Sammanfattning

Vi lever i en värld där produkter konsumeras i en allt snabbare takt och där det sällan tas ansvar för det skapade avfallet. Plast är på många sätt ett otroligt material men det sätter en stor belastning på miljön både genom produktion och som avfall. Alternativ till konventionell, helt fossilbaserad plast har funnits och utvecklats under en tid nu, till exempel genom återvinning av PET-flaskor. Industrin har dock varit tveksam till att implementera dem i tekniska applikationer och uttryckt misstro till deras prestanda. I detta projekt har biobaserad och återvunnen plast, både normal och fiberförstärkt, jämförts med de plasterna som i nuläget används i en mindre IT-produkt. Plasterna har jämförts genom mekaniska kompressionstester och standardiserade slagprover, värmeåldring och genom exponering för andra skadliga miljöer. Studien kompletterades också med en jämförande livscykelanalys som tar både energiförbrukning och koldioxidavtryck i beaktande. Resultatet har visat att återvunnen plast inte bara överträffade den biobaserade och konventionella plasten i testerna utan också hade den lägsta miljöpåverkan av de tre plastkategorierna. Den biobaserade plasten presterade sämre än de andra i testerna, men presterade fortfarande inom kraven som ställs på produkten och höll en stark andraplats inom låg miljöpåverkan.

Acknowledgements

This Master's Thesis project has been carried out during the spring of 2021, from January to June, and in collaboration with a company making small IT-products in Lund. The project was done with the goal of improving the environmental impact of the company in the scope of serving as a Master's Thesis project for two engineering students.

The project would not have been successful if not for our stupendous supervisors, Malte Lennerstedt and Azra Selimovic, who gave their support and guidance and always highlighted the importance of having fun in what we were doing. At the company, many people have helped us and lent their time and interest in order to make the best of the project. We would like to thank Jonas Jönsson for the enthusiasm and appreciation shown regarding tests, and the sustainability group for the discussions and counsel regarding the Life-cycle assessment, Magnus Klügel was a great resource for anything concerning plastics, and always responded quickly and comprehensively. As stated, many others took part of this, and we would like to thank you all, you know who you are. From the university we would like to thank Luke Hankin and his team at Lund Nanolab, who were very supportive and helpful in supplying necessary equipment and education at their lab.

- Hanna and Joaquin

Division of labour

This Thesis took 6 months to complete and a significant effort has been put into it by both of us. Most of the work has been done continuously by the two of us working together, but separate tasks, such as writing certain parts of the report or searching for specific information, has been done individually. In general, Hanna has taken a slightly bigger responsibility over the environmental part of the project while Joaquin has been focused more on the material and mechanical parts. We have shared all knowledge with each other and when writing the report, both of us have been involved in writing all parts.

Contents

1 Introduction 10
1.1 Problem definition 10
1.2 Aim of the project 10

2 Background - Plastics 11
2.1 Overview 11
2.2 Selected plastics 12
  2.2.1 Acrylonitrile Butadiene Styrene 13
  2.2.2 Polyamide 13
  2.2.3 Polybutylene terephthalate 13
  2.2.4 Polycarbonate 14
  2.2.5 Polyethylene terephthalate 14
2.3 Plastic blends 14
2.4 Reinforced plastics 15
2.5 Manufacturing - Injection molding 15
2.6 Sustainability and plastics 16
  2.6.1 Recyclability of different plastic materials 17

3 Background - Material Properties 18
3.1 Fracture mechanics 18
  3.1.1 Mechanisms of yielding in plastics 19
  3.1.2 Yielding and fracture of Fiber-reinforced plastics 20
  3.1.3 Creep rupture 20
  3.1.4 Environmental stress cracking 20
3.2 Impact strength 21
3.3 Degradation 22
  3.3.1 Thermal degradation 22
  3.3.2 Effect of fluids 23
3.4 Accelerated aging 23
3.5 Characterisation methods 24
  3.5.1 Scanning electron microscopy 24

4 Background - Environmental assessment 24
4.1 Goal and Scope Definition 25
4.2 Inventory Analysis 26
4.3 Impact Assessment 27
4.4 Interpretation 28

5 Methodology 29
5.1 Materials and parts 29
  5.1.1 Assembly of unit 30
5.2 IK Rating 31
5.3 Evaluation of properties 31
  5.3.1 Compression tests 31
  5.3.2 Impact test 32

5.3.3 Organic Oil test 33
5.3.4 Thermal Aging Test 34
5.3.5 Temperature Cycling Test 35
5.3.6 3D-scanning 36
5.3.7 SEM 36
5.4 LCA 37
5.4.1 Goal and Scope Definition 37
5.4.2 Inventory Analysis 39
5.4.3 Calculations 40
5.4.4 Impact Assessment 41
5.4.5 Interpretation 41

6 Results **42**
6.1 Material test results 42
6.1.1 Compression tests 42
6.1.2 Impact tests 45
6.1.3 Thermal aging 49
6.1.4 Organic Oil test 50
6.1.5 3D scanning 53
6.1.6 Fracture surfaces in SEM 55
6.2 Production issues 56
6.3 LCA: Inventory analysis 57
6.3.1 Transport 57
6.3.2 Plastic pellet production 58
6.3.3 Manufacturing of parts 58
6.3.4 EOL 58
6.4 LCA: Impact Assessment 59

7 Discussion **62**
7.1 Material properties 62
7.1.1 Mechanical stability 62
7.1.2 Aging & degradation 64
7.1.3 Sources of error 65
7.2 LCA: Interpretation 66
7.2.1 Sources of error 68

8 Conclusion **69**
8.1 Outlook 69

Appendices **76**

A EduPack data **76**

B Transport **81**

C Results **84**

D Lund Nanolab **98**

Definitions

Additives are in the context of polymer science added to polymers in order to in some way alter properties, either to plasticize, make flame retardant, color with pigments, or stabilize the polymer. A polymer with additives is considered a plastic.

Amorphous polymers are polymers where there is no long-range order, i.e. crystallinity, but the chains instead are perceived to be randomly intertwined.

Biobased polymers are polymers made in part or completely out of biological feedstock, as opposed by fossilbased feedstock. Not necessarily biodegradable.

Biodegradable polymers can through biological processes decompose into water, CO_2, biomass and inorganic matter. Often specific facilities are needed to maintain the controlled environment required for this to happen.

A CO_2-equivalent is used to, in terms of climate change due to greenhouse gases, express how many kgs of CO_2 are equivalent to the amount of greenhouse gases (GHGs) a process generates.

Conventional polymers are in the scope of this project defined as conventionally used fossil-based polymers.

Granta EduPack is a set of teaching resources for materials science which include a comprehensive materials database and tools for evaluating sustainability.

GaBi is a software for performing extensive Life-cycle analyses, commonly used in the industry.

Glass transition temperature (T_g) is the temperature at which a polymer starts to change from a hard solid to a viscous or rubbery material. It is an important parameter that characterises a given polymer.

A Part is in this report classified as a component of the studied product.

Plastic is a material made from one or several types of polymers mixed with additives to obtain desired properties.

A Polymer is a long chain of repeating, organic molecules.

The product refers to the small IT-product that is being examined in this study.

Recycled polymers are polymers made in part or completely out of recycled polymer material.

A Sample is in this report classified as either a single part, a subassembly of parts, or a unit, which has undergone a test.

Semi-crystalline polymers are polymers with a certain extent of crystallinity, having crystalline areas with amorphous areas in between. Often results in stiffer, harder plastics.

SimaPro is a software for performing extensive Life-cycle analyses, commonly used in the industry.

A Subassembly is an assembled set of at least two parts, but not the complete product.

A Unit refers to a complete product.

Acronyms

ABS Acrylonitrile-Butadiene-Styrene.

CLC Configuration and logistic center.

EMS Electronics Manufacturing Services.

EOL End-of-Life.

ESC Environmental Stress Cracking.

FRCP Fibre-Reinforced Composite Plastic.

fU functional unit.

GHG Greenhouse gas.

GWP Global warming potential.

LCA Life-cycle assessment.

PA Polyamide.

PBT Polybutylene terephtalate.

PC Polycarbonate.

PED Primary energy demand.

PET Polyethylene terephtalate.

SEM Scanning electron microscope.

1 Introduction

1.1 Problem definition

In today's society, plastic plays a vital role as a material, not only in small electronic products, but also in areas of construction, consumer goods, the automotive industry, packaging and textiles, just to mention a few [1]. It is a material which can be cheap yet hold remarkable qualities, among others great durability. As we have increased our dependence on plastics, the challenges of waste treatment and pollution have increased as well.

Since the 1950's, estimations put the total global production of plastics around 8.3 billion metric tonnes. About 9% of this is estimated to have been recycled, while 12% has been incinerated. The rest has ended up in nature or in a landfill [2]. The majority of the plastic produced is derived from fossil fuels, and the production of plastics stands for as much as 6% of the global oil consumption in modern times [3]. Each year, the production of plastic together with their incineration emits 400 million tonnes of CO_2 into the atmosphere, which contributes to the global warming [4].

This has created a global driving force pushing industry towards taking environmental responsibility and making products and services more sustainable. The company this project was made in cooperation with is no exception, and has a continuous plan to work with sustainability in all its business processes as well as throughout the entire value chain. This Master thesis project is part of their effort to decrease their environmental impact and reach their sustainability goals.

The substantial concern for plastic and its environmental impact has lead to a rise in the number of recycled and biobased plastics available in the recent decade, as alternatives to fossil-based, virgin plastics. But due to many of the plastics being relatively new there is a deficiency in data regarding their properties and how they perform compared to conventional plastics. There appears to exist a general preconception that non-virgin plastics are inferior, which may originate from the fact that recycled plastics can be of poor quality [5]. Thus engineers and designers are in need of validation of whether or not biobased and recycled plastics are good enough to be used in the same applications as virgin plastics. At the same time the actual environmental gain from using recycled or biobased plastics is in many cases unclear due to complex production chains and lack of understanding of the currently used materials' environmental impacts.

1.2 Aim of the project

This Master's thesis project was conducted at a company which produces small IT products with several plastic components. This thesis will, through experimental measurements and literature studies, allow to develop an understanding of how the properties of biobased as well as recycled plastic materials relate to the properties of virgin plastics, and answer why there may be a difference if any is found. It will also, using the methodology of a Life-cycle assessment (LCA) focused on primary energy demand and CO_2-equivalents, draw conclusions about the relative environmental gain of switching to alternative materials in relevant products.

The thesis aims to answer the following questions:

- Which of the relevant material properties are affected by using alternative materials, and by what magnitude are they affected?
- What could be the causes to the possible difference in properties between biobased/recycled and virgin plastic materials?
- How big environmental impact do the currently used materials have from an energy usage and CO_2-equivalent perspective, and how does the environmental impact of the alternative materials compare to it?
- What flaws could be present in the performed environmental analysis, and how could these flaws be minimized?

2 Background - Plastics

2.1 Overview

To begin to analyse plastic as a material one must start on the molecular level with the main component: the polymer. A polymer is a large molecule built from many smaller repeating units, monomers, covalently bonded together in a long chain, linear or branched, or a cross-linked structure. The number of monomers in each polymer can under certain conditions grow immense, which can result in extremely large molecules with very high molecular weight. In an amorphous polymer, the molecular chains of the material will be disordered, while in a semi-crystalline polymer, interloped with amorphous regions, there will be crystalline regions where the chains have a more long-range order. Polymers gradually transition from from solid to liquid state as temperature is raised and passes through a temperature called the glass transition temperature, T_g. It is first when the polymer is heated beyond T_g that it starts to soften and becomes rubberlike. The value of T_g can be found by examining the free volume of the polymer following a change in temperature, as seen in Figure 1. A completely amorphous polymer will follow the curve from A-D, while perfectly crystalline parts of a polymer would follow the lower curve from A-H. The crystalline parts will not experience a glass transition because of the absence of disordered chains in the material. However, in practice no perfectly crystalline polymers exist, and semi-crystalline polymers usually end up somewhere in between, following the curve from A-F [6].

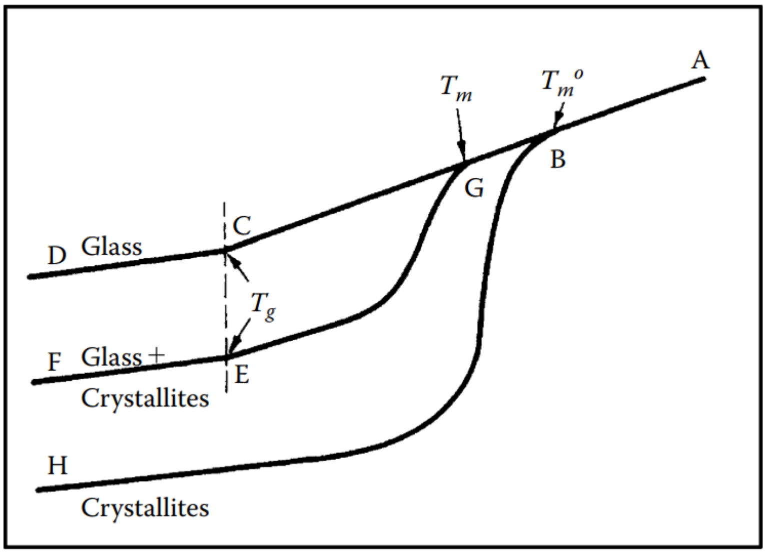


Figure 1: Schematic representation of the change of specific volume v of a polymer with temperature T for (i) a completely amorphous sample (A–C–D), (ii) a semi-crystalline sample (A–G–F), and (iii) a perfectly crystalline material (A–B–H). Source:[6]

Polymers can be synthesised using different methods, or be naturally formed. They can be derived from organic materials such as cellulose, natural gas and, of course crude oil. Today most of the polymers produced are derived from crude oil. To make polymers from crude oil it is necessary to process the oil first in an oil refinery, to separate the oil into fractions according to size and structure of the hydrocarbon chains. Two ways of synthesising polymers exist, either chain-growth polymerisation, sometimes referred to only as polymerisation, and step-growth polymerisation also named condensation polymerisation. The chain-growth polymerisation involves an active site where new molecules attaches and extends the chain while step-growth involves a random combination between molecules or polymers of random length [4].

A plastic is as a polymeric material that fulfills the main criterion that it can be formed into complex shapes at the application of heat or pressure. It can be made of one or several types of polymers and various additives. A useful subdivision of plastics is to divide them into *thermosets* and *thermoplastics*, where the thermosetting plastics become permanently hard after being heated above a certain temperature while a thermoplastic can be softened and reshaped multiple times by heating it above T_g [6].

2.2 Selected plastics

There exist a large number of plastics in the world and they all have their own set of properties useful for different applications. Here follows a short introduction to the plastics that will be included in this project.

2.2.1 Acrylonitrile Butadiene Styrene

ABS is a amorphous polymer made from the acrylonitrile, butadiene and styrene monomers in various proportions, as seen in Figure 2. It has a high rigidity and good impact resistance, good strength, and durable over time. The blending of ABS with other polymers is common and the most widely used combination is ABS/PC blends [7].

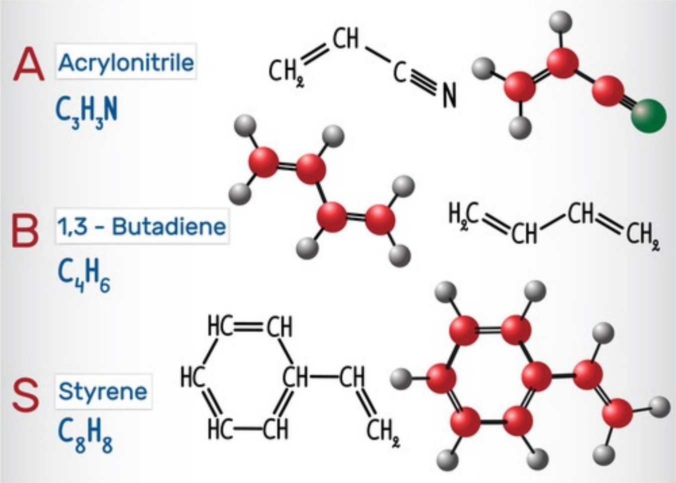


Figure 2: The three monomers that make up ABS. Source: [7]

2.2.2 Polyamide

PA is a polymer with repeating amide linkages. It is technically more a family of polymers since there are many different variations. The numbers following "PA" is the number of carbons in the diamine and the dicarboxylic acid respectively, ex PA410 means it has 4 carbons in the diamine chain and 10 in the acid. Some types of PA can be reinforced with glass fibers to display a stiffness comparable to metals and can therefore act as a replacement in some products [8]. Long chains in the polymer lead to properties such as low moisture absorption and high cristallinity, making it a semi-crystalline polymer [9].

2.2.3 Polybutylene terephthalate

PBT is a member of the polyester family of polymers. The polymer is produced by combination of terephthalic acid and 1,4–butanediol with the chemical formula, $(C_{12}H_{12}O_4)_n$, see Figure 3. It is semi-crystalline, and it is common to reinforce PBT with glass fibers to increase the tensile and compressive strength [10].

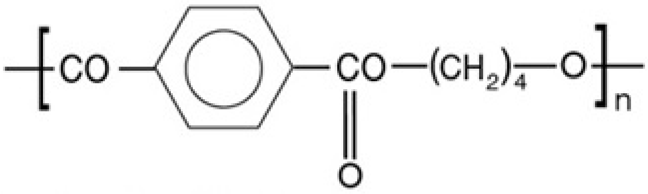


Figure 3: The molecular structure of PBT. Source: [10]

2.2.4 Polycarbonate

PC polymers create an amorphous thermoplastic that is strong, tough, lightweight, and usable in a wide range of temperatures. The molecular structure is shown in Figure 4. It is widely used in blends with other polymers due to its excellent compatibility [11]. It is originally transparent, a common attribute in amorphous polymers, and has the highest impact strength of all transparent plastics. The plastic is susceptible to environmental stress cracking (ESC) and abrasion as well as attacks by acid and alkali solvents. The PC/ABS blend forms an amorphous plastic, less sensitive to ESC, with good processability and flow characteristics combined with good mechanical properties [12].

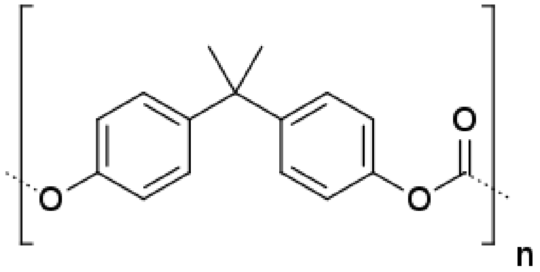


Figure 4: The molecular structure of PC. Source: [11]

2.2.5 Polyethylene terephthalate

PET is a polyester and is one of the more, if not the most, recycled thermoplastic in the world. In general some of the advantages of PET compared to PBT are the high stiffness, the broader range of use temperature, the electrical insulation and protective properties against gas and moisture. It can be either amorphous or semi-crystalline. Blending PET with other polymers is very common and due to its recyclability it is often reused to generate plastics that are recycled to various extents [13]. PBT/PET blends have mainly been developed to improve processability, impact strength and dimensional stability.

2.3 Plastic blends

As mentioned above, sometimes polymers are mixed and blended together in order to lower the cost, improve the material properties, or both. The blends can be either miscible, where they have a single phase down to the molecular level, or immiscible, where they contain more than one phase in the microstructure. In some cases, like for PBT/PET, they can be miscible in the amorphous phase but immiscible in the crystalline phase [14]. Most polymers are immiscible, but by adding so-called compatibilizers, the energy at the interface between the polymers can be reduced in the melt phase to allow a finer dispersion, as well as creating a sufficient adhesion at the solid state, and so an otherwise unstable blend can be stabilized. In particular, a blend of PC/ABS will benefit from the processability of ABS and from the very good mechanical properties, UV resistance, heat deflection temperature and dimensional stability of PC. A blend of PBT/PET will have good processability, impact resistance, and surface properties [12].

2.4 Reinforced plastics

Fiber-reinforced composite plastics (FRCPs) are plastic composites infused with fibers, often with very high aspect ratio, and are used when the properties of the bulk plastic is not enough and a strong, light-weight alternative to conventional materials is required. The most commonly used fibers are glass fibers and carbon fibers. Carbon fibers usually have the best structural properties but are more expensive to manufacture, and the low price and still impressive properties given by glass fibers have caused the vast majority of all FRPCs to be glassfiber-based [15]. Reinforcing recycled plastics to be FRPCs can minimize the degrading effect of recycling on the mechanical properties of the material, and thus prevent the need for down-grading the plastics to less structurally demanding applications [16].

2.5 Manufacturing - Injection molding

Injection molding is a technique for batch manufacturing large quantities of identical objects. For the case of plastic, a giant screw with surrounding heaters blends and melts the plastic pellets fed into it, and forces the melt under high pressure with a hydraulic thrust into a mold, which is sometimes heated. The plastic melt will take the shape given by the mold, cool for a short time, and then be punched out as the mold opens up. The mold then closes and the process starts again [17]. Some defects may manifest during production, such as weld lines, which form where two or more plastic fronts meet in the mold, resulting in a aesthetic defect, and possibly a weak spot. Weld lines can be made less prominent by changing the parameters dictating various aspects of the injection molding process. Changes can either be made to the machine, as for example using a higher temperature melting the plastic before injection, allowing the molten plastic to better connect when the fronts meet, or by increasing the injection speed, so the plastic does not have time to solidify as much. Changes could also be made to the mold, increasing the temperature of it to allow for a better flow, or relocating the injection gate of the plastic into the mold, so it has better conditions to flow in an evenly distributed way. Another defect is what is known as "blush", and characterized by a discoloration of a cloudy nature, often spreading out from close to the gate. This can be caused by for example too high injection velocity, and/or a low melt temperature, and will in either case cause both mechanical and aesthetic problems [18]. In addition to these parameters many others can and should be tweaked and optimized in order to acquire an adequate injection molded part, since they otherwise could affect the final material properties in a detrimental way. This is particularly important when producing parts in novel plastics [19].

2.6 Sustainability and plastics

There are some ways to solve or at least work with the challenges introduced by the massive use of plastics. Reuse is one of the simplest ways to decrease the harmful impact, but it is impossible in many cases when the product reaches the end of its lifetime. In that case recycling becomes an interesting method of waste treatment.

Recycling of plastics can add value to the discarded material, but unfortunately that value is currently still very low. Furthermore, the recycling process is burdened with the fact that it almost always causes a deterioration of properties [20]. However, there are also numerous ways to improve the properties of recycled plastics and for many applications these properties might very well still be enough.

It is common to divide recycling of plastics into different stages, where the first is *primary mechanical recycling*, see Figure 5. It is mostly employed by the manufacturer with the waste generated from the industrial process of manufacturing. It is characterized by the recyclates being uncontaminated and suffering minimal loss of properties. The next stage is *secondary mechanical recycling*, which is used when the exact grade and content of the plastic is unknown and a separation step is therefore necessary. This kind of recycling causes the molecular weight of the polymer to drop which might affect the mechanical properties. Contamination with other plastics is another problem that may affect the properties in a negative way, since most polymers are not compatible with each other. *Tertiary recycling* is when a chemical process is used to convert the polymer chains into smaller molecules that can be reused as feedstock. The biggest issue with this is the increased cost of processing to acquire the monomers, ramping up the price compared to virgin monomers, which makes implementation of these techniques impossible without subsidies. Incineration is sometimes referred to as the *quaternary recycling* technique and it is one of the most widespread methods of dealing with plastic waste [20].

Also worth mentioning is biological degradation as a way to return the material to the biological cycle. Certain polymers may be degraded by microorganisms into monomers or other small molecules. However, this method is usually limited to naturally existing polymers or ones designed to imitate them.

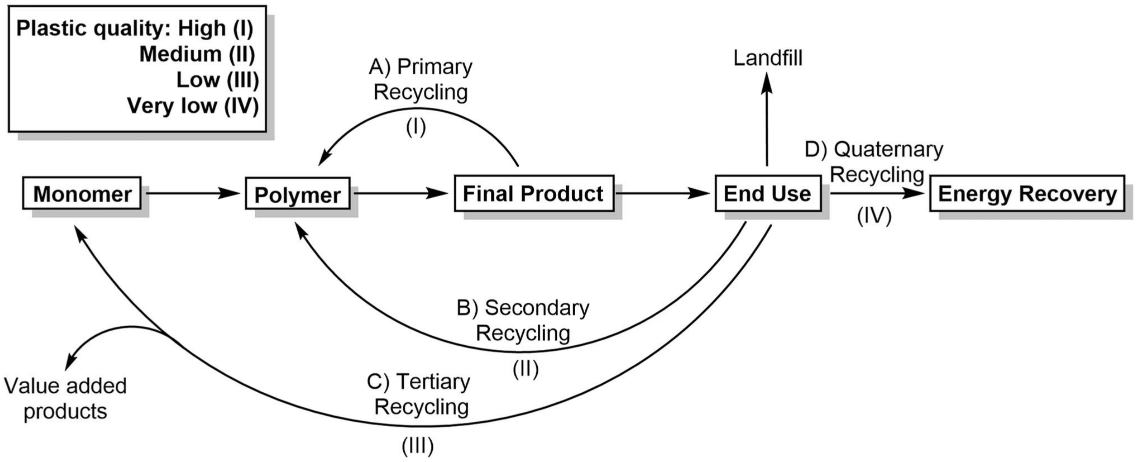


Figure 5: The four possible waste treatment options for plastics and the associated paths. Source:[21]

2.6.1 Recyclability of different plastic materials

Not all plastic materials can be recycled equally. On one hand thermosets, which are permanently crosslinked and thus cannot be melted, are only feasible to recycle as filler material in e.g. concrete after being chopped up. Thermoplastics on the other hand can be melted and reshaped, but there is often a major deterioration in properties if two different plastics are mixed in an uncontrolled manner, partly due to immiscibility of the polymers. In addition, some plastics are more practical to recycle than others due to various reasons; for example PET only accounts for ~14% of the plastic waste, but is the most recycled plastic since the products it is often used in, transparent plastic bottles, are easily identified and sorted. If a plastic is present in sufficiently large volumes it may also be feasible to recycle on its own. The six most prevalent consumer plastics each have a marking, stating a number (1-6) and abbreviation of its name. All additional plastics or blends go into a seventh group and marking. These markings, along with scanning IR-lasers, are used in recycling facilities to sort the plastics, and any plastic belonging to group 7 is most likely to either get burned up or placed in a landfill [22].

Nowadays, recycling is mostly limited to these six plastics, and even then, if they have additives such as flame retardants, they may not be suitable for recycling. Blends may now not be recycled in large scale, but show promise to be recyclable in a not-too-far-away future, which will be positive for both environmental as well as economical reasons [23].

FRPCs being constituted of various materials with different characteristics are problematic to recycle in an efficient manner. They are generally burned up to recover energy, or placed on landfills, but there are ways to recycle them, even if they are mostly restricted to academic research at the moment. It is possible to mechanically recycle FRPCs, but each processing step through which this is done will significantly decrease the fiber's length by interaction with other fibers and equipment, which greatly affects the material's properties. It can somewhat be remedied by addition of virgin material, but still remains a problem [22]. A different perspective lies in trying to extract and recycle only the fibers, which particularly for the case of carbon fibers has a strong economical driving point. There are various methods for extracting fibers, including variations of pyrolysis of the plastic matrix, or chemical recycling using solvolysis, dissolution or hydrolysis, each with their advantages and drawbacks. Pyrolysis for fiber extraction is a mature process where the material is exposed to an oxygen-free environment at 400-700°C, and where the matrix decomposes into oil and gas which in turn can act as feedstock for the continuing process. The fibers tend to suffer detrimental effects on their mechanical strength though, in part due to char formation on their surfaces, but there are chemical treatments which reduce the effects. An alternative method is microwave pyrolysis, which has a low energy waste and produces residual fibers with properties very close to virgin ones.

Chemical recycling, where the FRPC matrix is disintegrated by solvents or water and alcohol at supercritical conditions, shows promising results in terms of preserving fibers' mechanical properties, but may have environmental problems if harmful chemicals are used, and may in certain cases not be economically viable [24][25].

3 Background - Material Properties

The study of the properties of materials is essential for engineers. Determining the strength of a material and what deformations that occur can tell you what kind of loads can be supported. Testing the impact strength and performing a compressive test are two ways of analysing the mechanical properties of a material. But many things can affect the performance of a material, especially environmental factors such as temperature, humidity and solar radiation, but also time. The mechanical properties must then be evaluated when these factors are taken into consideration [26][27].

3.1 Fracture mechanics

Fracture mechanics explore and explain the mechanisms and details surrounding crack initiation and propagation in various materials. Some mechanisms might seem very similar for two materials on the macroscopic level, but in reality the initiation can be quite different at the microscopic level. For example, a crack in a ceramic material, which is crystalline by nature, is initiated where some kind of flaw or imperfections is present, and the resulting higher stress concentration eventually causes the flaw to grow. This can create a crack which in turn might propagate through the brittle material, breaking bonds in the crystal structure along the way. Plastics on the other hand are constituted by long molecular chains, and two kinds of bonds are involved in the fracture of plastics: both covalent bonds along the length of the chain, and van der Waals forces from interaction between the molecular chains. When these chains are allowed to detangle and slide alongside one another, breaking the van der Waals bonds, the plastic can yield. If they are not allowed time to separate, i.e. due to the strain rate being too high, the covalent bonds are instead broken, but often this happens after some yielding has occurred, and created for example so-called crazes. Breaking of mostly van der Waals bonds is an example of when a plastic might show a ductile behaviour, similar in how metals deform by crystal planes sliding parallel to each other, while when the breaking is predominantly of covalent chains a brittle reaction might occur.

Factors affecting how plastics react to stresses include temperature, strain rate, and molecular structure. Lower temperatures tend to promote more brittle than ductile behaviour, as do higher strain rates, since the molecular chains do not have the same possibility to adapt to a deformation. Highly cross-linked plastics also show a more brittle nature, since instead of van der Waals bonds breaking and allowing the chains to detangle, actual covalent bond are required to be broken in order to deform [28].

3.1.1 Mechanisms of yielding in plastics

Plastics tend to yield when exposed to sufficient strain, but unlike metals, which yield by slipping crystal planes, plastics yield either by *shear banding* or *crazing*. The principle of shear banding is similar to that of metals, in that molecular structures align to be more parallel, almost flowing. It is often characterized by a change in shape but not in volume, and the presence of regions of shear deformation called shear bands, developed at a 45° to the direction of the stretch. It is most common in ductile plastics under tensile stress [17]. Crazing is the phenomenon of microvoids being created as a consequence of tensile load, where molecular chains align in bundles creating microfibrils of 0.6-30 nm in diameter, see Figure 6. In aligning, the chains take up a lesser volume, and thus the voids are created between the fibrils. The craze zone, which often is perpendicular to the primary normal stress and is some nm to µm wide, appears as whitened or in the case of transparent plastics, foggy, due to the craze having a lower refractive index [28].

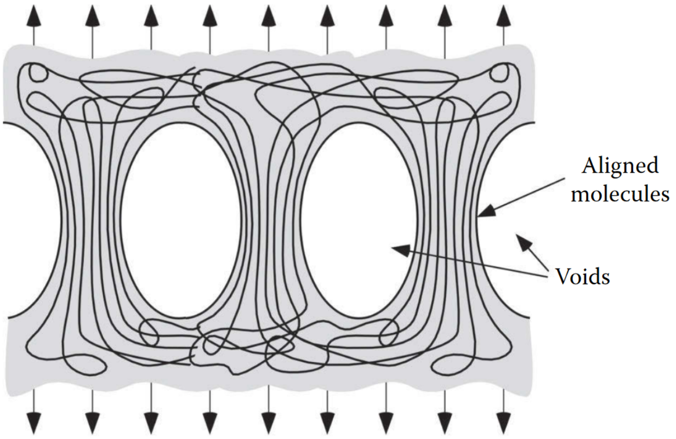


Figure 6: Illustration of the microfibrils created by tensile stress, causing crazing in the plastics. Source: [28]

The fibrils can carry a higher stress than the amorphous surrounding material, and will incorporate more chains if needed in order to get longer. The start of an actual crack will begin once a fibril breaks. If the load from the broken fibril, now distributed on the surrounding fibrils, is high enough for them to break, the voids will start to coalesce and a crack is created and will start to propagate. Most brittle fractures in plastics are caused by crazes initiating cracks. It should be noted that crazing and shear banding can both be present when a material is under a load, and temperature and strain rate can affect which of them is dominant [28][17].

3.1.2 Yielding and fracture of Fiber-reinforced plastics

In a FRCP, the combination of the more ductile plastic matrix and more rigid fibers can achieve a material which compared to metals, exhibit better ratios of both stiffness (Young's modulus) vs weight and strength vs weight. Since the material is not homogenous and the fibers can have a common orientation, FRPCs may have some problems with orthotropic behaviour, i.e. that they may show different characteristics depending on the direction of a stress. It may therefore show different failure mechanisms than a homogenous plastic.

When a crack is starting to propagate through the plastic matrix, it can be deviated by the hard fibers, forcing it to change direction and consume energy, and thus slowing it down. The increased toughness of the material can partially be explained by fibers bridging cracks perpendicular to them in the matrix, holding the two surfaces together. The crack may spread along the fiber and forcing it to detach from the matrix, or if enough stress is applied and the fiber-matrix interface is not strong enough, fibers may eventually "pull out" and detach from the matrix without the cracks extending along the interface first.

Delamination occurs from out-of-plane stresses, and is as the name implies when laminates of fibers and matrix detach from one another.

Generally for this types of composites, a failure is not due to a singular crack spreading throughout the material, but instead a multitude of small cracks eventually coalescing, causing a failure [28].

3.1.3 Creep rupture

When a visco-elastic material such as plastic is subjected to a load over time, even if the load might be low, it may show creep behaviour. This is characterized by deformation of and crack initiation in the material due to polymer chains having time to detangle and to a certain extent flow, which in turn can cause cracks to form and propagate, causing a creep rupture.

3.1.4 Environmental stress cracking

Environmental stress cracking (ESC) occurs when some external factor causes cracking or crazing in plastics at an applied stress often significantly lower than the mechanical strength of the plastic. It can be observed when plastics come into contact with certain solvents, such as organic oils, but also detergents and surfactants, inks, and adhesives. For the case of a solvent, it penetrates the plastic and by various mechanisms induces internal stresses and locally solves the plastic, plasticizing it and lowering its yield strength. With applied stress, crazes are formed, which develop into cracks and finally lead to failure. Different plastics are often susceptible to different agents, depending on for example solubility parameters of the plastic and liquid agents [29].

ESC is generally more prominent in amorphous plastics, due to them having a larger free volume than semi-crystalline one, but the amorphous parts of semi-crystalline plastics can still be affected. Since ESC stands for a significant part of unexpected plastic part failures, there have been several methods for counteracting it [30]. When performing a material selection it is important to choose the correct plastic considering the environment of both manufacturing and use, taking into account the various possible ESC-agents it can come into contact with. One way to improve the ESC resistance (ESCR) is using a plastic blend, either introducing a more crystalline polymer, or blending in another amorphous polymer with a higher ESCR. An example of this is the addition of ABS to PC in order to gain higher resistance to some environments. Another method is by reinforcement with fibers, which will effectively bridge the cracks produced by ESC and prevent them from propagating [29].

3.2 Impact strength

The impact strength of a material is the amount of energy that said material can withstand if the force is applied instantaneously. Plastic materials are more prone to failure under such impacts as opposed to slowly-applied loads. Especially semi-crystalline thermoplastics, such as PBT, are particularly sensitive to impacts due to their brittle tendencies. This in combination with the fact that testing is both fast and easy, has led to impact strength data being widely used technical data sheets and material specifications [26]. Two commonly used impact tests are Charpy impact test and Izod test.

Both tests makes use of a pendulum arm with an attached hammer that pierces the specimen, which is in a customised shape of a bar with a small notch in the middle. The hammer is set to a position that corresponds to an energy, and when it is released, will hit and break the specimen and then continue its trajectory. The energy needed to fracture the specimen will be equal to the lost potential energy seen as the pendulum reaches its highest point, and is defined as the impact strength. The main difference between the tests is the orientation of the specimen, in the Charpy test the bar is set horizontally while the Izod test examines the specimen in a vertical position. Furthermore, the size of the specimen, the notch dimensions and facing direction of the notch are other differences [31].

The impact strength of each material is important in many cases. But when talking about a specific product it becomes vital to be able to describe what impact the product can withstand without the product breaking, see section 5.3.2. The whole product's impact strength is not so easily deducted from the strength of the individual materials.

3.3 Degradation

Degradation effects can be classified into two types: *chemical* and *physical* degradation. Chemical degradation is always irreversible and is a result of a chemical reaction of some sort. It can be induced by thermal energy, exposure to oxygen or aggressive liquids or electromagnetic radiation, but in most cases it is a combination of various mechanisms. The degradation is polymer specific and the effects are difficult to generalise. Physical degradation refers to mechanisms that alters the physical properties of the plastic without altering the chemical composition of the macromolecules. This includes absorption of fluids, fractures, and physical aging and are in many cases, theoretically reversible [32]. Aging is the mechanism for which a material's properties change, with time being one of the major influencing factors.

3.3.1 Thermal degradation

Degradation processes, both chemical and physical, that occur due to exposure to elevated temperatures are bundled as thermal degradation, and around 4% of failures in plastic materials are caused by this [33]. The increased temperature will accelerate most processes of degradation such as oxidation, mechanical creep and chemical attacks, though oxidation is generally considered to be the most serious problem. All plastics contain a certain degree of free radicals, atoms with unpaired electrons that are extremely reactive, as a residue from the polymerisation or due to cleavage of bonds. These radicals can react with oxygen to produce peroxides:

$$\mathrm{P}\bullet + \mathrm{O}_2 = \mathrm{POO}\bullet \tag{1}$$

The peroxide radical will react with hydrogen on adjacent polymer molecules which will contribute to breakdown of the polymer chains with a lower molecular weight as a result. The propagation of the radical is slow which leads to an induction time during which the degradation and its effect on the mechanical properties is minimal. Elevated temperatures can induce the formation of radicals and will also shorten the otherwise long induction time [33]. Usually the oxidation leads to increased brittleness and a deterioration of strength. Polymers with unsaturated double bonds or highly branched structures are more prone to react with oxygen in this way [17].

The physical and chemical structure of the polymer as well as additives and presence of stress will affect the thermal aging. Anti-oxidants can counteract the radicals and suppress the reaction while the presence of metal catalyst, e.g. from a pigment, might promote degradation. Stress might be induced by a mismatch in thermal expansion coefficient between different polymers in a blend or between matrix and fiber in a FRCP. Thermal cycling might therefore cause mechanical degradation [34].

The relationship between degradation, time and temperature can be approximated by the Arrhenius relationship:

$$\text{Rate of reaction} = Ae^{-E/RT} \tag{2}$$

where A is a constant, E is the activation energy of the reaction, R is the universal gas constant (8.3 J/(mol*K)) and T is the absolute temperature. This equation, if E is assumed to be independent of temperature, can be employed to find a selection of test conditions, time and temperature, that correspond to a certain degree of degradation. The integration of the reaction rate equation reveals a linear relationship between the logarithm of the time and the reciprocal of the absolute temperature:

$$ln(\text{time}) = \frac{A}{T} + E \tag{3}$$

This is the underlying theory behind thermal aging tests where for example a 5 year exposure in room temperature can be exchanged for 3000 h in 65°C. The activation energy typically ranges from 50 to 150 kJ/mol and is assumed to be 80 kJ/mol for all plastics in this study. For a common activation energy of 100 kJ/mol, a 10°C increase in temperature corresponds to a rise in degradation rate by a factor between 2 and 3 [33].

3.3.2 Effect of fluids

Chemical attacks are another common cause of degradation in plastics, and include processes where a polymer undergoes irreversible modification due to interaction with a fluid. 7% of failures in plastics are inflicted by chemical attacks [33]. The most common mode of irreversible failure is hydrolysis, where the water molecule adds itself to the polymer by breaking other bonds. Polyesters, for example PET and PBT, and polyamides such as PA are particularly susceptible due to their ester and amide groups. The hydrolysis reaction will lead to a reduction of molecular weight, which in turn leads to loss of toughness. Stress is known to enhance the fluid uptake and accelerate the hydrolysis process [34].

Another aspect of water and fluids is the fact that the plastic or composite could absorb the fluid which it is in contact with. This might lead to swelling, reduction of T_g and change of material properties. This might also increase the hydrolysing effect of water since the water molecules will reach further into the material. The chemical structure of a polymer determine the fluid absorption kinetics, and it differs widely between various combinations of plastic blends and fluids. The absorption can greatly affect how the plastic reacts to stress and how susceptible it will be to other degradation mechanisms [34].

3.4 Accelerated aging

The materials examined in this thesis are expected to perform for an extended period of time without failure. It has become increasingly important to be able to examine and predict long-term performance of plastic materials, in a shorter period of time. By exposing the materials to various aggressive environments and degradation agents, the change in properties of the plastics which might otherwise take longer time to become apparent are accelerated. In some circumstances, only a few hours of exposure may lead to failure or seriously compromise structural integrity

[34]. The aging can be induced by a number of different factors such as humidity, solvents and oil, ultraviolet radiation, and thermal exposure. Certain plastics will be more susceptible to some agents than others and combinations of factors may lead to complex synergistic degradation.

3.5 Characterisation methods

3.5.1 Scanning electron microscopy

A scanning electron microscope (SEM) makes use of a beam of high energy electrons to examine samples and create an image of the sample. The beam is moved across the sample and the electron's interactions with the sample will generate signals such as electromagnetic radiation or electrons, which will reveal information about the sample. In general, SEM is a surface sensitive tool because the electrons will mainly interact with the uppermost layers of the sample. It can give information regarding shape and size of surface features, orientation of grains and chemical composition etc. The technique is therefore a useful tool for topographical characterisation of materials. The biggest advantage of SEM compared to optical microscopes are the high spatial resolution, which in the best of cases are a few nm. Non-conductive materials, such as the majority of plastics, will charge up over time in a SEM, resulting in bright and difficult to see images. This can be avoided by coating them with thin layers of metal, which can conduct the electrons [35].

4 Background - Environmental assessment

A life-cycle assessment (LCA) is a way to analyse how a product system, from start to end-of-life (cradle-to-grave) or from start to factory gate (cradle-to-gate) impacts the environment. It is defined by ISO standards ISO 14040 and ISO 14044 as follows [36][37]:

> *"LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences." [38]*

When considering the life cycle of a product and its environmental impact, there are various stages to take into account. In simple terms, these could be divided into the extraction of raw material, manufacturing of product (both intermediate products and end product), the use/reuse/maintenance phase, and the end-of-life, with transport between each of them. Each of these generate some output, whether as solid waste, gas emissions or other outputs.

The LCA is used to compile the relevant inputs (energy, raw materials) and outputs (environmental releases), and then evaluate the environmental impact each of these may have and interpret the results. The method can be valuable to present something seemingly complex and intangible in an understandable manner for decision makers.

An LCA is usually performed in 4 parts:

1. Goal and Scope Definition
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

It is possible when performing a comparative LCA to use a so called *Black box method*, where parts of the product systems which are very similar may be excluded since they will impact the system in the same way. This allows for LCAs to be performed even when not all data is available, as long as it is known that the products undergo the same procedures.

4.1 Goal and Scope Definition

The goal definition must provide answers to questions regarding the fundamental concepts of the study, such as:

- What is the objective of the study?
- Why in particular is an LCA study conducted?
- For whom will the study be conducted?
- Are comparative assertions intended in the study and in that case what kind?

Once these questions have been answered, the scope should be defined. The description of the product system allows for setting a boundary for which parts of the system to consider and which are negligible. So-called "cut-off criteria" can be used to remove parts with low contribution ($\leq$ 1% mass, energy and/or environmental relevance of the entire system) from the analysis, but care should be taken as to not omit something which in one category might be $\leq$ 1%, but in another has a greater contribution, since this skews the analysis.

The product system is part of a larger system referred to as the technosphere, defined as "everything under human control", which together with the ecosphere, or "the environment" constitutes the world we live in. The system boundary, which separates the product system from the ecosphere and the rest of the technosphere, has inputs entering from the surrounding systems and in turn releases outputs into them. The inputs include the raw material from which the products are made, the energy used during the product's lifetime (cradle-to-grave), and possible ancillary products. The outputs include solid waste, gaseous waste, waste water, secondary raw material and possible co-products [39].

The system also needs to, if possible, have geographical and temporal boundaries. The geographical boundaries relate the relevant processes in the product system to a specific geographical area which in turn influence the outputs. The temporal boundaries allow for analysis over longer time periods, in certain cases trying to take into account how processes may develop and change how the LCA may look.

Both these types of boundaries are difficult to implement in a complete and efficient manner due to, for the first case, lack of data on origins of commodity materials, and for the second, lack of certainty of the future.

In order to be able to compare products within a comparative LCA, a functional unit (fU) must be defined. It is often related to the functional nature of the products compared, and can for example in the case of a surveillance camera be defined as surveilled area in m^2, as this allows for comparison to other alternatives such as several smaller cameras or security guards patrolling. The choice of fU heavily affects the results of the study, as it quantifies the desired product function.

Different so-called impact categories are used when performing an LCA, to divide the outputs of the system depending on what environmental aspect they affect. An example is Global warming potential (GWP), which bundles together the various GHGs emitted from the product system into a CO_2-equivalent. These categories use impact indicators as a way to quantify the impact in that particular category. If a study chooses to only use one impact category it should not be called an LCA, since it omits crucial perspectives for getting an overview of the complete environmental impact of a product system. Performing a study of only GHG-emissions is not worthless though, and for very similar products it can be a way to get a notion of potential benefits from choosing one alternative over the other.

4.2 Inventory Analysis

The second phase of an LCA is the compilation and analysis of material and energy inputs and outputs for the product, the life-cycle inventory analysis (LCI). The product's life can be divided into unit processes that require analysis, where each process have inputs of raw or intermediary material, and energy and outputs such as emissions and waste heat, as illustrated in Figure 7. Several unit processes can be combined into bigger processing steps to be analysed. Processes outside the system boundaries as described in the scope will not be analysed. Further narrowing of the LCA can be done in this step when processes or outputs of low interest are found, for example by excluding co-products with small effect on the chosen impact categories.

The environmental impact from each process is determined in this phase, which requires in-depth data regarding materials, tools and manufacturing processes. It is common to use some type of database to do this and many databases are integrated with commercial LCA software systems. Examples of established LCA softwares are SimaPro and GaBi [40]. These databases contain data regarding energy use for material and processes in different parts of the world and emissions of not only GHGs but other volatile and harmful substances that can be included in a full LCA to cover all sustainability aspects. This generic data for processes and material may be used in this phase, however it is important to note that collection of primary data might be necessary if the generic data is unavailable or deemed to be of to low quality. Furthermore, some data will have to be approximated when no primary or generic data can be found. It is always necessary to state whether the data used is primary, generic or approximated.

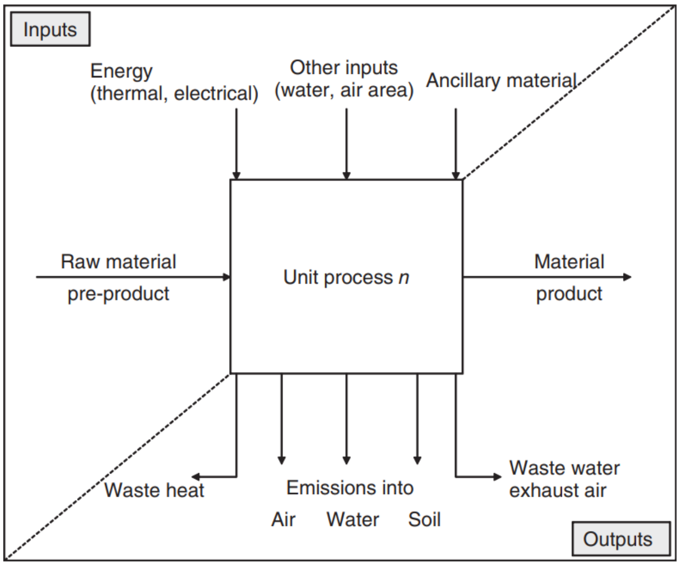


Figure 7: Schematic image of a unit process and the involved inputs and outputs. Source: [38]

4.3 Impact Assessment

There are three mandatory elements to an impact assessment, namely: selection of impact categories, classification, and characterisation. The selection of impact categories belongs to this part of the LCA study but it can be beneficial to do in the beginning of the study as they need to correspond to the goal and scope. There are no recommended impact categories in ISO 14044, but it is instead up to the author of the LCA to decide them, although it is recommended that they are internationally accepted [37]. Some examples of such categories are human toxicity, global warming potential, eutrophication and acidification. When selecting impact categories it is also important to decide the indicator, which will be the quantifiable result of the impact category [38].

Classification is the assigning of the result from the LCI to the different impact categories, and in some cases a result can be assigned to multiple categories. For example NO_x gases have an impact on both acidification and eutrophication, and should be counted in both categories. The last step is characterisation, which involves the conversion of the results to a common unit as well as the merging of these results within one impact category. Characterisation factors are commonly used to convert the results to a common unit. For instance in the case of the category climate change, a factor is used to convert other GHGs to their GWP expressed in CO_2-equivalent. The factor depends on the time horizon for the analysis, 100 years is commonly used, and how strongly the gas will affect the climate change during that time.

4.4 Interpretation

The final phase of all LCAs, and in general any kind of environmental analysis, is the interpretation of the results. For an LCA the interpretation is described in ISO 14040 as the phase where the inventory analysis and the impact assessment are considered together to deliver results "which reach conclusions, explain limitations and provide recommendations" [36]. The first step is to identify significant issues and results from the LCI and the impact assessment, and to define a significance criteria valid in respect to the data quality of the study. The next step is to evaluate the results, which can be done by doing a check of either *completeness, sensitivity* or *consistency.* The most common choice is to do a sensitivity check to estimate the uncertainties in the results, by for example modeling different scenarios where one parameter is being altered so that the influence of that parameter can be determined. After this, the final conclusions based on the results can be done and summarised as recommendations or proposals in accordance to the goal of the study [41].

A requirement for a study to be accepted as an LCA according to the ISO standards is that it goes through a critical review from an independent panel of interested parties. This is to be done as a last step and must be included in the final report that will be published [36][37].

5 Methodology

5.1 Materials and parts

The types of plastic blends that have been evaluated in this study can be found in Table 1. Six types of plastics were evaluated; two with recycled content, two biobased and two conventional ones made from fossil fuels. Three of them are FRCPs with a glass fiber content of 15% or 30%. The alternative plastics were chosen to be as similar to the conventional ones as possible but were limited to the types available to the company. Five internal plastic parts of the product were chosen, as seen in Figure 8. All of the parts has been manufactured in three types of material, the original conventional plastic, one recycled and one biobased plastic. A total of 30 pieces for each case has been manufactured at the same injection molding factory and with the same tools that the conventional parts are made with.

The parts have each been given a letter, found in Table 2, and will be referred to by that letter for rest of the report.

Reinforcement	**Tradename**	**Polymers**	**Type**	**Mass of fU**
Fiber-reinforced	Valox	PBT+GF	Conventional	47 g
	Schuladur	PBT/PET+GF	Recycled 50%	52 g
	EcoPaXX	PA410+GF	Biobased	47 g
Non-reinforced	Cycoloy	PC/ABS	Conventional	40 g
	Infino	PC/ABS	Recycled 80%	38 g
	EcoPaxx	PA410	Biobased	38 g

Table 1: The six types of plastics and plastic blends that were evaluated and what category they belong to: *conventional*, *recycled* or *biobased.* The amount of recycled content is noted if applicable. Three of the plastic blends are fiber-reinforced with glass fibers(GF).

Notation	**Part name**	**Reinforcement**
A	Holder pan	Fiber-reinforced
B	Holder rotate	Fiber-reinforced
C	Cover view	Non-reinforced
D	Cover mask	Non-reinforced
E	Cover PCB	Non-reinforced

Table 2: The parts, their respective letter notation, and whether or not they are reinforced.

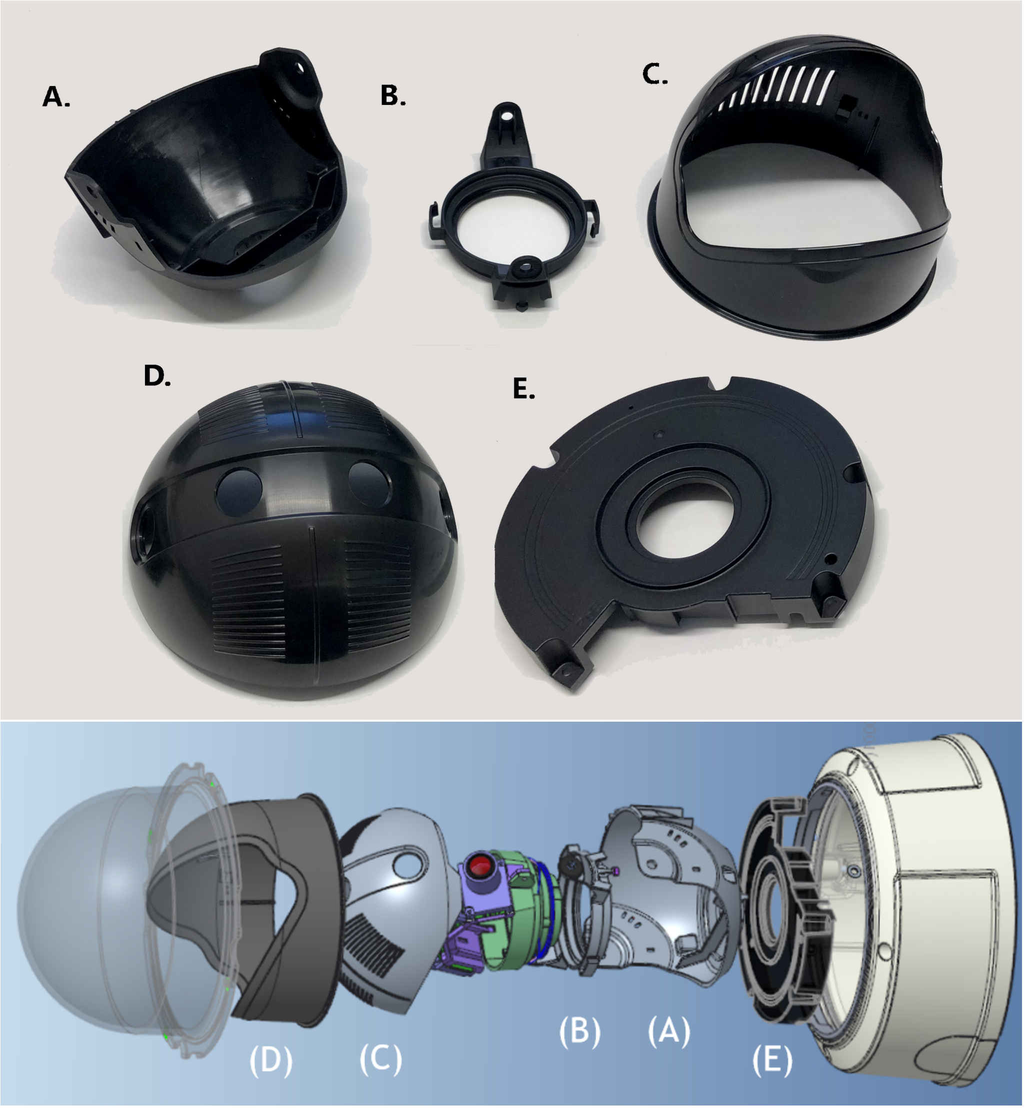


Figure 8: The five parts that have been evaluated in this study, and how they relate to each other in the product. The type of reinforcement used for each part can be found in Table 2.

5.1.1 Assembly of unit

There exists a detailed instruction on how all the five parts in Figure 8 should be assembled, which specifies what screws and torque to use as well as the order of assembly. To summarise, first the bottom of part (A) is attached with screws to the hole in the middle of part (E), which is screwed onto the aluminium chassis. Then, part (B) is attached with two screws to the "ears" of part (A). Part (B) also holds the optical assembly of the product, onto which part (D) can be snapped on, with each hole covering one lens. Lastly, part (C) is placed on top of the whole assembly, and fastened with snap fits onto the back rim of part (A). The assembly is then covered with a protective dome that is fastened onto the chassis. Figure 10 shows how all parts look when assembled but without the dome.

5.2 IK Rating

The IK rating is an international numeric classification related to "degrees of protection provided by enclosures for electrical equipment against external mechanical impacts" [42]. The rating is described in the Swedish standard SS-EN62262[42] which essentially is the same as the European standard. It consists of 10 degrees between IK 01 and IK 10, and the rating describes how much impact energy, in joule, that the enclosure can withstand. See Table 3 for the details surrounding different degrees of IK-ratings. It is important that the sample is mounted with rigid support and that the weight is dropped on a surface perpendicular to its trajectory.

IK rating	IK 01-05	IK 06	IK 07	IK 08	IK 09	IK 10
Impact energy (Joule)	<1	1	2	5	10	20
Mass (kg)	0.25	0.25	0.5	1.7	5	5
Probe fall height (cm)	<28	40	40	29.4	20	40
Diameter Probe (mm)	18,5	18,5	35	60	80	100

Table 3: The IK-codes and corresponding impact energy as well as the probe weight and fall height used for each rating.

5.3 Evaluation of properties

This thesis will evaluate the compressing strength as well as the impact strength of the plastics and investigate how organic oil, thermal aging and temperature cycling will affect the materials.

5.3.1 Compression tests

One mechanical property evaluated was the resistances to compressing forces. The tests were performed in a ZwickRoell ProLine Z005, hereafter referred to as "the Zwick", with the test set up as seen in Figure 9.

This project did not have access to plastic specimens of standardised shape, and thus the compressive tests could not be performed according to any national or international standard. The tests were instead comparative in nature, and performed on the parts seen in Figure 8.

Two compression tests were performed on two different subassemblies of the parts. The first test was performed on part (E) with a printed circuit board (PCB) snapped in, attached to its aluminum chassis by five screws fastened with the torque stated in the assembling instructions. The chassis was screwed in to the Zwick so that the probe was centered over the opening of part (E). The test was run so that the probe descended 12 mm starting from contact with the part, with a constant velocity of 5 mm/min, measuring the required force needed to maintain said velocity. The distance of 12 mm was chosen based on the distance required for the inner rim of the opening of part (E) to come in contact with the PCB. The results were plotted as force (N) vs distance (mm).

The second test was of similar nature, but instead on a subassembly consisting of parts (A), (B), and (E) attached to each other and to the aluminum chassis. In addition, an aluminum frame used in the product is also attached with screws to part (B), which in this test is the part of the subassembly upon which the probe makes contact. The setup is shown in Figure 9. In this test, instead of a particular distance travelled, the end-condition for the test was for it to reach an applied force of 1 kN. This value was chosen based on a dummy test with conventional plastic which showed failure at slightly higher forces, and thus seemed like an appropriate breaking point for comparisons. The velocity of the probe was chosen to be 5 mm/min.

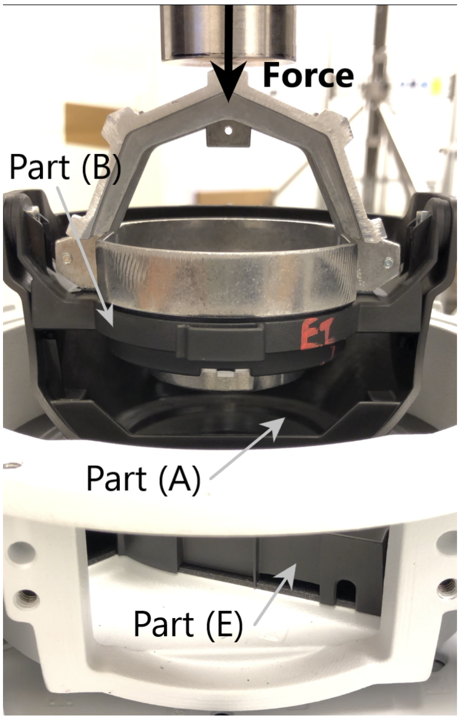


Figure 9: The subassembly with part (A), (B) and (E) marked. The sample is placed in the Zwick for a compression test.

5.3.2 Impact test

The impact tests performed within this project were of two types, one on a subassembly of parts, and the other on a complete product.

The test with subassemblies consisted of the complete product excluding the protective dome surrounding it. The objective of this test was to see how the assembled parts in one plastic category resisted direct impacts. When the product is in use, these parts would normally be protected by the dome, but during a sufficiently forceful impact the dome can flex and come into contact with the underlying parts, transferring some of the impact's force to them. An IK 8 test was performed in

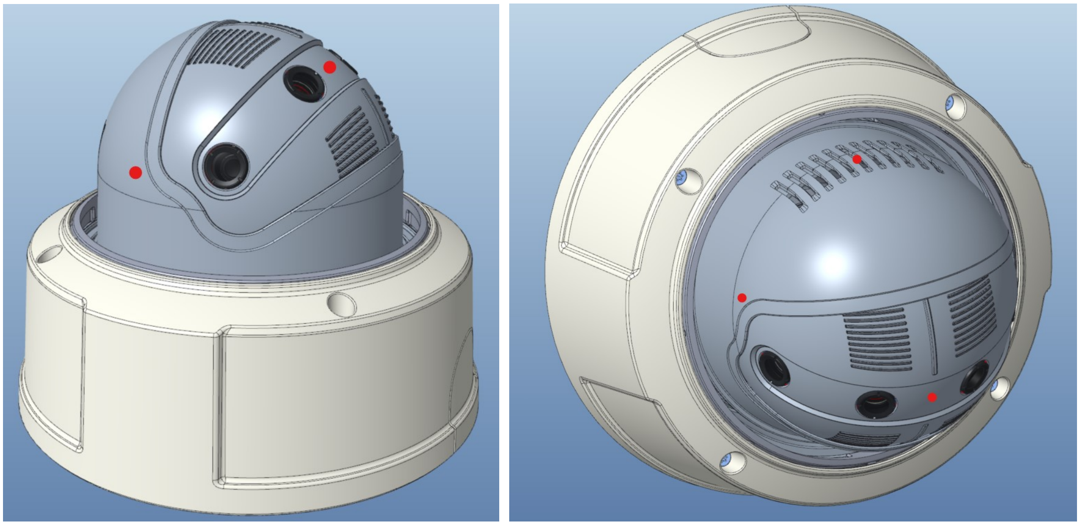

(a) (b)

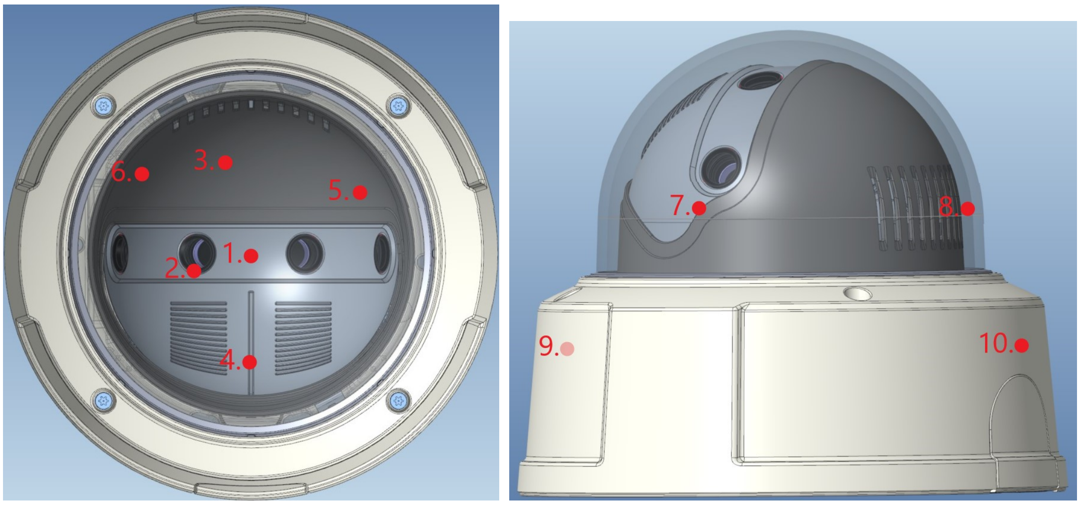
Figure 10: (a) shows two of the impact points from the IK-test on the subassembly marked in red from a side perspective, and (b) shows all the impact points marked in red from a top-down perspective. In both figures, a CAD-model is used to represent the product.

two runs, with one run being defined as hitting 3 points of the product; the front, the side, and the back as seen in Figure 10, with a force of 5 J per hit. The hits were perpendicular to the impact surfaces. They were performed in succession and if the outer part, part (C), came off, it was inspected for cracks and then reattached regardless. An IK 7 test was also performed once, with the same three points, and evaluated in the same way. The results of the subassembly tests were evaluated on a visual basis and all impacts were filmed with a camera in slow motion to make the evaluation easier.

The complete product was tested with all parts exchanged to recycled plastics. The unit was then tested in accordance to a IK 10 rating and three replicates were tested. Each unit was hit 10 times with 8 hits on the dome and 2 on the chassis, according to Figure 11. Afterwards, a functionality check and visual inspection were performed according to the company standard. The functionality was also checked during the test by taking snapshots with the product before and after an impact.

5.3.3 Organic Oil test

This test was performed to determine the environmental stress cracking (ESC) resistance of the plastic. Generally, semi-crystalline plastics are more resistant to ESC, but all plastics in this project were tested the same way. The majority of the parts to be tested were assembled so that stress from screws and snap-fits was applied the same way as it would when in use. The exception was part (D), which was instead mounted as can be seen in Figure 12. The load was larger than what the part would normally be exposed to in order to see if cracks would manifest more easily. Reference parts without any load were also used for all parts, to compare the results



(a) (b)

Figure 11: (a) shows the six first impact points from the IK-test on the complete unit marked in red from a top perspective, and (b) shows the last four impact points marked in red from a side perspective. The ninth impact point is on the backside of the image. In both figures, a CAD-model is used to represent the product.

of the application of stress. Oil, in this case olive oil, was applied to the inside and outside of the plastic with a paintbrush, and paper was used to wipe off excess oil. The parts were then put in a heat chamber at 45℃ for 72 h, after which they were removed from the chamber and stored at room temperature for at least 16 h. The parts were then inspected visually and with an optical microscope to determine if any cracking had manifested.

Figure 12: The mount upon which part (D) was mounted for inducing stresses during the organic oil test. The distance between screws was the same for all samples.

5.3.4 Thermal Aging Test

A thermal aging test was performed by putting the samples in a drying oven, Pol-Eko SLW 400, at 85℃ for five weeks, or approximately 850 h. The exact humidity could not be controlled in this kind of oven, but it was a dry oven so it was assumed to be low. All samples were put separately on the shelves so that no sample was touching another sample, as seen in Figure 13. All six types of plastics were tested at the same time. After the parts had been taken out of the oven and cooled to room temperature, they were exposed to compression tests on subassemblies as described above. This was done in order to evaluate the effect of thermal aging on the structural properties of the plastics.

Figure 13: The samples placed inside the drying oven.

5.3.5 Temperature Cycling Test

A temperature cycling test, hereby called temp-cycling, was performed in a Clima Temperature Systeme (CTS) C-70/350 climate chamber. The temperature was cycled from 65℃ with 85% rH to -40℃ with a speed of 3°C/min and held at the extreme temperatures for 4 hours. The program can be seen in figure 14. A total of 18 cycles were performed during 7 days. The samples subjected to the test were the same parts that were chosen for the 3D-scanning, namely part (A) and (E). Part (B) was also added to the test assembly to increase the resemblance to the real forces applied on the parts. Prior to entering the climate chamber the parts were assembled according to working directions that specified the torque to be applied to the screws. Three subassemblies were prepared, one with conventional plastics, one with the recycled plastic and one with the biobased plastics. The evaluation of the test was done using 3D-scanning.

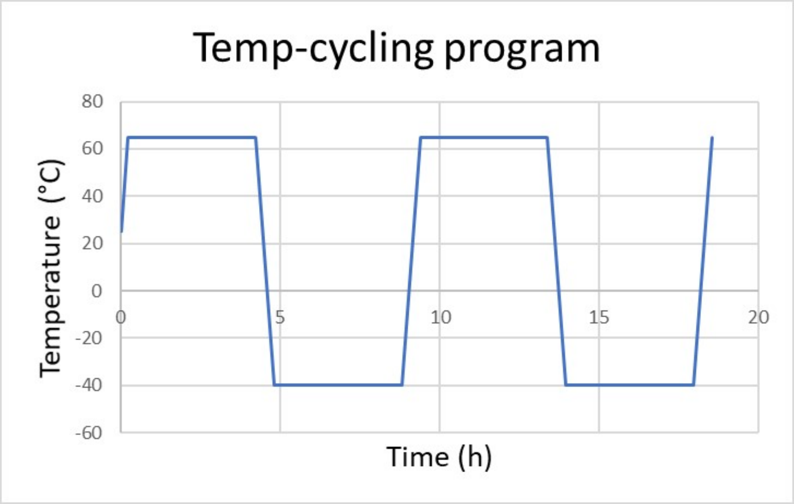


Figure 14: The first two cycles of the program used for the temperature cycling: starting at 25°C with the top temperature of 65°C held for 4 h and a minimum temperature of -40°C held for equal time. The temperature changed with 3°C/min and the test lasted 7 days.

5.3.6 3D-scanning

The dimensions of a part and the matching tolerances are important. To measure how well the dimension of a part matches the design parameters a type of 3D-scanning was used. The parts were first coated with titanium dioxide and then strung up in a GOM ATOS Triple Scan and scanned from all directions [43]. Two parts were chosen for this, part (A) and (E), due to their more simple structure. With more time, all samples could have been scanned. These scans were used to evaluate how well the parts correlated to their CAD design, as well as how the temperature cycling affected the plastics. The same exact parts were not scanned before and after the temperature cycling, since it was unclear how the layer of titanium oxide would affect the test in the climate chamber, and it was assumed that the differences between samples would be smaller than the deformations caused by the cycling test.

5.3.7 SEM

A SEM was used to examine the surface structure of the plastics. The machine used was a SEM - LEO 1560, which is a thermal field emission SEM available at Lund Nanolab. The sample in conventional plastic was from a fracture in part (A) due to an impact, the sample in recycled plastic was from a broken-off piece of part (B), and the biobased sample was from part (A) after a compression test. The samples were coated with a 2 nm thick layer of platinum and palladium (80:20) using the Sputter - Q150T ES before examination in the SEM. Only the fiber-reinforced plastics were examined due to lack of time, and each of them were imaged at 150x-200x to facilitate comparison. The accelerating voltage was 10 kV and the samples were imaged at between 150 x and 6.12 kx magnification, with a working distance between 5.6 mm to 8.3 mm. The angle for most samples was 0°, but for some it was 15°. For information regarding the cost of operating the machines, see Appendix D.

5.4 LCA

This assessment has followed the ISO 14040 standard as much as possible, but due to limited software and data some parts will deviate from the standard [36]. The assessment has been divided into four parts: goal and scope definition, inventory analysis, impact assessment and interpretation.

5.4.1 Goal and Scope Definition

The goal of this assessment was to get an insight and evaluate the relative environmental impact of conventional plastics versus recycled or biobased plastics. The study is of interest as it may allow for potential environmental gains of using alternative plastics to be shown in a clear way and additionally relate the results to the the mechanical investigation also performed in this thesis. The results are intended to aid in a more conscious future material selection. Furthermore, the result of the study may be of value to similar industries using the selected materials. The method of evaluating the mechanical as well as environmental aspects of the plastics can potentially be of interest to all whom wish to find more sustainable alternatives for their products.

As mentioned, an LCA was chosen to perform this task, as it is a powerful tool to outline the various possible environmental impacts throughout a product's lifetime. If performed thoroughly, it can give a lot of insight into which parts of the process might cause more or less impact, but for this particular case a partial LCA could be sufficient. It can still give an estimate of what the environmental gain might be from using biobased or recycled plastics, and how that relates to some other major processes in the product's lifetime.

The product system was defined as shown in Figure 15. The three sources of raw material are listed at the start of the chart, each in a different color, and after reaching the injection molding the path is more or less the same independent of what plastic is used. In this case, the product system which was examined is within the grey box, which includes the process from extraction of raw material up to before shipping to the Electronics Manufacturing Service (EMS). The end-of-life (EOL) of the materials will also be considered in the analysis. The choice of material was assumed to not affect the environmental impact of the user phase and it was therefore not considered in the analysis. Effects of infrastructure and machinery used in manufacturing will also not be considered. This study will only examine the life and effects of the plastic part in the chosen material, while other environmental aspects and effects from the product will not be considered.

The functional unit (fU) was 1 unit of part (A), see Figure 8, an internal component of the product.

The lifetime of the examined IT product is presumed to be 10 years. After those years the product is assumed to be collected and processed as waste. In this case

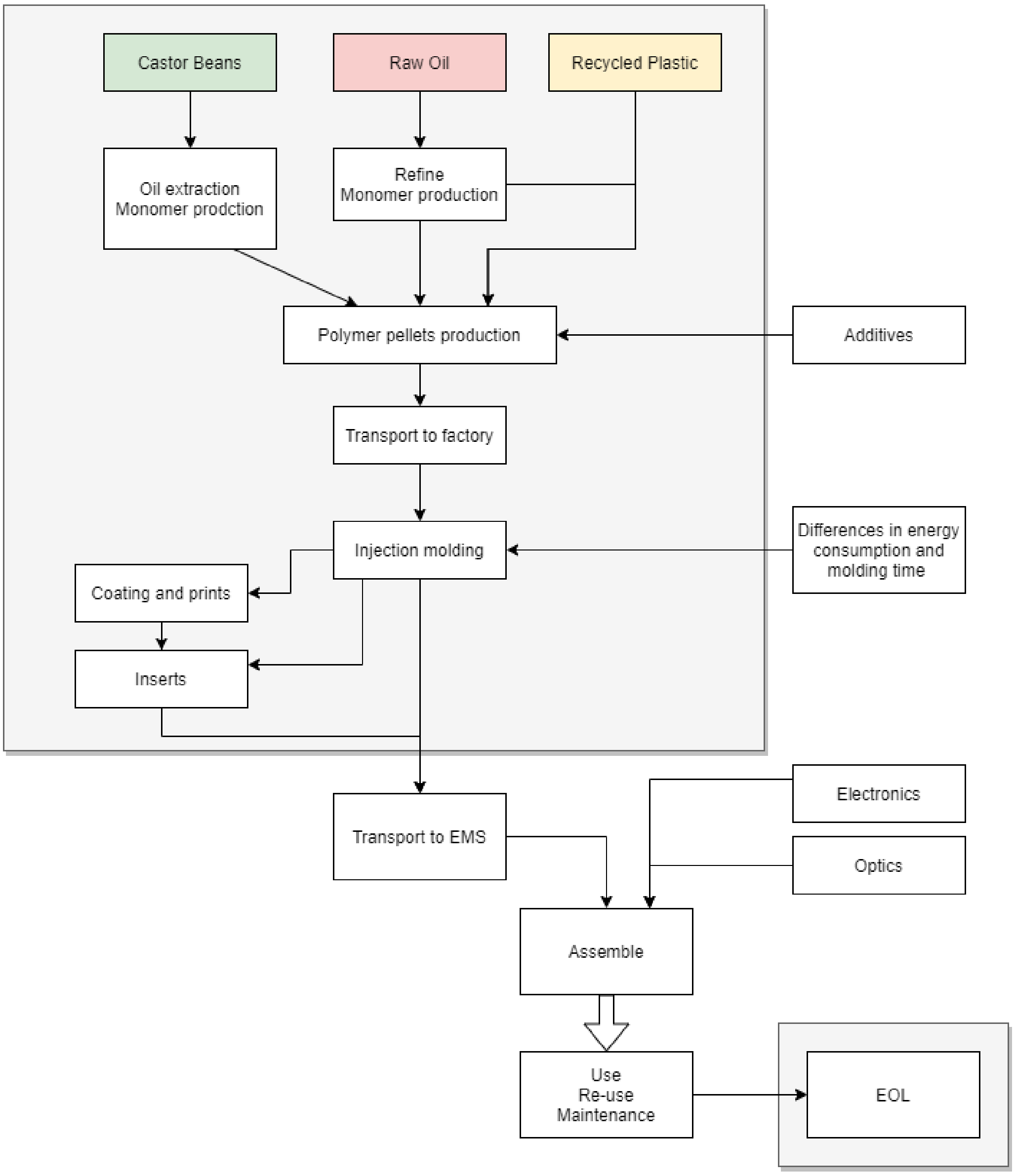


Figure 15: Flowchart of the process system for the plastic parts, with the system boundary indicating the processes that was evaluated.

only the EOL of the specific plastic parts was considered, and the waste treatment of the rest of the product will only be discussed briefly. The impact categories used for this analysis are global warming potential and primary energy demand.

5.4.2 Inventory Analysis

Data for the LCI has been collected from multiple sources, but the most significant one is the Granta Edupack database. The data collected from EduPack can be found in Appendix A [44]. Other key sources have been the plastic molding company, RiLong (RiLong Precision Mold Company [45]), the plastic pellet suppliers, and the IT company this thesis was made in cooperation with. The data found could be categorized as either primary, generic or approximated.

The life cycle of the plastics has been divided into the following four processes:

- Transportation
- Plastic pellet production
- Manufacturing of parts
- End-of-life

The collection of data for the plastic pellet production, manufacturing of parts and EOL has included primary data from some material suppliers and secondary data from EduPack [44]. The primary data only includes CO_2-emissions for both Eco-PaXX plastics and is based on an internal LCA at the manufacturer. Secondary data from EduPack includes embodied energy from primary production, as well as the CO_2-emissions and energy for manufacturing, heat of combustion and combustion CO_2, and the energy required and CO_2-emissions that are generated from recycling 1 kg of material. Most of the data is estimated by EduPack due to lack of direct sources, and the sources present are 5-6 years old. For one plastic blend, Schuladur PBT/PET, the data was not available in the database, and thus the values were estimated from assuming the ratio of PBT/PET to 50/50 and averaging the values from both constituent plastics.

The estimations of the energy consumption and CO_2-emissions from EduPack take into account both the energy required to run the processing equipment as well as the facility, and are estimated for high volume production.

For the reinforced plastics which were not available as glass fiber-filled in EduPack a reduction equal to the % of glass fiber (GF) filling has been applied to heat of combustion and combustion CO_2-emissions since the glass fibers will not attribute to these, and for those with flame retardants an additional % equal to the percentage of flame retardant is deducted.

Data regarding the transport has primarily been collected from both the molding company and the company making the product. The data consists of the locations for all the stages in the production and the means of transport, from the factory making the plastic pellets to when the finished product reaches the distributor. EduPack has provided estimated data to calculate the CO_2-emissions and energy usage depending on the method of transport between each stage. Distances between locations has been calculated using Google Maps.

Regarding the EOL of the product, estimations have been made concerning to what extent the plastics will end up being recycled, incinerated or deposited as landfill. The energy and emissions connected to the EOL options have been acquired from EduPack. Different countries and regions differ greatly in how they treat plastic waste from electronic products and therefore various scenarios has been considered.

5.4.3 Calculations

The environmental effect of transport is usually calculated from the amount of tonne-kilometres(tkm), which is equivalent to one metric tonne of the material traveling one kilometer. By multiplying the number of tkm for each plastic with the transport energy for the specific type of transport, the total energy usage and CO_2-emissions have been calculated. The conversion factor between energy use and CO_2-emissions was set to be 0,072, which is based on the conversion of fossil fuels to electric or thermal energy [44]. When there have been multiple types of transport for one step, an average transport energy corresponding to the ratio has been calculated. A summary of these calculations can be found in Table 14 in Appendix B.

The primary energy usage and the carbon footprint from production were specified in Edupack and needed only to be multiplied with the weight of the functional unit. The same goes for the energy needed and the emission caused by the molding of the parts.

To calculate the effect of EOL handling, three possible ways for the plastics to end their life have been considered. The first path is incineration, which means that the plastic will be put in a furnace and combusted into ash. The released heat will be converted into useful energy in the form of electricity and district heating. The heat of combustion for each plastic is presented in Appendix A. A power plant used for combustion of the plastics is expected to have an efficiency of about 82.6% [46]. The second path is recycling, which in this case refers to mechanical or chemical recycling. The plastics will then be used in a new product and their life cycle is prolonged. This results in a decrease in the resources needed for the plastic in the next life cycle. This can be seen as a saving in energy and in the scope of this project, that saving will added as a decrease in total energy needed for the plastic. The third way is for the plastic to end up in landfill. In all three cases, energy for collecting and sorting the plastic is also considered.

With this, three scenarios have been created where the plastic end up in one of these paths to various extents. In the first scenario 95% is being incinerated and the last 5% ends up in landfill.

In the second scenario maximal recycling is assumed, which was decided to be 33%, since it reflects the current situation of recycling on average in Europe [4]. 42% is being incinerated and the last 25% ends up in landfill. The fiber-reinforced plastics has been treated differently in the calculations, with 75% being incinerated and 25% landfilled instead, due to the fact that they generally cannot be recycled.

In the third scenario 100% is going to landfill.

5.4.4 Impact Assessment

The impact categories selected for this analysis are GWP and primary energy demand (PED). This choice is mainly based on limited access to complete databases. The impact on global warming will be expressed in kg CO_2-equivalents per fU. Primary energy demand will be expressed in MJ per fU. No normalisation or weighting will be used.

Global warming potential as a result of different GHGs and their effect on the climate is a very complex question. In this study the impact category of global warming will only include the calculated CO_2-emissions from the four processes that were chosen. Data regarding any other GHGs has not been collected. The energy usage has an indirect effect on the global warming but is in this case its own impact category. This means that factors to convert other gas emissions to CO_2-equivalents will not be necessary.

PED is simply a summation of the energy needed in the different processes and phases of the products life cycle. Energy may in many cases originate from fossil fuels and other non-renewable sources, and is therefore a limited resource, but in this study there is no distinction between energy from different sources.

5.4.5 Interpretation

The result will be evaluated and compared, but due to the reinforced plastics and the non-reinforced plastics serving different purposes, these categories will not be compared. The final result will be checked for significance, and according to the Edupack database, the eco-properties used in the analysis have a high uncertainty which is why it is recommended to use a significance level of at least 20% [44]. The different processes of the life cycle will be individually regarded and evaluated. This is a comparative study and processes where the impact is equal in all stages of the life cycle does not need to be a part of the evaluation.

The high level of uncertainty makes it even more important to perform a sensitivity analysis where the effect of increasing or decreasing certain values is examined. A way to do this is to examine different scenarios or simply increase or decrease one of the parameters. One scenario that will be examined is if all production and manufacturing were to be moved to Europe instead of Asia. This could have an effect on the resulting impact for several of the processes. Europe has in general a lower share of the energy coming from fossil fuels, which should mean a lower carbon footprint. It might also lead to the transporting distance being shortened which might decrease the total impact from transportation.

6 Results

6.1 Material test results

6.1.1 Compression tests

The results of the compression tests are comprised of visual inspection of the samples after test completion, as well as graphs showing force vs time or distance from the Zwick. The first test, on only part (E) in all three plastic categories, resulted in the force vs time graphs as can be seen in Figure 16. The sharp, sudden decreases in the beginning of the curves were due to an edge of the part deflecting outwards and then not offering the same mechanical support. The sharp decrease in force for the biobased plastic after 65 s is due to it suffering a brittle failure, as can be seen in Figure 17c. The biobased part could withstand a total force of 1050 N before failure in the first run and on the second try it failed at 847 N. The probe moved a total distance of 5.42 mm and 4.5 mm respectively, from the start of the tests until failure.

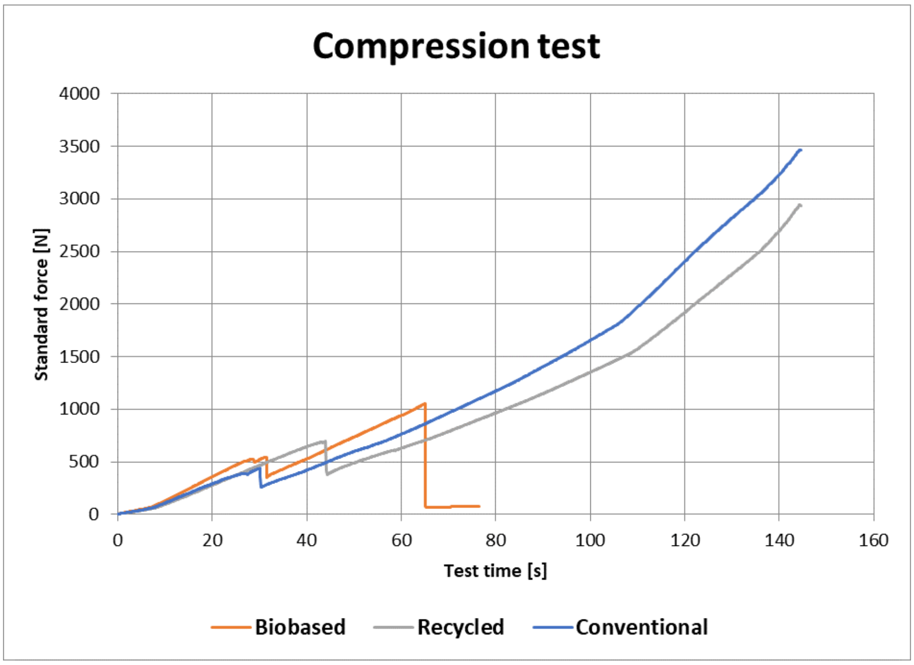


Figure 16: Force vs time during a compression test on part (E), displaying the result for biobased, recycled and conventional plastics.

The second test, where the subassembly was evaluated, resulted in the graphs shown in Figure 18. The visual inspection showed that parts (A) and (B) were more prone to break than part (E). Before reaching the full load of 1 kN all samples failed, either fracturing entirely or showing significant cracks. The subassembly in conventional plastics, Cycoloy and Valox, showed cracks in part (A) as seen in Figure 19a. The cracks resulted in two dips in force as can be seen in the graphs. In one of the three test performed, the positioning spike on part (B) broke off, as shown in Figure 19b, and the sharp dip in in the end of the curve for the conventional plastic in Figure 18b is most likely due to the breakage of this spike. The parts in recycled plastics, Infino

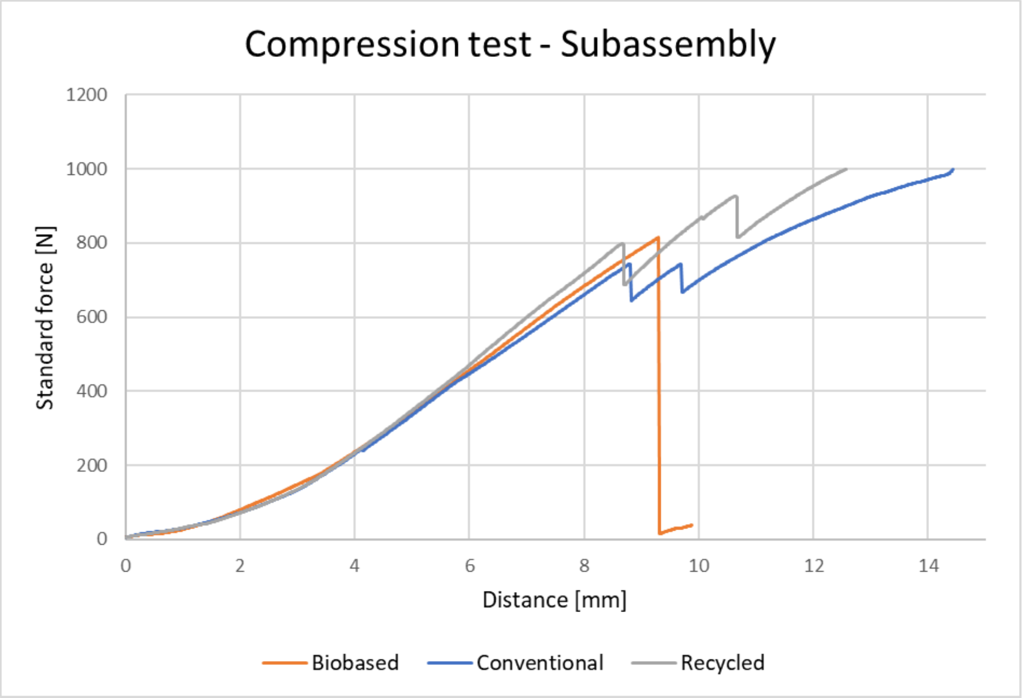
(a)

(b)

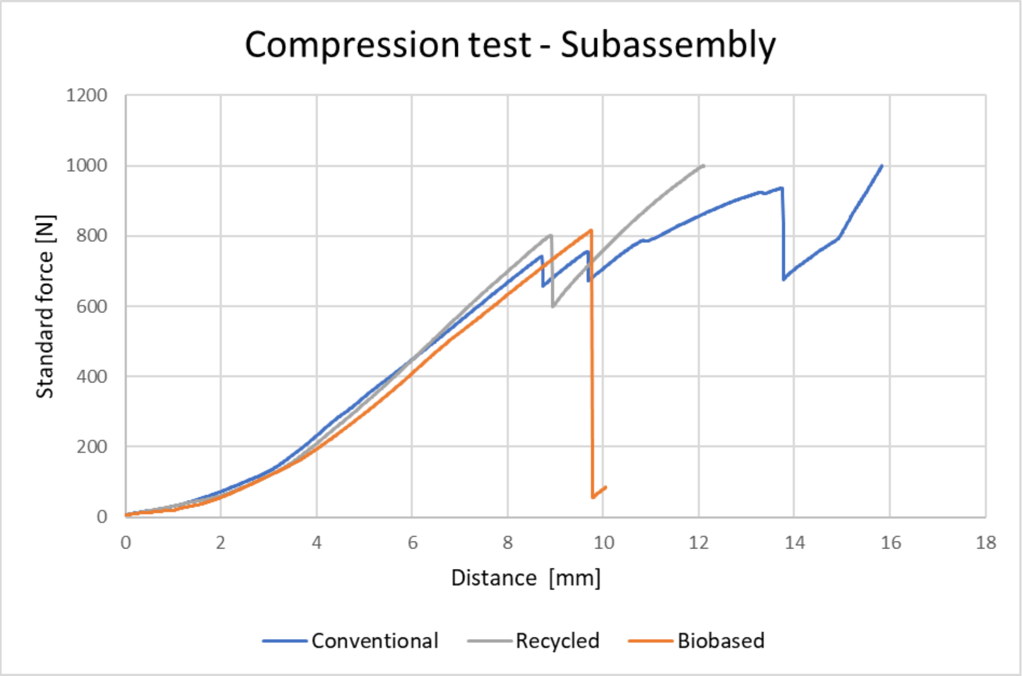
(c)

Figure 17: Part (E) in the three plastics after being submitted to a compression test. (a) is the conventional plastic Cycoloy, (b) is the recycled plastic Infino, and (c) is the biobased plastic EcoPaXX. The conventional and recycled plastics showed some indentation from the probe, and the biobased plastic suffered from a brittle failure.

and Schuladur, showed the same cracks in part (A) as the conventional plastics, see Figure 19a. No other failures could be found. The biobased plastics, EcoPaXX and EcoPaXX GF, did not show the same cracking of part (A) as the conventional or recycled plastics. On the other hand, all test runs ended with a full fracture of part (A), (B) or both, shown in Figure 20. The failure happened at a load of 815 N and 818 N.

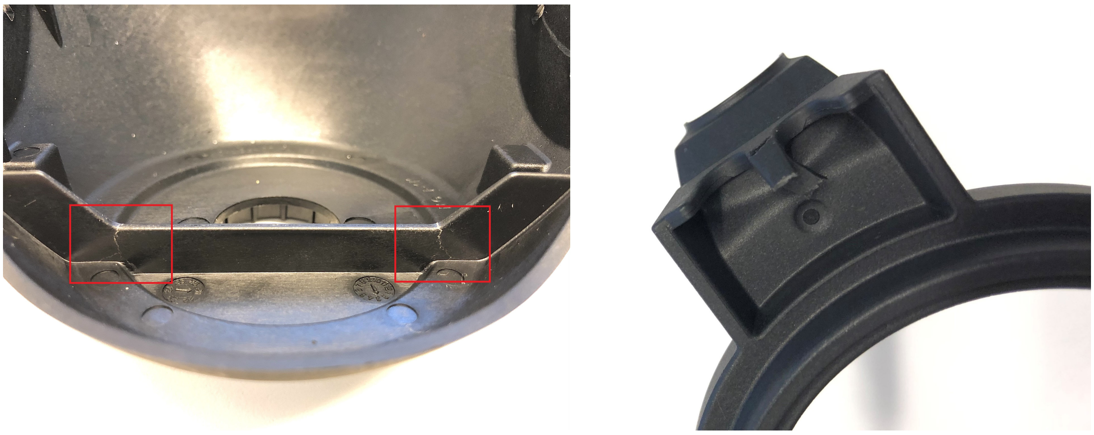


(a)



(b)

Figure 18: Force vs Distance during the compression test 1 (a) and 2 (b) on the subassembly, displaying the result for biobased, recycled and conventional plastics.



(a) (b)

Figure 19: (a) shows the cracks that appeared in part (A) in conventional plastic during a compression tests of the subassembly. Similar cracks appeared when the recycled plastics were tested. (b) shows how the positioning spike on part (B) failed during one compression test with conventional plastic.

6.1.2 Impact tests

The result from the IK 7 test was that all assemblies passed without any visible cracks or other damages. For impact 2, the snap fit of part (C) detached for both the conventional and the biobased plastics, and for impact 3 it came off for only the biobased plastic.

The impacts from the IK 8 test resulted in cracks and even failure of primarily part (A) and in some cases part (C). For the conventional plastics, part (A) displayed cracks around the bottom hole after both test runs and in the second run the crack was reaching up towards the attachment of part (B). The second test also resulted in bits of the back of part (A) almost coming off. The cracks are shown in Figure 21. Part (C) came of during the last impact of the first run and during all impacts in the second run.

The recycled plastics passed the IK 8 test without almost any damage. Part (C) came off due to some of the impacts, but was easily put back on, and apart from this only a small crack manifested itself at the base of part (A) after the first run, as can be seen in Figure 22.

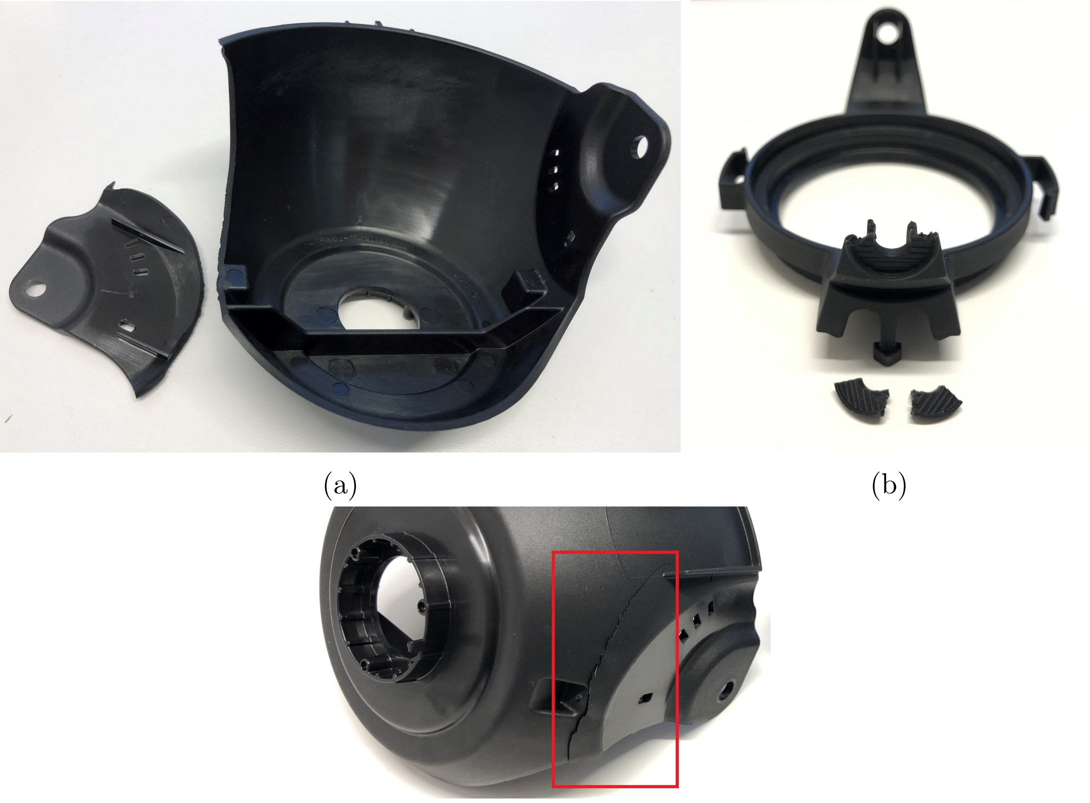

(a) (b) (c)

Figure 20: (a) and (c) shows the failure of part (A) in biobased plastic after two different compression tests. (b) shows the failure of part (B), also biobased, that appeared in another test.

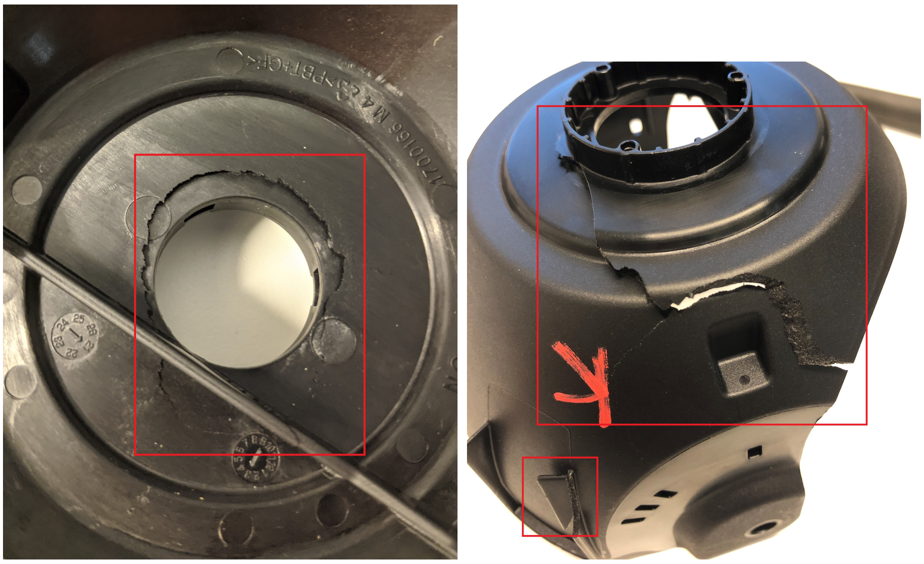
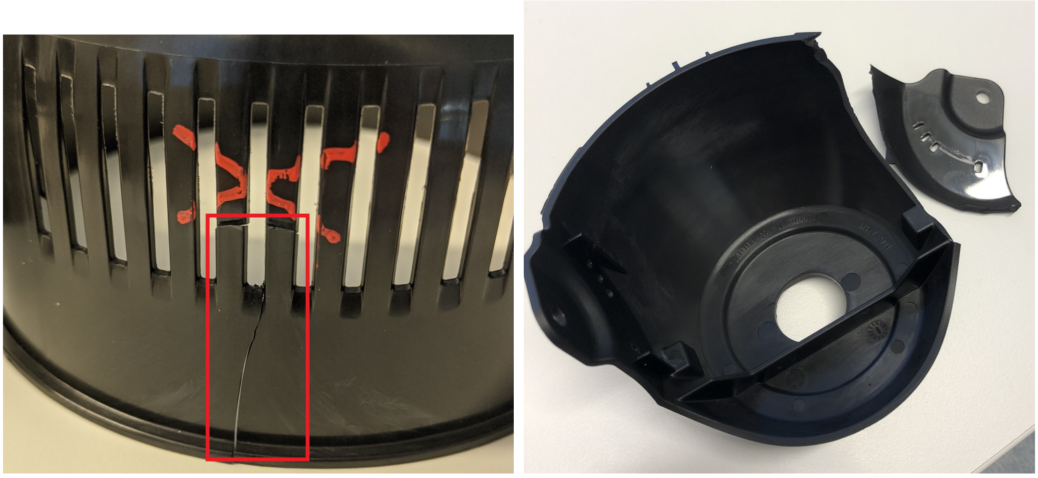

(a) (b)

Figure 21: (a) shows the cracks in part (A) made of conventional plastics following the first impact test IK 8, and (b) shows the cracks in the bottom of part (A) and the broken off fin.

Figure 22: The crack in part (A), which appeared after the first impact test IK 8 on recycled plastic.

For the biobased plastics, both part (A) and (C) were damaged, part (A) to the point of full failure. All documented damages can be seen in Figure 43 and 44 in Appendix C. Both test runs resulted in failure on the right side of part (A), as can be seen in Figure 23b. Part (C) displayed cracks following both test runs, see Figure 23a, in the back where the impact occurred. Part (C) also came off during all of the impacts, except the first impact of the first run. All parts not mentioned in the result above got through the impacts without any visible damage.

The final impact test on the complete product was performed on three equal, brand new units. The result of the functionality check after the test is found in Table 4. All three units performed equally well and showed no signs of failure during the functionality checks.



(a) (b)

Figure 23: Parts (A) and (C) in biobased plastics after impact test with IK 8. (a) shows the cracks in part (C) and (b) shows the failure that appeared on part (A) following both impacts test.

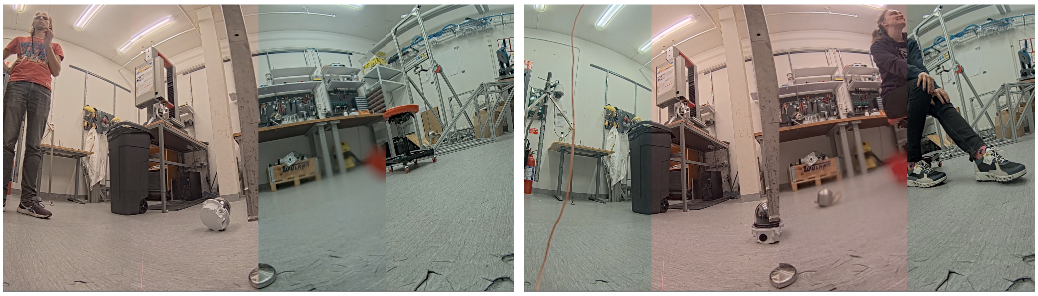
Table 4: The result from the functionality check on the three units that went through the final IK 10 test.

Unit	1	2	3
Overall function	OK	OK	OK
Image quality	OK	OK	OK
Memory card insertion	OK	OK	OK
Saving a video	OK	OK	OK

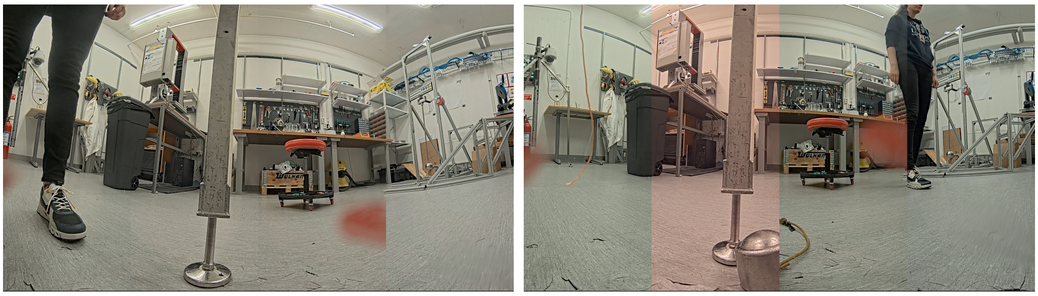
The units were also visually checked for failures and defects and the result for each part is found in Table 5. The first thing to be visually inspected was the dome, which had taken the most damage. All impacts created marks on the dome, like stretchmarks reaching out from the point of impact in a circle with a diameter of about 1-2 cm. There were also some scratches and marks on the outside of the domes, but no failure. When the units were disassembled it was noted that the outermost screws in the aluminium chassis had been loosened. The internal parts were basically all unharmed. Part (C) showed the smallest of marks at the point of impact 7, where the dome must have reached it during the impact, but no other defect could be found. The snapshots taken during the tests showed that the impacts had little effect on the units. Some impacts pushed the units a few centimeters out of place as can be seen by comparing Figure 24c and 24d. After impact number 8, a slight change in the image quality could be seen. Figure 24 shows that some of the sections of the image has an orange tone after impact.

Table 5: The results of the visual inspection of parts A-E as well as the outer chassis and dome.

Part	Unit 1	Unit 2	Unit 3
Overall	OK	OK	OK
A	OK	OK	OK
B	Squeaky	OK	OK
C	Impact 7 left a small mark	Impact 7 left a small mark	OK
D	OK	OK	OK
E	OK	OK	OK
Chassis	Screws loosened & small scratches	Screws loosened & small scratches	Screws loosened & small scratches
Dome	Scratches and marks	Scratches and marks	Scratches and marks



(a) Before (b) After



(c) Before (d) After

Figure 24: Images taken with unit 2 ((a) & (b)) and unit 3 ((c) & (d)) before and after impact number 8. A slight change in color can be seen in some of the sections.

6.1.3 Thermal aging

No visual change after the thermal aging could be seen. The parts were tested in a compression test on a subassembly. The parts showed similar failure mechanics as before thermal aging. Part (A) cracked in the same manner for both conventional and recycled plastics, as seen in Figure 19a. However, in this test the biobased part (A) also exhibited the same crack, though only on the left side of the piece. The failure on part (C), as seen in Figure 19b, were also present for all categories at least once. The compression tests also generated force vs distance graphs, all which can be found in Appendix C (Figure 45, 47 and 49).

6.1.4 Organic Oil test

All non fiber-reinforced plastics had some cracking around the screw holes of part (E), where screws had been fastened with torque in accordance to the assembling instructions. A reference with screw holes not exposed to the test, but with screws fastened in the same manner, did not show any cracks at all. For all plastics, the screw head left a circular indentation in the plastic on the top part around the screw hole. The cracks differed somewhat between the plastics: the conventional plastic had numerous small cracks which were visible if the part was flexed so that the oil on the surface either was absorbed into the cracks, or expelled from them. This can be seen in Figure 25. It also had a few larger cracks, one of which can be seen in Figure 26. All holes had some cracks present.

The recycled plastic had few cracks, and several of the screw holes showed no sign of cracks. Two of the cracks which were found can be seen in Figure 27. The crack on the left shows some whitening along the edges, and is less opened up than the crack to the right. The crack on the right is similar to the one seen for the conventional plastic in Figure 26.

The biobased plastic showed several, albeit mostly small cracks. The majority of these were concentrated to the area most close to the screw hole, in the indentation cause by the screw, as can be seen in Figure 28. An interesting feature, which was not seen for the other plastics and might be difficult to discern from the figure, were the cracks perpendicular to the screw hole's edge, as can be seen in the upper central red square in the right image of Figure 28. There were also some larger cracks present, drawing from the screw hole to the exterior of the structure, as can be seen in the left image in Figure 28. These were exclusively observed from the bottom of the part, i.e. the area in contact with the aluminum chassis.

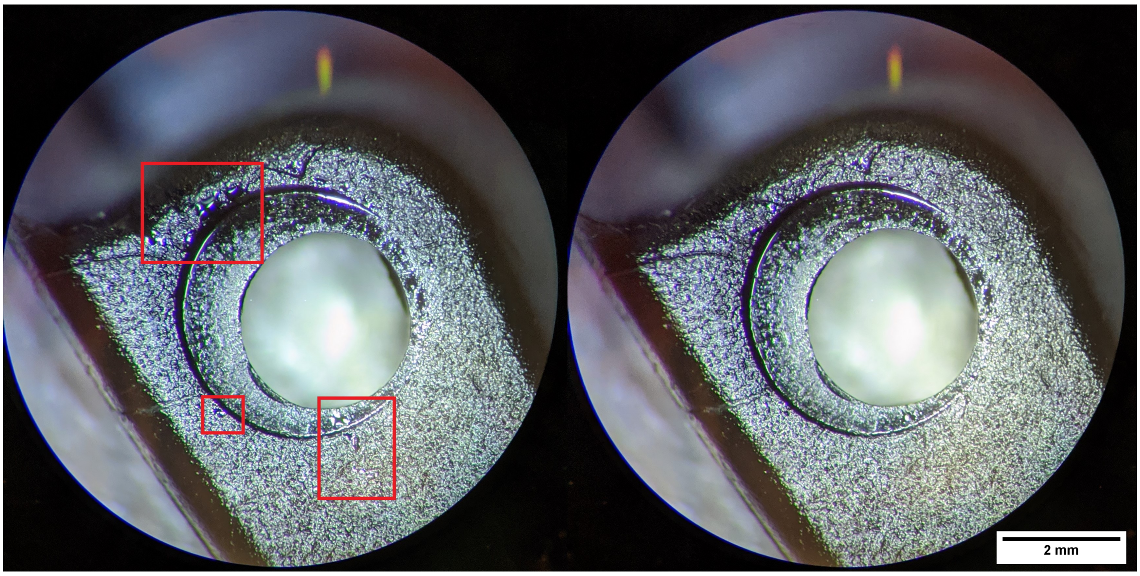


Figure 25: In this figure with the conventional plastic after an organic oil test, the two images show the same sample with and without some flexing of the part. This allowed for small, otherwise indistinct cracks to become visible as the remaining olive oil was expelled from them. These images were taken from the top of the part, and the cracks are marked with red rectangles.

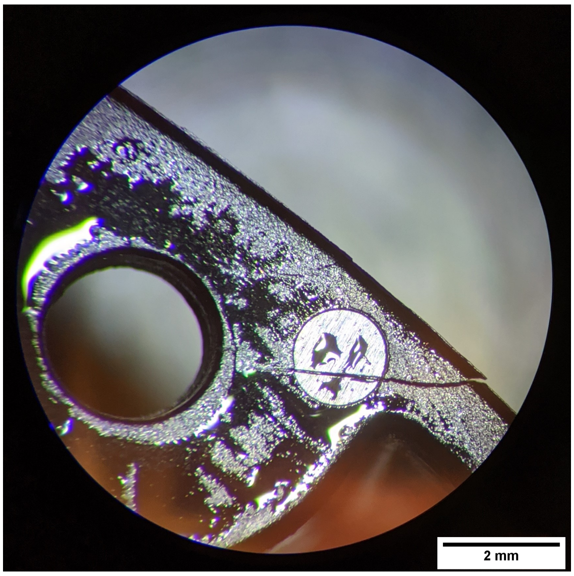


Figure 26: Here a long and wide crack can be seen in part (E) made of conventional plastic after an organic oil test, running from the screw hole all the way out to the edge of the part. This image was taken from the bottom of the part.

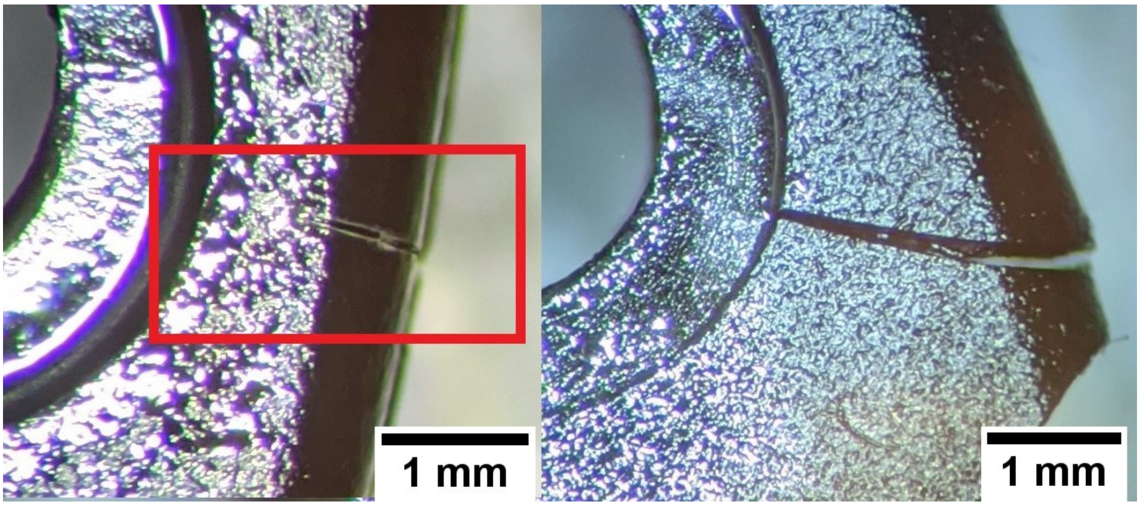


Figure 27: Here, two of the few cracks found for the recycled plastic after an organic oil test are shown. To the left, a crack with white borders, which could alternatively be a strange reflection of the oil, and to the right, a deeper, wide crack, not quite reaching the screw hole. Both images were taken from the top of the part.

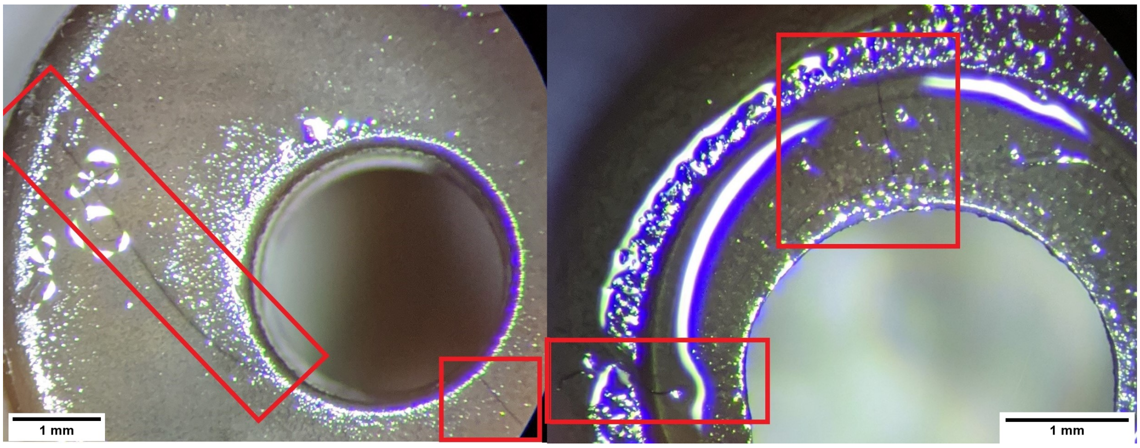
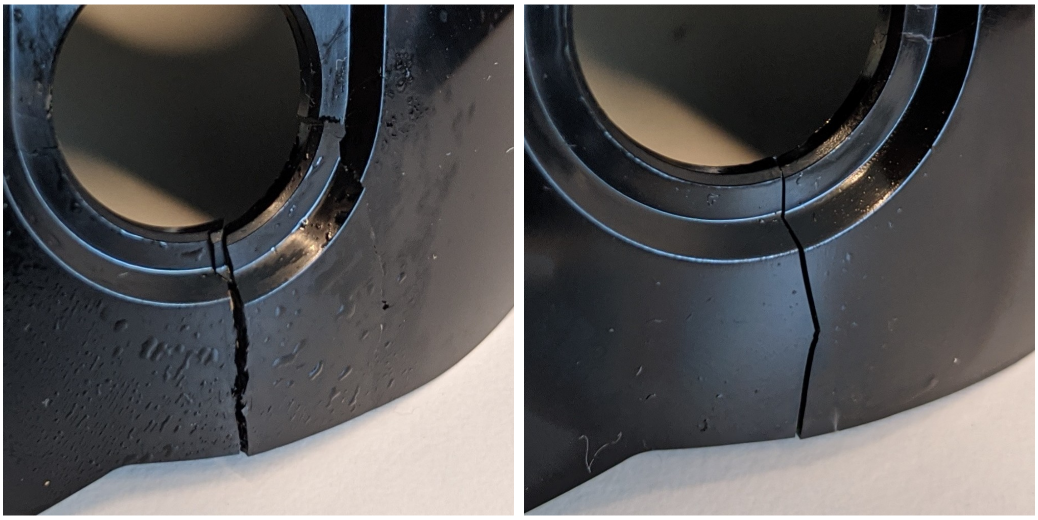


Figure 28: Both images show cracks in the biobased plastic after an organic oil test. To the left, an image of the bottom of the part with one large and one smaller crack can be seen, and to the right an image of the top of the part with a visible indentation of the screw head in the plastic and several cracks can be seen.

The results of the organic oil test on part (D) are seen in Figure 29. The biobased plastic did not suffer any cracks on the part, but both the conventional and the recycled plastics cracked on the same side. The recycled only had a single crack, while the conventional had several cracks, with the plastic between them barely still attached. All plastics suffered some deformation in the direction in which the part was elongated.



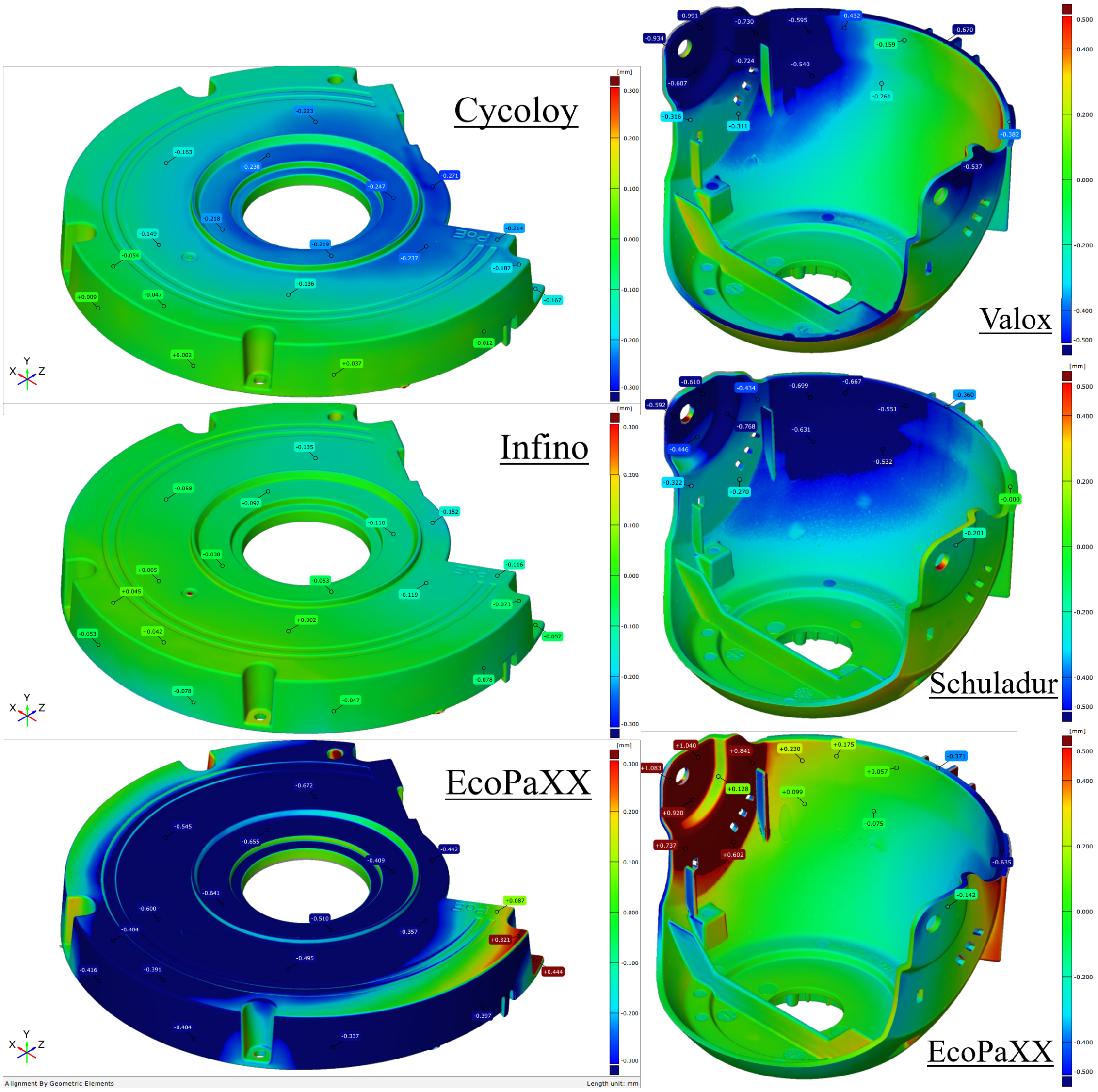
(a) (b)

Figure 29: The cracks caused by the organic oil test on part (D) are shown, where (a) is the conventional plastic and (b) is the recycled plastic.

6.1.5 3D scanning

The results of the scanning of the parts was presented as a series of images in a comprehensive report, detailing with colors where and to what degree the dimensions of the scanned part deviated from that of the CAD model. The results for the part prior to testing showed some significant dimensional deviations, mostly for the biobased and somewhat for the conventional plastic, see Figure 30. Considering part (E), the recycled plastic (Infino) showed very small deviations from the expected dimensions, even better than the currently used conventional one (Cycoloy). The biobased plastic (EcoPaXX) showed some considerable deviations, especially around the middle of the part, but seemed to be acceptable in its dimensions around the screw holes, which is the most critical part for assembling the unit. For part (A), all three plastics showed deviations around the furthermost area, where Valox (conventional) and Schuladur (recycled) both were deformed outwards from the center of the part, while EcoPaXX GF (biobased) instead was deformed inwards. It should be noted that all plastics showed the deformation on the same side.

Regarding the evaluation of the temperature cycling, only the scanning of part (E) could be performed in time, and gave no notable differences between the before and after of each plastic.



(a) (b)

Figure 30: In a) the scanned part (E) can be seen for the three categories of plastics, with conventional on the top, followed by recycled and in the bottom, the biobased. The highest deviations are for the biobased plastic, for which the highest is -0.655 mm around the center of the part. (b) shows the equivalent setup but for part (A). Here all plastics show quite severe deviations, especially around the section in top left, with the conventional and biobased having ∼1 mm deviations, and the recycled at most having ∼0.77 mm deviations. A larger version can be found in Appendix C.

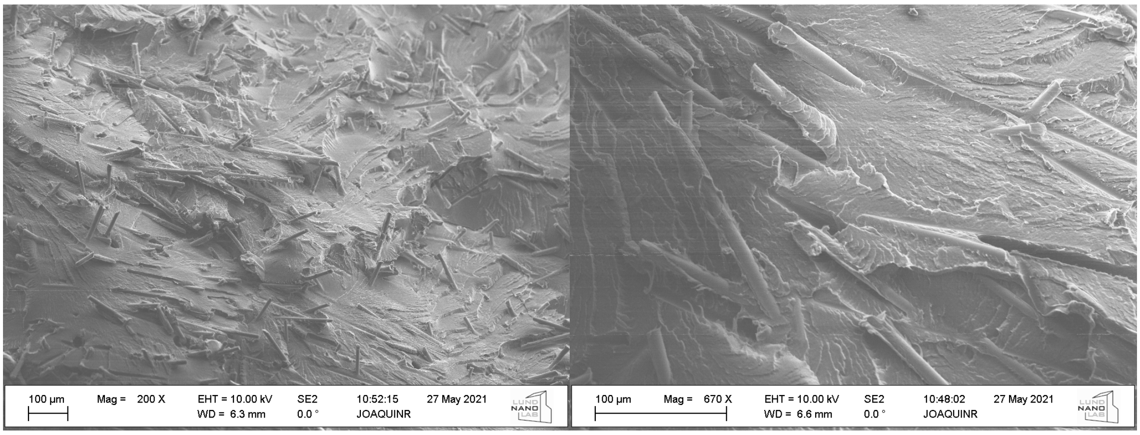
6.1.6 Fracture surfaces in SEM

The images had some issues with interference and static, but were sufficiently clear to analyse. The images from the conventional plastic can be seen in Figure 31, the recycled in Figure 32, and the biobased in 33.

The sample in the conventional plastic appeared to have a rather wide distribution of orientations of the fibers, and the fracture has left many fibers still protruding from the surface, probably having been broken and suffered pull-out from the matrix. The fracture surface's topology in general was quite even.

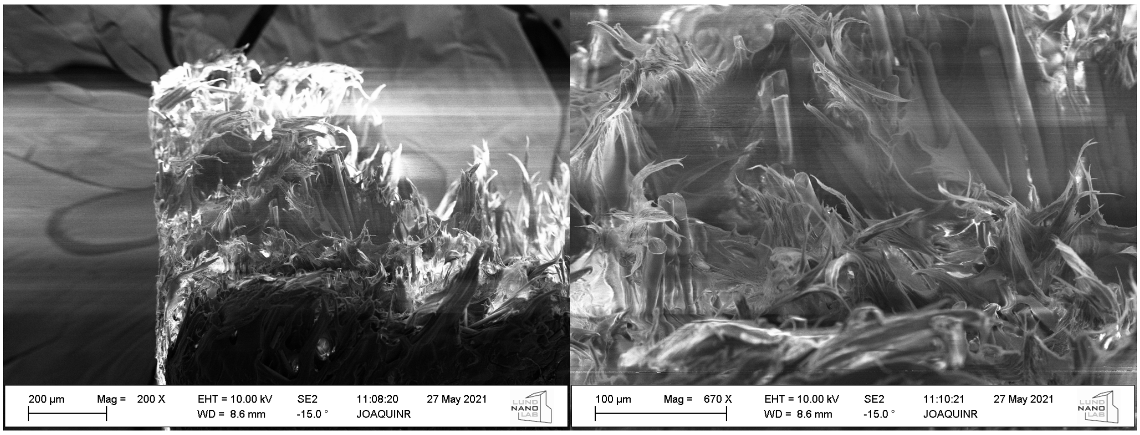
For the sample in recycled plastic, the case was quite different. The directionality of the fibers was more prominent, and the surface of the fracture was rough with elongated tendrils of plastic shooting out of it.

The biobased plastic sample also showed more directionality of the fibers, but also a topography without tendrils not other particular artifacts. Pull-out of the fibers can be noted, both in the remaining protruding fibers, as well as from some of the cavities where fibers have left the matrix.



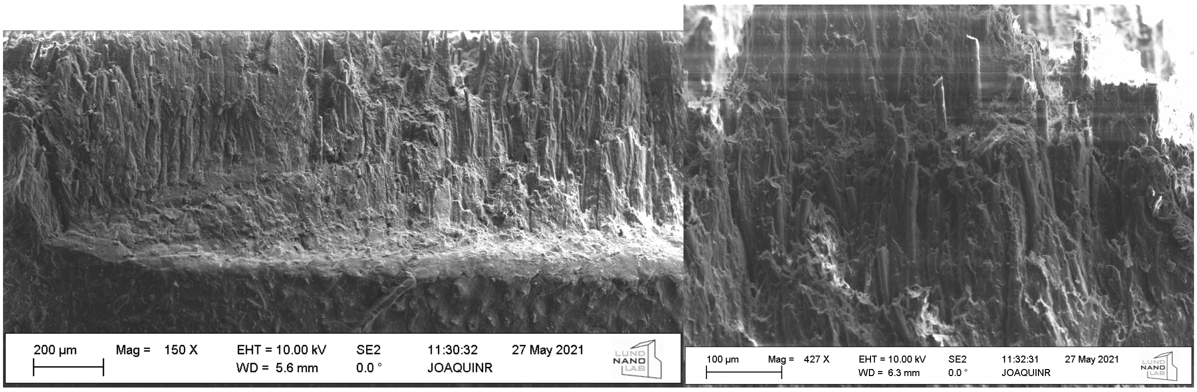
(a) (b)

Figure 31: Two SEM images of the fracture surface of part (A) in conventional plastic (PBT+GF) at 200x and 670x magnification.



(a) (b)

Figure 32: Two SEM images of the fracture surface of part (B) in recycled plastic (PBT/PET+GF) at 200x and 670x magnification. The bright distortions in a) are due to the sample getting charged up.



(a) (b)

Figure 33: Two SEM images of the fracture surface of part (A) in biobased plastic (PA410+GF) at 150x and 427x magnification. The bright distortions in b) are due to the sample getting charged up.

6.2 Production issues

Some parts had some defects caused in production, as can be seen in Figure 34, where it is clear that two specimen of part (D) in the biobased plastic have suffered from blush. These two were the only ones that manifested this phenomenon.

(a) (b)

Figure 34: Here, so-called "blush" can be seen in two specimens of part (D) in biobased plastic. This was caused in production, and was not discovered in any other parts in any other plastic apart from these two.

6.3 LCA: Inventory analysis

The four processes: transport, production, manufacturing and end-of-life, and the calculated result of their impact is presented in the following sections.

6.3.1 Transport

The objective with the LCA is to be able to compare the plastics. This implies that transport that is the same for all types of plastic is not as interesting as where it differs. The transport steps that have been considered in this analysis are as follows:

- Pellet factory to molding factory
- Molding factory to Electronics Manufacturing Services (EMS)
- EMS to a logistic centre (CLC)
- CLC to distributor

The plastic pellets used by the molding company are produced at different sites around Asia and are then transported to the molding factory by boat and truck, or only by truck. This is the only distance that is unique for each type of plastic. The transport steps and the corresponding type of transport are listed in Appendix B, as well as the calculations for all transport steps. An extra 5% of weight has been added in the first transport step as it has been assumed that the yield of the production is not 100%. The total environmental impact from the transport phase for the two categories are shown in Table 6.

Table 6: The energy usage (MJ/fU) and carbon footprint(g CO_2/fU) from the transport of all plastics per fU.

Plastic	Footprint (g CO_2-eq)	Energy (MJ/fU)
Valox	259	3,59
Schuladur	284	3,94
EcoPaXX GF	261	3,63
Cycoloy	220	3,06
Infino	211	2,93
EcoPaXX	215	2,98

6.3.2 Plastic pellet production

The energy needed for the production of the plastics and the related CO_2-emissions are shown in Table 7. There is a clear difference between the conventional plastics, Valox and Cycoloy, and the more sustainable alternatives, especially when it comes to carbon footprint. The energy usage is highest for the biobased plastics, where a lot of energy is needed for the cultivation of castor beans. The reinforced plastics have a larger impact for all types of plastics.

Table 7: The resulting energy usage (MJ/fU) and carbon footprint(g CO_2/fU) from the plastic pellet production per fU.

Plastic	Footprint (g CO_2-eq)	Energy (MJ/fU)
Valox	235	4,7
Schuladur	121	2,4
EcoPaXX GF	140	10,3
Cycoloy	207	4,2
Infino	88	1,9
EcoPaXX	80	8,5

6.3.3 Manufacturing of parts

The results are presented in Table 8. The impact of the process of manufacturing shows little difference between the plastics. The non-reinforced plastics showed a somewhat lower impact in both impact categories.

6.3.4 EOL

The resulting impact from the EOL is presented in Table 9 and visualised in Figure 61. The first scenario has a high percentage, 95%, of material being incinerated, which leads to a substantial amount of energy being returned. This also means a lot of CO_2-emissions are getting released into the atmosphere though. The second scenario leads to a higher energy return for the plastics without fiber reinforcement,

Table 8: The total energy usage (MJ/fU) and carbon footprint(g CO_2/fU) from the manufacturing of the parts.

Plastic	Footprint (g CO_2-eq)	Energy (MJ/fU)
Valox	70	0,93
Schuladur	79	1,05
EcoPaXX GF	71	0,95
Cycoloy	60	0,81
Infino	61	0,82
EcoPaXX	60	0,81

and EcoPaXX exhibits the biggest difference in saving of energy due to the recycling. In general, the first scenario leads to the highest emissions of CO_2 while scenario 2 has a higher energy return. The third scenario has almost no effect on the chosen impact categories.

Table 9: The resulting energy usage (MJ/fU) and carbon footprint(g CO_2-eq/fU) for the three EOL scenarios. Scenario 1: 95% incinerated and 5% in a landfill. Scenario 2: 33% recycled, 42% incinerated and 25% in a landfill. Scenario 3: 100% landfill. A negative sign means a saving in energy due to energy generated when the plastic is being incinerated or due to less energy needed when a plastic is being recycled.

	Scenario 1		Scenario 2		Scenario 3	
	Energy (MJ/fU)	Footprint (g CO_2-eq)	Energy (MJ/fU)	Footprint (g CO_2-eq)	Energy (MJ/fU)	Footprint (g CO_2-eq)
Valox	-0,68	75	-0,53	59,3	0,009	0,68
Schuladur	-0,71	81	-0,56	63,7	0,010	0,74
EcoPaXX GF	-0,78	70	-0,61	55,0	0,009	0,67
Cycoloy	-0,95	95	-1,33	75,4	0,008	0,57
Infino	-1,10	111	-1,30	9,1	0,008	0,55
EcoPaXX	-0,91	90	-2,23	37,3	0,008	0,55

6.4 LCA: Impact Assessment

The compilation of impacts from the four processes: transportation, production, manufacturing and EOL, is shown in Table 10 with a visual representation in Figure 35 and 36. EOL scenario 2 is used for the compilation and can be seen as the part of the bars below zero for the energy usage, since it results in energy being returned. A comparison of the effects from all the EOL scenarios can be seen in Figure 61. The process production of pellets, offers the biggest variance in impact between the plastics and can be seen in itself in Figure 37.

Table 10: The total impact from all processes with scenario 2 chosen for the EOL of the material.

Plastic	Footprint (g CO_2-eq)	Energy (MJ/fU)
Valox	622	8,7
Schuladur	547	6,9
EcoPaXX GF	527	14,3
Cycoloy	563	6,7
Infino	369	4,3
EcoPaXX	393	10,0

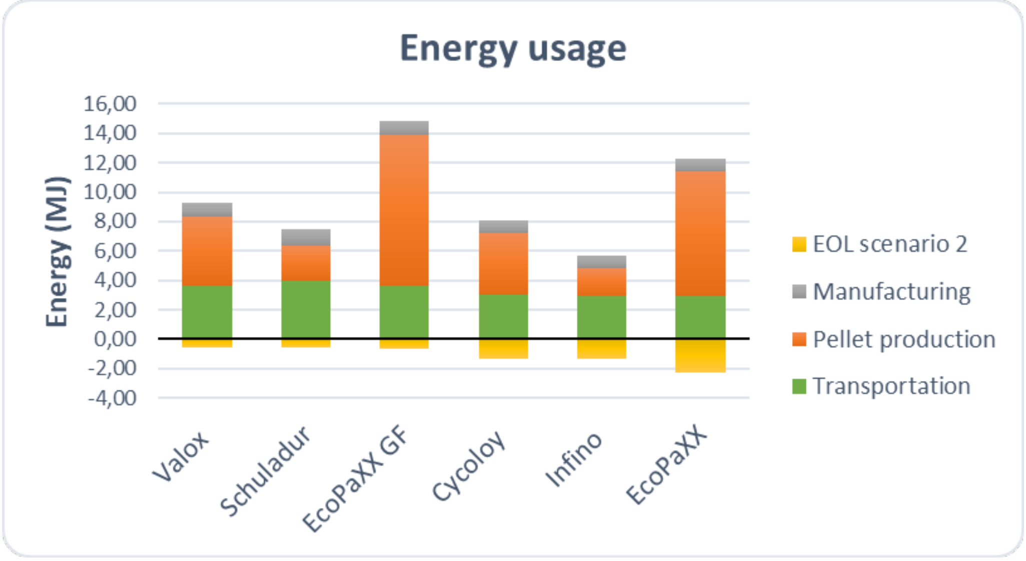


Figure 35: The impact for the energy usage category, showing the impact from each of the processes.

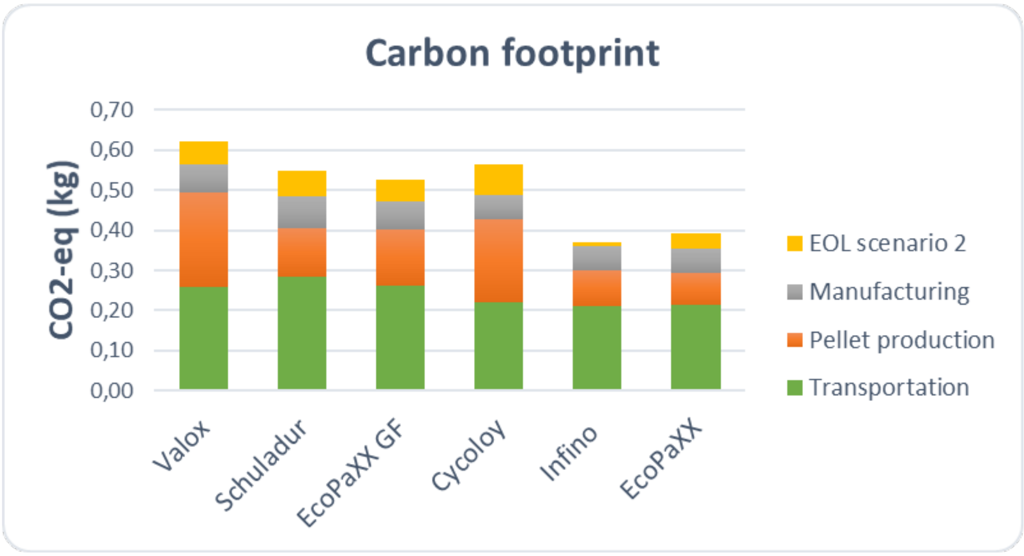


Figure 36: The impact for the carbon footprint category, showing the impact from each of the processes.

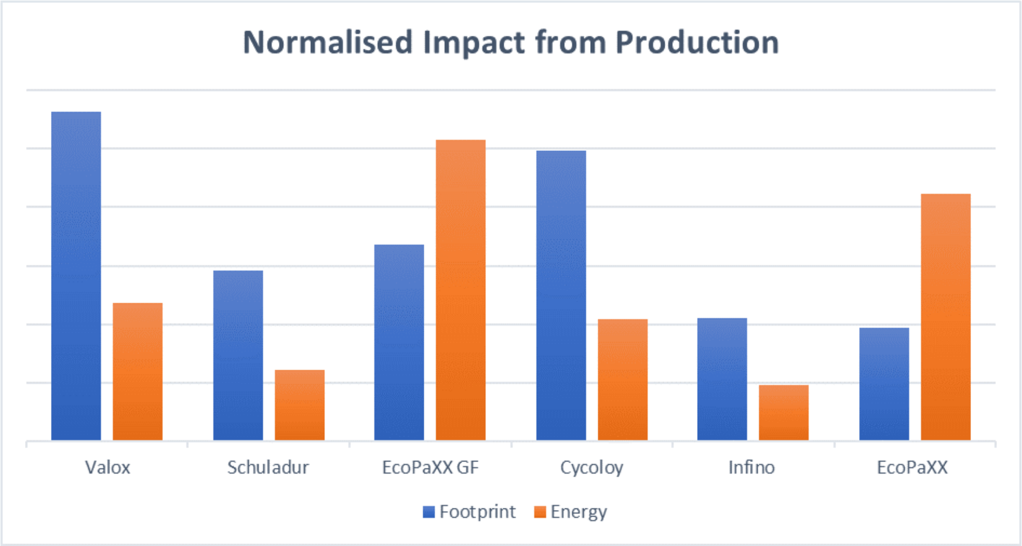


Figure 37: The comparative result from both impact categories when only production of pellets is considered.

7 Discussion

7.1 Material properties

7.1.1 Mechanical stability

The results of the compression test on part (E) showed that both the conventional and the recycled plastics fare better than the biobased. The biobased PA410 is semi-crystalline and thus stiffer than both the conventional and the recycled amorphous PC/ABS blends. The stiffness of the biobased plastic can be noted in Figure 16, where it shows a higher value of force required to reach the same distance as the other plastics. It also appears to be more brittle, which is seen with the sudden decrease of force at ∼65 s in the aforementioned figure, where the biobased plastic suffers the brittle failure of which the effects can be seen in Figure 17c. This could be used as an argument against the biobased plastic, but the force at which it breaks, at around 900 N on average, is considerably higher than what the part would suffer when in use or even subjected to during normal product testing, indicating that the part could in fact be good enough.

The subassembly compression test showed that all setups failed in some way before reaching 1 kN of force. The conventional and recycled plastics failed in a similar way, with the ridge seen in Figure 19a cracking and alleviating the stress caused by the widening of the part further up. It is interesting here to note that the biobased setup did not suffer these cracks, but instead continued to deform under the pressure for a little longer before failing catastrophically, in a similar way to the compression test on part (E). For the instances where the "ear" cracked or got entirely detached, as seen in Figure 20a and 20c, the damage occurred on the same side of the part each time, indicating the possibility of an asymmetry in the part. This theory is reinforced when observing the 3D-scanned representation of the part in Figure 30b, where the dimensional deviations inwards are significantly more prominent on the side seen in red in the figure, which is the same side as where the failures occur.

The conventional and recycled plastics in turn showed a tendency of deformation outwards in the 3D scans, meaning they were probably under some tensile stress already when part (B) was fastened. These different initial conditions could affect how the forces were then distributed through the subassembly during the test.

When evaluating the various ways of failure, the conventional and recycled subassemblies' way of failing was to prefer over that of the biobased one, since the cracks would not affect the product's function, while the failure of the biobased one would render the product quite useless. It should be noted, as with the compression test only on part (E), that the forces used were excessive when put into contrast to what the product could actually be exposed to in use, considering it would have a protective dome surrounding it. The tests show that all setups would be capable of enduring the realistic forces they could be exposed to, and then some.

The impact tests without the protecting dome were also quite excessive when considering the protective dome normally surrounding the parts, preventing contact except for the most unfortunate or hard impacts. Still, it was interesting to evaluate the difference between plastics since the results could be transferable to other products. All three setups endured the IK7 with no damages more than some marks where the weight hit. This IK level would probably reflect the energy transferred to the parts in the case where the protective dome might flex and come into contact with the parts, indicating that they all should manage when in use. The IK8 test's results were more interesting, where the recycled setup was vastly superior than the other two in how it took minimal damage from the tests. For all plastics, the damage was limited to part (A), and for the conventional and biobased, also the back of part (C). The damage on part (C) was clearly due to the last direct hit to the back of it, where slender bars form a grate. The bars in the middle had broken in half due to the force of the impact. For the failure of part (A), the transferral of force went through the cone-shaped part to the bottom of it, where it was concentrated and sufficient to cause a failure.

For the recycled part, no more than a small crack was found at the bottom of the part, which would not have been noticed if the subassembly had not been disassembled. For the other two plastic sets, the damage was more substantial. The cracks in the conventional plastic ran through vital parts of the product, around where part (A) was attached to part (E), and in one case all the way to the edge of the part, as can be seen in Figure 21. These damages would not have been acceptable for continued use. The same applies to the biobased set, where like in the compression test, an "ear" came off. The ear was opposite to where the second impact hit, and most probably could not handle the forces which were transferred to it at impact.

Since the project budget only allowed for one set of complete IK tests with brand new products, and the compiled results indicated that the recycled plastic had endured the tests with the least damage, it was chosen for the final mechanical tests. In short, the test was passed with no major complications. All the plastic parts were intact, some screws loosened but the camera remained fully functional. Something which was noted was a color change in the output feed after some of the impacts, but these were all remedied by restarting the product. It turns out this problem is due to an IR-filter in the optical unit which sometimes moves a little at an impact, but resets when the product restarts, so it does not permanently affect the functionality of the product.

The results of the SEM imaging were interesting in that they were so varied. The varied directions of the glass fibers in the conventional plastic could be attributed to the molding process, where the plastic at the location from which the sample was taken might have not flowed unidirectionally during molding. The even surface suggests the fracture was brittle, which is in line with that is was caused by an impact, i.e. a large force over a very short amount of time. The recycled plastic on the other hand seemed to have suffered a ductile fracture, where the plastic almost seemed to have flowed out from the surface as the fracture widened. The fibers seem to mostly be in the same direction, probably due to the sample being a slender rod where the plastic has only flowed in one direction. The noise in the image, the bright features in Figure 32a, could have probably been avoided if the sample had been sputtered with either a thicker layer of Pd/Pt, or been placed with the fracture surface pointing up during sputtering. The biobased plastic also showed glass fibers pointing in the same direction, and the smooth surface which characterizes a brittle fracture.

The blushing that was observed was considered an isolated occurrence, and thus was not something that was further investigated.

7.1.2 Aging & degradation

Regarding the tests determining the effect of thermal aging, the results are inconclusive. The parts reacted in a very similar way to the un-aged parts, and the insecurities of the graphs from the compression tests are larger than any difference which could be noted. It should be mentioned that the aging was stopped ahead of time by approximately one week of six planned weeks, due to lack of time. If this additional week would have changed the outcome is beyond this project, but a conservative estimation would suggest it would not do a significant difference.

The organic oil test gave more interesting results. It was assumed that since the biobased plastic was highly semi-crystalline, it would not be affected to the same extent by the oil and stress, if even at all. For the strung up part (D), this was accurate. Both the conventional as well as the recycled plastics had cracked at the edge on one side, greatly alleviating the stress it was under. Both cracked on the same side, and upon closer inspection, the weld lines from the injection molding seems to coincide with the location of the cracks, indicating a weak spot. The biobased part showed no intention of cracking, and seemed to have been unaffected by the test other than partly maintaining the deformed shape acquired by being placed in the fixture.

When observing the screw holes of part (E) though, a different result was seen. The recycled plastic showed little cracking, with the few cracks that were found being singular but deep. The conventional plastic suffered, in addition to similar cracks as the recycled, from a multitude of interconnected fine cracks around the screw hole, which would probably not have been visible if not for the oil moving into them or getting pushed out when the plastic was slightly bent, but surely affected its mechanical properties in a deteriorative fashion. The cracks which the biobased plastic suffered were not as wide as the cracks from the recycled, but more frequent and as long. It also showed smaller cracks concentrated around the screw hole, which showed that also the semi-crystalline PA410 was sensitive to ESC.

The temperature cycling gave no clear result, which in part can be explained by the fact that not the exact same parts were used for the before and after, and part (E) was not under any notable stress, leaving little if any difference between the images. If part (A) had been scanned it might have showed some deformation, but that will not take part in this report. An interesting thing, unrelated to the temperature cycling, was that the non-reinforced biobased plastic showed a significant shrinkage, as could be seen in Figure 30a. This was somewhat noted when assembling the product too, that the screw holes for part (E) sometimes seemed a little misaligned, as well as part (C) being considerably more difficult to snap on for the biobased plastic than the others. This second example could also in part at least be explained by the biobased plastic being stiffer, and thus more difficult to snap on. Part (D) was also more difficult to attach, but these problems could probably be remedied by changing the parameters in the injection molding machine to accommodate for the shrinkage.

7.1.3 Sources of error

As mentioned in the discussion, the performed tests were quite excessive and would not be a realistic representation of the forces which the parts would be exposed to during normal use. The final IK test is the toughest mechanical test normally done on this kind of product, and is less severe than several of the tests done in this project. One should therefore be careful to draw conclusions regarding predictions on how the alternative plastics would perform in a real case scenario.

The injection molding process is a factor that might have affected the test results, since all parts were injection molded using molds primarily built and optimised for the conventional plastics. The various types of plastics in the study have different molding properties, such as degree of shrinkage when cooled, and thus need the parameters of the machine adjusted accordingly. The biobased plastic is relatively new in the molding factory and the parameters may not yet have been fully optimised. As seen by the 3D-scanning, especially the biobased plastic had a large deviation in dimensions compared to the model, which could affect the mechanical tests in multiple ways. It could lead to different initial stresses, worse fit between parts, and defects. Some parts demonstrated initial defects such as discoloration, whitening and other blemishes. These defects most probably arose during manufacturing, and may be fixed with optimised parameters. Also, if blemishes only are an aesthetic problem, the plastic could still be used if it is coated.

Another possible source of errors is the low number of replicate tests used. For most mechanical tests, only two or three replicate tests were performed due to lack of resources and time, and while the results did not vary significantly, it is possible that they were outliers.

In addition, the method for positioning the setup for the IK-tests was quite rudimentary, and the weight may have hit on slightly different spots, and sometimes twice due to the weight bouncing off the assembly and hitting again. This should not have made any considerable difference though, since the second impact was much weaker.

The exact composition of the plastics was unknown, as for example if the blends were single phase or multiphase, the ratio of polymers in the blends, as well as the aspect ratio of the fibers in the fiber-reinforced plastics, and that has made it difficult to relate the result to the individual properties of the polymers.

As for the SEM imaging part, the samples were not as similar as they could have been which made it difficult to draw comparative conclusions. The samples could instead have been fractured in the same way and in about the same place, perhaps by notching them beforehand. This was somewhat experimented with, but it was difficult to replicate the fracture with the same plastic twice. It appeared to suffer a brittle failure during one try, and a ductile failure the following try, so it was decided that fractures which had already been caused by the tests to be investigated, even though it would make it difficult to compare the plastics.

7.2 LCA: Interpretation

The relative difference between the results, presented in section 6.4, is shown in Table 11. Comparing the reinforced with the non-reinforced plastics has little meaning since they are mostly used in different applications. The conventional plastic is used as the reference and the chosen significance level was 20%. With that level, no significant difference could be seen between the reinforced plastics Valox, Schuldadur and EcoPaXX GF, regarding the total carbon footprint. A significant difference exists however between the non-reinforced plastics in the carbon footprint, and for all plastics in the energy category.

Table 11: The relative difference in the total impact of the two categories, with the conventional plastic as the reference.

	Valox	Schuladur	EcoPaXX GF	Cycoloy	Infino	EcoPaXX
Footprint	Ref	-12%	-15%	Ref	-34%	-30%
Energy	Ref	-21%	+63%	Ref	-35%	+49%

When examining each of the four processes in the life cycle one by one, it becomes evident that the impact does not change much between the plastics for some of the processes. Manufacturing for example, here the primary energy and carbon footprint associated differs only slightly, which is probably explained by the higher density, and thus mass, of some of the plastics. The impact from manufacturing is about 15% of the total impact and thus not small enough to be removed due to the cut-off criteria. However since this is a comparative analysis, processes where the difference in impact is too small do not need to be part of the analysis. If the conventional FRPCs, Valox, is seen as a reference then the recycled plastic has a 13% higher impact and the biobased only 2% higher, regarding manufacturing. For the non-reinforced this difference is even smaller, the plastics impact is distinguishable by only one percentage, which means that it could be excluded from analysis.

Transportation is the largest contributor to the footprint but the difference there might mainly be due to the density. Schuladur has the highest density and consequently also the biggest impact. Another factor that varies between the plastics is the location of the production. All production sites are located in Asia, but Infino has to travel the greatest distance to arrive at the manufacturing facility in China. However, the step responsible for the biggest impact is not the first step from pellet factory to molding factory, but the one where the parts are transported by air fright from Asia to Europe or USA. That type of transportation has a seven times higher energy use than by truck.

For the purpose of making a sensitivity check another transportation scenario was explored: how the impact would be affected if production of pellets and manufacturing of parts were located in Europe. The resulting impact for the scenario and the percentual change on the total is presented in Table 12, with corresponding calculations in Appendix B. By moving production and manufacturing to Europe the impact from transport decreased with approximately 59% for each plastic which resulted in a decrease of around 30 % in the total impact. However since they all decreased with the same percentage it does not affect the comparison of the impact between the plastics. Infino was the one to experience the biggest effect, which is probably due to it having the lowest impact overall and therefore having transport as a bigger contributor.

Table 12: The scenario where both production and manufacturing is being located in Europe instead of Asia. The table displays the energy usage (MJ/fU) and carbon footprint(g CO_2/fU) from all plastics per fU and the effect that change in impact has on the total impact of each plastic.

	New impact, transport		Percentual change on total impact	
	Footprint (g CO_2-eq)	Energy (MJ/fU)	Footprint	Energy
Schuladur	116	1,62	-31%	-34%
Infino	86	1,20	-34%	-40%
EcoPaXX GF	105	1,46	-30%	-15%
EcoPaXX	86	1,20	-33%	-18%
Valox	106	1,47	-25%	-24%
Cycoloy	90	1,25	-23%	-27%

A different way to measure the sensitivity of the model is to examine how the initial parameters influence the end result. For example, if the pellet production impact was to increase by 20% it would influence the result in the way presented in Table 13. The relationship between the impact of a processes and the end result is linear, which means that changing the impact of one of the processes will result in a very predictable change. The sensitivity of the processes was therefore assumed to be equal.

Table 13: The percentual change in total impact as a result of a 20% increase in impact from pellet production.

	Valox	Schuladur	EcoPaXX GF	Cycoloy	Infino	EcoPaXX
Footprint	7,5%	4,4%	5,3%	7,3%	4,8%	4,1%
Energy	10,9%	7,1%	14,4%	12,5%	8,7%	16,9%

The two biobased plastics, EcoPaXX with and without GF, stand out in a negative way with a much higher amount of energy needed for production of the pellets. EcoPaXX GF has almost twice the energy use compared to the other plastics. It could be a result of the farming of the raw material or the fact that the polymerisation reactions needs a lot of energy. However, no evidence could be identified to back up these theories and the data will be regarded as questionable.

Biobased plastics present advantages over non-biobased plastics that are not being taken into consideration in this limited LCA. Foremost, biobased plastics are derived from renewable sources and no fossil based material is needed. Fossil fuels are a non-renewable resource, and may not be sustainable to use in the long run, in addition to polluting the environment and releasing more CO_2 into the atmosphere. Biobased plastics may in part avoid this by the plant acting feedstock absorbing CO_2 and becoming carbon neutral. On the other hand, cultivation of the raw material requires land, which could result in production of biobased plastics competing with growing of produce. This is another negative aspect that the limited LCA does not cover.

A conclusion that can be drawn from the result presented and the discussion above is that the production of pellets is the most interesting process. It has the next biggest influence on the total impact and it also has the biggest variance between plastics. It has less dependence on the density and the accuracy is as good as from the other data acquired from Edupack. The result in Figure 37, consider only the impacts from the production of pellets. The graph shows that the recycled plastics, Schuladur and Infino have the smallest impact when considering both categories and is thus also the best alternative when considering the environmental impact. The biobased plastics however, still have a significantly lower carbon footprint than the conventional plastics, and could also be a viable alternative.

7.2.1 Sources of error

The main issue with the assessment is the origin of the data for the model. EduPack is a limited software and not designed to perform elaborate LCAs. The data was difficult to validate and the underlying calculations and assumptions are not completely known. The significance level of 20% is a way to counteract this uncertainty but the analysis could have greatly benefited from more reliable sources. The performed LCA is very simplified, and access to more substantial data could have generated an assessment that covered more environmental aspects of the materials. It could very well affect the end result significantly.

Another issue is with the EOL scenarios and their connection to the recyclability of the plastics. Most of the plastics used in this kind of applications are engineered plastics and various blends, all belonging to plastic group 7. The assumption that some of these plastics can be recycled is an idealisation of the current global situation, but there are still promising outlooks that it might be possible in a not-too-far future, when the recycling technologies have matured.

8 Conclusion

The mechanical tests showed that the recycled plastics were unanimously superior to the biobased, and even the conventional plastic, and thus, if economical and aesthetic matters allow, should be used. However, just because the biobased plastic did not perform as well in the tests does not mean it is not good enough, and it should be taken in consideration when performing a material selection in the development phase.

From an environmental point of view the recycled plastic was also the best candidate, having the lowest impact in both categories used in the LCA, but as with the mechanical tests, the biobased was not to be discarded so easily. The biobased was still better than the conventional plastic, especially in the carbon footprint category.

The transport was one of the largest contributors of environmental impact, and by for example producing the plastics and manufacturing the parts in Europe instead of China, the impacts could be reduced by ∼30%.

To sum up and visually display the results that were evaluated, a radar chart was used, as seen in Figure 38. The recycled plastic showed the best result overall while the biobased performed better in the ESC category and equally good in the total CO_2 category.

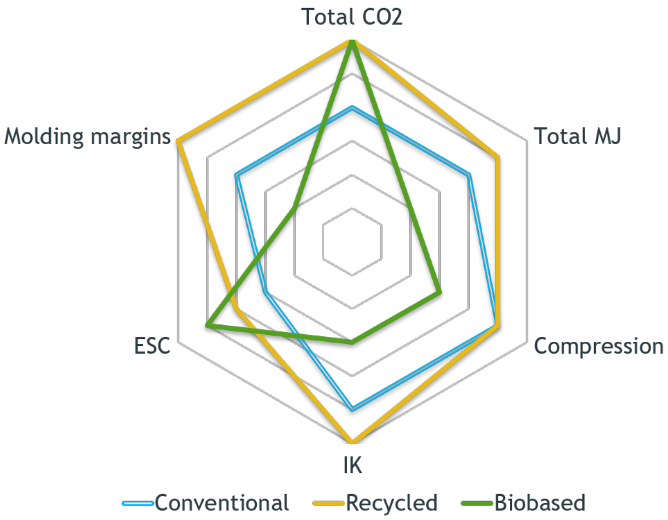


Figure 38: A radar chart summing up the performance of the conventional, recycled and biobased plastics.

8.1 Outlook

Due to the time aspect and economical limitations in this project, not all aspects that initially were thought of could be explored. For example, the plastics chosen were limited to those that were currently available to the company at which the project was performed. In part these were probably some of the more promising plastic for this particular application, but a broader exploration of the alternatives could have been performed, also evaluating biobased direct equivalents of the conventional plastics.

The tests that were performed were of a comparative nature in part due to the lack of availability of dog bone test samples and appropriate testing equipment for performing a Charpy or Izod impact test. It could be interesting to perform these tests to confirm the material properties of the plastics.

Since the tests were of a more applied nature, as the plastics were parts in a product, an initial FEM analysis could have been used to predict the behavior of the parts under any given stress conditions. This could optimise the test process so that tests on individual parts or smaller subassemblies were adapted to more accurately represent the relevant stresses in the complete product.

With better resources and more suitable software, a more elaborate LCA with more impact categories present could have been performed, which would have provided a wider picture on the environmental impact. For the purpose of lowering the environmental burden from the product one might also want to include all aspects of the product's life cycle, so that the benefits of choosing an alternative material could be put into relation to other possible efforts to decrease the environmental impact.

The EOL proved to be difficult to model and a way to make sure that the product and its parts are being handled in an adequate way is to expand the product circularity. It can be done by taking responsibility for the products when they have served their time and for instance collect all used products and recycle what can be recycled. That would put the producer of the product in control of the EOL which makes decreasing the environmental impact a much easier task.

Economical aspects were not considered in this project, but should be evaluated as the required volumes of the chosen alternative plastic increases, since the price would then go down.

References

[1] T. M. Letcher, "Chapter 1 - introduction to plastic waste and recycling," in *Plastic Waste and Recycling*, T. M. Letcher, Ed., Academic Press, 2020, pp. 3–12, ISBN: 978-0-12-817880-5. DOI: `https://doi.org/10.1016/B978-0-12-817880-5.00001-3`. [Online]. Available: `http://www.sciencedirect.com/science/article/pii/B9780128178805000013`.

[2] (2018). "Beat plastic pollution," [Online]. Available: `https://www.unenvironment.org/interactive/beat-plastic-pollution/` (visited on 01/28/2021).

[3] E. Kosior and J. Mitchell, "Current industry position on plastic production and recycling," in. Jan. 2020, pp. 133–162, ISBN: 9780128178805. DOI: `10.1016/B978-0-12-817880-5.00006-2`.

[4] European Parliament, "Plastic waste and recycling in the eu: Facts and figures," 2018. [Online]. Available: `https://www.europarl.europa.eu/news/en/headlines/society/20181212STO21610/plastic-waste-and-recycling-in-the-eu-facts-and-figures`.

[5] A. K. Frederiksen. (2018). "Quality of recycled plastic too poor," [Online]. Available: `https://www.dtu.dk/english/news/2018/11/quality-of-recycled-plastic-too-poor??id=fba6a830-9bc0-41d7-85e8-956b7cb3d1ef` (visited on 06/14/2021).

[6] J. Cowie and V. Arrighi, *Polymers: Chemistry and Physics of Modern Materials*, English, 3rd. US: Taylor & Francis Group, 2007, ISBN: 978-1-4200-0987-3.

[7] SpecialChem. (2021). "Acrylonitrile butadiene styrene (abs) and its features," [Online]. Available: `https://omnexus.specialchem.com/selection-guide/acrylonitrile-butadiene-styrene-abs-plastic` (visited on 02/03/2021).

[8] SpecialChem. (2021). "Polyamide (pa) or nylon: Complete guide (pa6, pa66, pa11, pa12. . .)," [Online]. Available: `https://omnexus.specialchem.com/selection-guide/polyamide-pa-nylon#PA6` (visited on 02/03/2021).

[9] "Zero carbon footprint claimed for new plastic," *Sealing Technology*, vol. 2009, no. 9, p. 4, 2009, ISSN: 1350-4789. DOI: `https://doi.org/10.1016/S1350-4789(09)70479-9`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S1350478909704799`.

[10] SpecialChem. (2021). "Complete guide on polybutylene terephthalate (pbt)," [Online]. Available: `https://omnexus.specialchem.com/selection-guide/polybutylene-terephthalate-pbt-plastic#Properties` (visited on 02/02/2021).

[11] SpecialChem. (2021). "A complete guide to polycarbonate (pc))," [Online]. Available: `https://omnexus.specialchem.com/selection-guide/polycarbonate-pc-plastic` (visited on 02/03/2021).

[12] L. A. Utracki and s. SpringerLink (Online, *Polymer Blends Handbook. [Electronic resource]*. Springer Netherlands, 2014, ISBN: 9789400760639. [Online]. Available: `http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat07147a&AN=lub.5672930&site=eds-live&scope=site`.

[13] SpecialChem. (2021). "Polyethylene terephthalate (pet): A comprehensive review," [Online]. Available: `https://omnexus.specialchem.com/selection-guide/polyethylene-terephthalate-pet-plastic` (visited on 02/03/2021).

[14] M. Nofar and H. Oğuz, "Development of pbt/recycled-pet blends and the influence of using chain extender," *Journal of Polymers and the Environment*, vol. 27, no. 7, pp. 1404–1417, Jul. 2019, ISSN: 1572-8919. DOI: `10.1007/s10924-019-01435-w`. [Online]. Available: `https://doi.org/10.1007/s10924-019-01435-w`.

[15] S. K. Gopalraj and T. Kärki, "A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: Fibre recovery, properties and life-cycle analysis.," *SN Applied Sciences*, vol. 2, no. 433, 2020. DOI: `https://doi.org/10.1007/s42452-020-2195-4`.

[16] L. Scelsi, A. Hodzic, C. Soutis, S. A. Hayes, S. Rajendran, M. A. AlMa'adeed, and R. Kahraman, "A review on composite materials based on recycled thermoplastics and glass fibres," *Plastics, Rubber and Composites*, vol. 40, no. 1, pp. 1–10, 2011. DOI: `10.1179/174328911X12940139029121`. eprint: `https://doi.org/10.1179/174328911X12940139029121`. [Online]. Available: `https://doi.org/10.1179/174328911X12940139029121`.

[17] J. Fried, *Polymer Science and Technology*, 2nd ed. Pearson Education, 2003, ISBN: 0130181684.

[18] D. Bryce, *Troubleshooting: A Guide for Injection Molders*. Techtrax, 2001, ISBN: 9780970519603. [Online]. Available: `https://books.google.se/books?id=-MC%5C_AAAACAAJ`.

[19] Y. Yang, X. Chen, N. Lu, and F. Gao, "1 - injection molding: Background," in *Injection Molding*, Y. Yang, X. Chen, N. Lu, and F. Gao, Eds., Hanser, 2016, pp. 1–37, ISBN: 978-1-56990-592-0. DOI: `https://doi.org/10.3139/9781569905937.001`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/B9781569905920500028`.

[20] I. Ignatyev, W. Thielemans, and B. Vanderbeke, "Recycling of polymers: A review," *ChemSusChem*, vol. 7, May 2014. DOI: `10.1002/cssc.201300898`.

[21] F. M. Lamberti, L. A. Román-Ramírez, and J. Wood, "Recycling of bioplastics: Routes and benefits," *Journal of Polymers and the Environment*, vol. 28, pp. 2551–2571, 2020, ISSN: 1572-8919. DOI: `https://doi.org/10.1007/s10924-020-01795-8`.

[22] N. Rudolph, R. Kiesel, and C. Aumnate, "3 - plastics recycling—conservation of valuable resources," in *Understanding Plastics Recycling (Second Edition)*, N. Rudolph, R. Kiesel, and C. Aumnate, Eds., Second Edition, Hanser, 2020, pp. 15–46, ISBN: 978-1-56990-846-4. DOI:

https://doi.org/10.3139/9781569908471.003. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9781569908464500047.

[23] A. Dorigato, “Recycling of polymer blends,” *Advanced Industrial and Engineering Polymer Research*, vol. 4, no. 2, pp. 53–69, 2021, Recycling of Polymer Blends and Composites, ISSN: 2542-5048. DOI: https://doi.org/10.1016/j.aiepr.2021.02.005. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2542504821000130.

[24] S. Karuppannan Gopalraj and T. Kärki, “A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: Fibre recovery, properties and life-cycle analysis,” *SN Applied Sciences*, vol. 2, no. 3, p. 433, Feb. 2020, ISSN: 2523-3971. DOI: 10.1007/s42452-020-2195-4. [Online]. Available: https://doi.org/10.1007/s42452-020-2195-4.

[25] D. S. Cousins, Y. Suzuki, R. E. Murray, J. R. Samaniuk, and A. P. Stebner, “Recycling glass fiber thermoplastic composites from wind turbine blades,” *Journal of Cleaner Production*, vol. 209, pp. 1252–1263, 2019, ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2018.10.286. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652618333195.

[26] P. S. Leevers, “Impact strength,” in *Mechanical Properties and Testing of Polymers*, G. M. Swallowe, Ed. Springer, Dordrecht, Netherlands, 1999, pp. 127–129, ISBN: 978-94-015-9231-4. DOI: https://doi-org.ludwig.lub.lu.se/10.1007/978-94-015-9231-4_27.

[27] G. M. Swallowe, “Tensile and compressive testing,” in *Mechanical Properties and Testing of Polymers*, G. M. Swallowe, Ed. Springer, Dordrecht, Netherlands, 1999, pp. 242–247, ISBN: 978-94-015-9231-4. DOI: https://doi-org.ludwig.lub.lu.se/10.1007/978-94-015-9231-4_52.

[28] T. L. Anderson, *Fracture mechanics : fundamentals and applications.* 4th. CRC, 2017, Accession Number: lub.1275541; Publication Type: Book; Physical Description: xvi, 688 s. : ill.; Language: English, ISBN: 9781498728133. [Online]. Available: http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat07147a&AN=lub.1275541&site=eds-live&scope=site.

[29] L. M. Robeson, “Environmental stress cracking: A review,” *Polymer Engineering & Science*, vol. 53, no. 3, pp. 453–467, 2013. DOI: https://doi.org/10.1002/pen.23284. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/pen.23284. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/pen.23284.

[30] J. Jansen, “Environmental stress cracking - the plastic killer,” *Advanced Materials & Processes*, vol. 162, no. 6, 2004. [Online]. Available: https://www.asminternational.org/news/magazines/am-p/-/journal_content/56/10192/AMP16206P050/PERIODICAL-ARTICLE.

[31] ". R. on the Web (CROW)". (2021). "Impact testing and ductile-brittle transition," [Online]. Available: `http://polymerdatabase.com/polymer%5C%20physics/ImpactTest.html` (visited on 02/16/2021).

[32] R. Yang, "Chapter 7 - polymer degradation and stability," in *Polymer Science and Nanotechnology*, R. Narain, Ed., Elsevier, 2020, pp. 125–148, ISBN: 978-0-12-816806-6. DOI: `https://doi.org/10.1016/B978-0-12-816806-6.00007-8`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/B9780128168066000078`.

[33] D. Wright, *Failure of Plastics and Rubber Products: Causes, Effects and Case Studies Involving Degradation.* Rapra Technology Limited, UK, 2001, p. 400, ISBN: 1-85957-517-X.

[34] A. S. Maxwell, W. R. Broughton, G. Dean, and G. D. Sims, "Review of accelerated ageing methods and lifetime prediction techniques for polymeric materials," National Physical Laboratory, Tech. Rep., Mar. 2005.

[35] K. Akhtar, S. A. Khan, S. B. Khan, and A. M. Asiri, "Scanning electron microscopy: Principle and applications in nanomaterials characterization," in *Handbook of Materials Characterization*, S. K. Sharma, Ed. Cham: Springer International Publishing, 2018, pp. 113–145, ISBN: 978-3-319-92955-2. DOI: `10.1007/978-3-319-92955-2_4`. [Online]. Available: `https://doi.org/10.1007/978-3-319-92955-2_4`.

[36] International Organization for Standardization, *Environmental management: Life cycle assessment: Principles and framework*, 2nd ed., (ISO 14040:2006), 2006. [Online]. Available: `https://www.iso.org/standard/37456.html`.

[37] International Organization for Standardization, *Environmental management: Life cycle assessment: Requirements and guidelines*, 1st ed., (ISO 14044:2006), 2006. [Online]. Available: `https://www.iso.org/standard/38498.html`.

[38] W. Klopffer and B. Grahl, "Introduction," in *Life Cycle Assessment (LCA).* John Wiley & Sons, Ltd, 2014, ch. 1, pp. 1–26, ISBN: 9783527655625. DOI: `https://doi.org/10.1002/9783527655625.ch1`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527655625.ch1`.

[39] W. Klopffer and B. Grahl, "Goal and scope definition," in *Life Cycle Assessment (LCA).* John Wiley & Sons, Ltd, 2014, ch. 2, pp. 27–62, ISBN: 9783527655625. DOI: `https://doi.org/10.1002/9783527655625.ch2`. eprint: `https://onlinelibrary.wiley.com/doi/pdf/10.1002/9783527655625.ch2`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527655625.ch2`.

[40] W. Klopffer and B. Grahl, "Life cycle inventory analysis," in *Life Cycle Assessment (LCA).* John Wiley & Sons, Ltd, 2014, ch. 3, pp. 63–180, ISBN: 9783527655625. DOI: `https://doi.org/10.1002/9783527655625.ch3`. eprint: `https://onlinelibrary.wiley.com/doi/pdf/10.1002/9783527655625.ch3`.

[Online]. Available: `https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527655625.ch3`.

[41] W. Klopffer and B. Grahl, “Life cycle interpretation, reporting and critical review,” in *Life Cycle Assessment (LCA)*. John Wiley & Sons, Ltd, 2014, ch. 5, pp. 329–356, ISBN: 9783527655625. DOI: `https://doi.org/10.1002/9783527655625.ch5`. eprint: `https://onlinelibrary.wiley.com/doi/pdf/10.1002/9783527655625.ch5`. [Online]. Available: `https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527655625.ch5`.

[42] Svenska Institutet för standarder, *Kapslingsklasser för elektrisk materiel: Skydd mot yttre mekanisk påverkan på höljen (IK-beteckning)*, (SS-EN 62262), Oct. 2008.

[43] GOM. (). “Gom– precise industrial 3d metrology,” [Online]. Available: `https://www.gom.com/` (visited on 04/30/2021).

[44] ANSYS, Inc., *Ansys GRANTA EduPack software*, version 21.1.0, Mar. 30, 2021. [Online]. Available: `www.ansys.com/materials`.

[45] RiLong Precision Mold Company. (), [Online]. Available: `http://www.rilong-mold.com/` (visited on 04/22/2021).

[46] Energimyndigheten and SCB, “Electricity supply, district heating and supply of natural gas 2018. final statistics.,” 2018, ISSN: 1654-3661. [Online]. Available: `https://www.scb.se/contentassets/36fb782741284c4590d11d437f515c89/en0105_2018a01_sm_en11sm1901.pdf`.

Appendices

A EduPack data

Valox - PBT+GF virgin

Primary production energy, CO2 and water					
	Lower		Upper	Mean	Unit
Embodied energy, primary production	96,1	-	106	101,05	MJ/kg
CO2 footprint, primary production	4,76	-	5,25	5,005	kg/kg
Processing energy, CO2 footprint & water					
Polymer extrusion energy	5,83	-	6,44	6,135	MJ/kg
Polymer extrusion CO2	0,437	-	0,483	0,46	kg/kg
Polymer molding energy	18,8	-	20,8	19,8	MJ/kg
Polymer molding CO2	1,41	-	1,56	1,485	kg/kg
Coarse machining energy (per unit wt removed)	1,22	-	1,34	1,28	MJ/kg
Coarse machining CO2 (per unit wt removed)	0,0912	-	0,101	0,0961	kg/kg
Fine machining energy (per unit wt removed)	7,88	-	8,71	8,295	MJ/kg
Fine machining CO2 (per unit wt removed)	0,591	-	0,654	0,6225	kg/kg
Grinding energy (per unit wt removed)	15,3	-	16,9	16,1	MJ/kg
Grinding CO2 (per unit wt removed)	1,15	-	1,27	1,21	kg/kg
Recycling and end of life					
Recycle	FALSE				
Recycle fraction in current supply	0,1		0,1	0,1	%
Downcycle	TRUE				
Combust for energy recovery	TRUE				
Heat of combustion (net)	17,9	-	19	18,45	MJ/kg
Combustion CO2	1,64	-	1,72	1,68	kg/kg

Schuladur - PBT+PET+GF recycled

Primary production energy, CO2 and water					
	Lower		Upper	Mean	Unit
Embodied energy, primary production				47,495	MJ/kg
CO2 footprint, primary production				2,35375	kg/kg
Processing energy, CO2 footprint & water					
Polymer molding energy				20,35	MJ/kg
Polymer molding CO2	1,45	-	1,6	1,525	kg/kg
Recycling and end of life					
heat of combustion				17,4825	MJ/kg
combustion CO2				1,64325	kg/kg

EcoPaXX - PA410+GF biobased

Primary production energy, CO2 and water					
	Lower		Upper	Mean	Unit
Embodied energy, primary production	210	-	232	221	MJ/kg
CO2 footprint, primary production	3		3	3	kg/kg
Water usage	8440	-	9330	8885	l/kg
Processing energy, CO2 footprint & water					
Polymer extrusion energy	5,84	-	6,46	6,15	MJ/kg
Polymer extrusion CO2	0,438	-	0,485	0,4615	kg/kg
Polymer extrusion water	4,84	-	7,25	6,045	l/kg
Polymer molding energy	19,3	-	21,4	20,35	MJ/kg
Polymer molding CO2	1,45	-	1,6	1,525	kg/kg
Polymer molding water	12,9	-	19,3	16,1	l/kg
Coarse machining energy (per unit wt removed)	1,8	-	1,99	1,895	MJ/kg
Coarse machining CO2 (per unit wt removed)	0,135	-	0,149	0,142	kg/kg
Fine machining energy (per unit wt removed)	13,7	-	15,2	14,45	MJ/kg
Fine machining CO2 (per unit wt removed)	1,03	-	1,14	1,085	kg/kg
Grinding energy (per unit wt removed)	27	-	29,8	28,4	MJ/kg
Grinding CO2 (per unit wt removed)	2,02	-	2,24	2,13	kg/kg
Recycling and end of life					
Recycle	TRUE				
Embodied energy, recycling	71,6	-	79	75,3	MJ/kg
CO2 footprint, recycling	1,75	-	1,92	1,835	kg/kg
Recycle fraction in current supply	0,672	-	0,742	0,707	%
Downcycle	TRUE				
Combust for energy recovery	TRUE				
Heat of combustion (net)	20,7	-	21,8	21,25	MJ/kg
Combustion CO2	1,53	-	1,61	1,57	kg/kg

Infino, PC+ABS recycled

Primary production energy, CO2 and water					
	Lower		Upper	Mean	Unit
Embodied energy, primary production	97	-	107	102	MJ/kg
CO2 footprint, primary production	4,63	-	5,11	4,87	kg/kg
Water usage	166	-	184	175	l/kg
Processing energy, CO2 footprint & water					
Polymer extrusion energy	5,88	-	6,5	6,19	MJ/kg
Polymer extrusion CO2	0,441	-	0,487	0,464	kg/kg
Polymer extrusion water	4,85	-	7,28	6,065	l/kg
Polymer molding energy	20,3	-	22,4	21,35	MJ/kg
Polymer molding CO2	1,52	-	1,68	1,6	kg/kg
Polymer molding water	13,3	-	19,9	16,6	l/kg
Coarse machining energy (per unit wt removed)	1,17	-	1,29	1,23	MJ/kg
Coarse machining CO2 (per unit wt removed)	0,0874	-	0,0966	0,092	kg/kg
Fine machining energy (per unit wt removed)	7,38	-	8,16	7,77	MJ/kg
Fine machining CO2 (per unit wt removed)	0,554	-	0,612	0,583	kg/kg
Grinding energy (per unit wt removed)	14,3	-	15,8	15,05	MJ/kg
Grinding CO2 (per unit wt removed)	1,07	-	1,18	1,125	kg/kg
Recycling and end of life					
Recycle	TRUE				
Embodied energy, recycling	34,7	-	38,3	36,5	MJ/kg
CO2 footprint, recycling	1,57	-	1,74	1,655	kg/kg
Recycle fraction in current supply	0,1			0,05	%

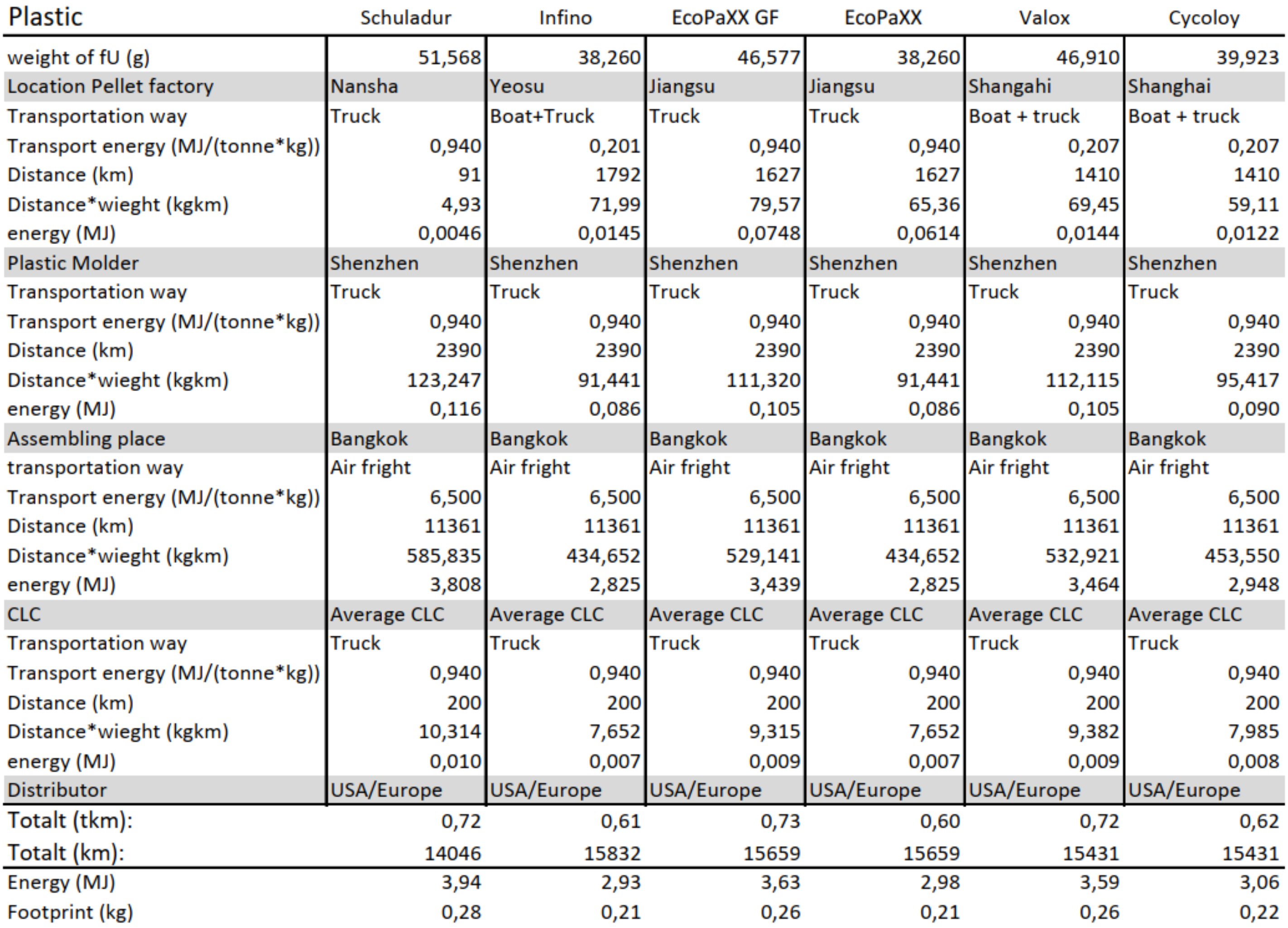
EcoPaXX - PA410 biobased

Primary production energy, CO2 and water					
	Lower		Upper	Mean	Unit
Embodied energy, primary production	210	-	232	221	MJ/kg
CO2 footprint, primary production	2,1			2,1	kg/kg
Water usage	8440	-	9330	8885	l/kg
Processing energy, CO2 footprint & water					
Polymer extrusion energy	5,88	-	6,49	6,185	MJ/kg
Polymer extrusion CO2	0,441	-	0,486	0,4635	kg/kg
Polymer extrusion water	5,05	-	7,27	6,16	l/kg
Polymer molding energy	20	-	22,1	21,05	MJ/kg
Polymer molding CO2	1,5	-	1,66	1,58	kg/kg
Polymer molding water	13,7	-	19,7	16,7	l/kg
Coarse machining energy (per unit wt removed)	0,99	-	1,09	1,04	MJ/kg
Coarse machining CO2 (per unit wt removed)	0,074	-	0,082	0,078	kg/kg
Fine machining energy (per unit wt removed)	5,64	-	6,2	5,92	MJ/kg
Fine machining CO2 (per unit wt removed)	0,422	-	0,466	0,444	kg/kg
Grinding energy (per unit wt removed)	10,8	-	11,9	11,35	MJ/kg
Grinding CO2 (per unit wt removed)	0,81	-	0,89	0,85	kg/kg
Recycling and end of life					
Recycle	TRUE				
Embodied energy, recycling	71,6	-	79	75,3	MJ/kg
CO2 footprint, recycling	1,75	-	1,92	1,835	kg/kg
Recycle fraction in current supply	0,672	-	0,742	0,707	%
Downcycle	TRUE				
Combust for energy recovery	TRUE				
Heat of combustion (net)	29,6	-	31,1	30,35	MJ/kg
Combustion CO2	2,42	-	2,54	2,48	kg/kg

Cycoloy - PC+ABS virgin

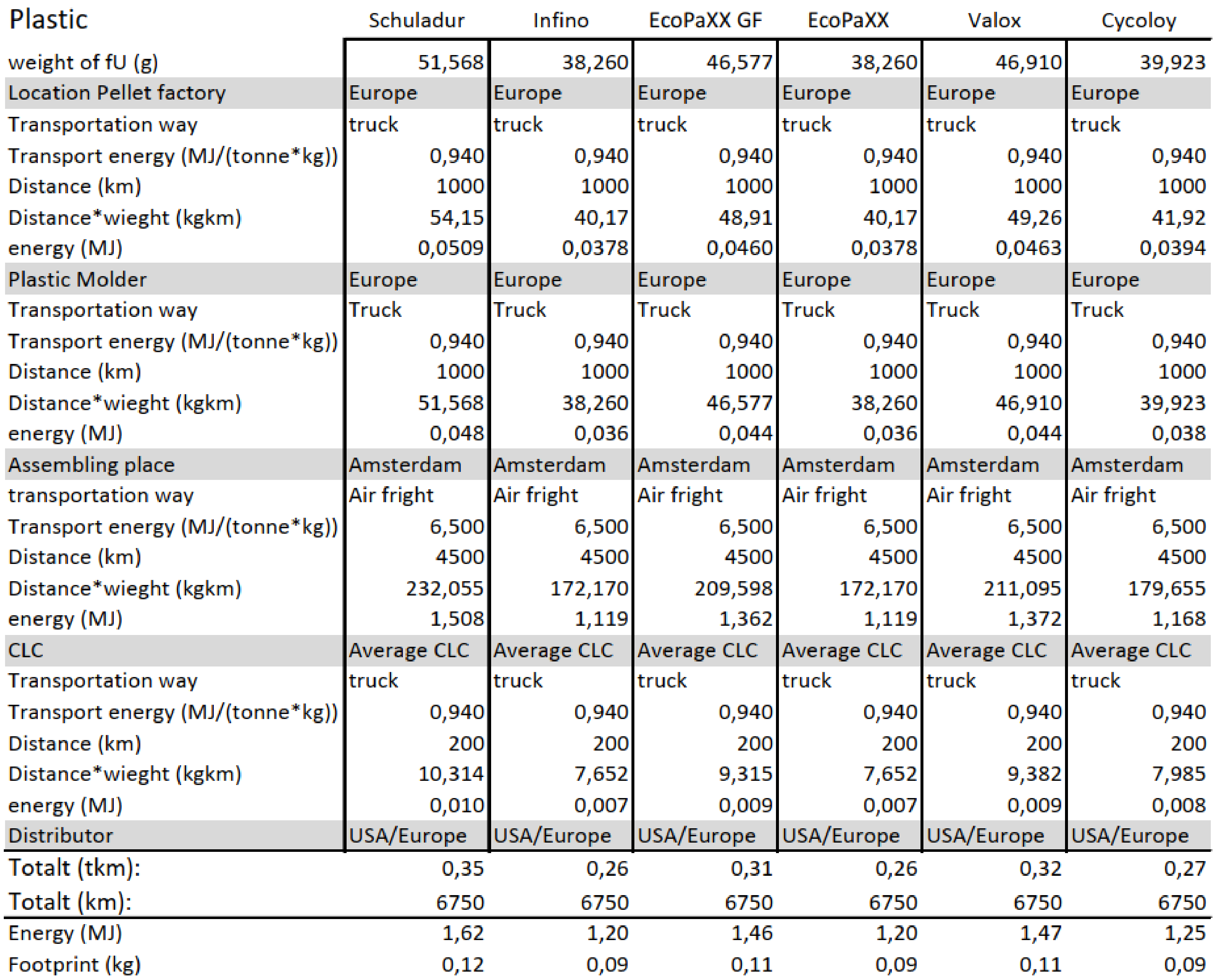
Primary production energy, CO2 and water					
	Lower		Upper	Mean	Unit
Embodied energy, primary production	99,8	-	110	104,9	MJ/kg
CO2 footprint, primary production	4,93	-	5,43	5,18	kg/kg
Water usage	166	-	184	175	l/kg
Processing energy, CO2 footprint & water					
Polymer extrusion energy	5,84	-	6,45	6,145	MJ/kg
Polymer extrusion CO2	0,438	-	0,484	0,461	kg/kg
Polymer extrusion water	4,83	-	7,25	6,04	l/kg
Polymer molding energy	19,2	-	21,2	20,2	MJ/kg
Polymer molding CO2	1,44	-	1,59	1,515	kg/kg
Polymer molding water	12,8	-	19,2	16	l/kg
Coarse machining energy (per unit wt removed)	1,08	-	1,2	1,14	MJ/kg
Coarse machining CO2 (per unit wt removed)	0,0813	-	0,0898	0,08555	kg/kg
Fine machining energy (per unit wt removed)	6,56	-	7,25	6,905	MJ/kg
Fine machining CO2 (per unit wt removed)	0,492	-	0,544	0,518	kg/kg
Grinding energy (per unit wt removed)	12,6	-	14	13,3	MJ/kg
Grinding CO2 (per unit wt removed)	0,948	-	1,05	0,999	kg/kg
Recycling and end of life					
Recycle	TRUE				
Embodied energy, recycling	33,2	-	36,7	34,95	MJ/kg
CO2 footprint, recycling	1,64	-	1,81	1,725	kg/kg
Recycle fraction in current supply	0,1			0,05	%
Downcycle	TRUE				
Combust for energy recovery	TRUE				
Heat of combustion (net)	27,8	-	32,7	30,25	MJ/kg
Combustion CO2	2,45	-	2,58	2,515	kg/kg

B Transport



Plastic	Schuladur	Infino	EcoPaXX GF	EcoPaXX	Valox	Cycoloy
weight of fU (g)	51,568	38,260	46,577	38,260	46,910	39,923
Location Pellet factory	Nansha	Yeosu	Jiangsu	Jiangsu	Shangahi	Shanghai
Transportation way	Truck	Boat+Truck	Truck	Truck	Boat + truck	Boat + truck
Transport energy (MJ/(tonne*kg))	0,940	0,201	0,940	0,940	0,207	0,207
Distance (km)	91	1792	1627	1627	1410	1410
Distance*wieght (kgkm)	4,93	71,99	79,57	65,36	69,45	59,11
energy (MJ)	0,0046	0,0145	0,0748	0,0614	0,0144	0,0122
Plastic Molder	Shenzhen	Shenzhen	Shenzhen	Shenzhen	Shenzhen	Shenzhen
Transportation way	Truck	Truck	Truck	Truck	Truck	Truck
Transport energy (MJ/(tonne*kg))	0,940	0,940	0,940	0,940	0,940	0,940
Distance (km)	2390	2390	2390	2390	2390	2390
Distance*wieght (kgkm)	123,247	91,441	111,320	91,441	112,115	95,417
energy (MJ)	0,116	0,086	0,105	0,086	0,105	0,090
Assembling place	Bangkok	Bangkok	Bangkok	Bangkok	Bangkok	Bangkok
transportation way	Air fright	Air fright	Air fright	Air fright	Air fright	Air fright
Transport energy (MJ/(tonne*kg))	6,500	6,500	6,500	6,500	6,500	6,500
Distance (km)	11361	11361	11361	11361	11361	11361
Distance*wieght (kgkm)	585,835	434,652	529,141	434,652	532,921	453,550
energy (MJ)	3,808	2,825	3,439	2,825	3,464	2,948
CLC	Average CLC	Average CLC	Average CLC	Average CLC	Average CLC	Average CLC
Transportation way	Truck	Truck	Truck	Truck	Truck	Truck
Transport energy (MJ/(tonne*kg))	0,940	0,940	0,940	0,940	0,940	0,940
Distance (km)	200	200	200	200	200	200
Distance*wieght (kgkm)	10,314	7,652	9,315	7,652	9,382	7,985
energy (MJ)	0,010	0,007	0,009	0,007	0,009	0,008
Distributor	USA/Europe	USA/Europe	USA/Europe	USA/Europe	USA/Europe	USA/Europe
Totalt (tkm):	0,72	0,61	0,73	0,60	0,72	0,62
Totalt (km):	14046	15832	15659	15659	15431	15431
Energy (MJ)	3,94	2,93	3,63	2,98	3,59	3,06
Footprint (kg)	0,28	0,21	0,26	0,21	0,26	0,22

Figure 39: The transport for each plastic from the pellet factory to the distributor in USA or Europe. The type of transport, length and use of energy is specified for each step. The energy and carbon footprint has be calculated using Table 14.



Plastic	Schuladur	Infino	EcoPaXX GF	EcoPaXX	Valox	Cycoloy
weight of fU (g)	51,568	38,260	46,577	38,260	46,910	39,923
Location Pellet factory	Europe	Europe	Europe	Europe	Europe	Europe
Transportation way	truck	truck	truck	truck	truck	truck
Transport energy (MJ/(tonne*kg))	0,940	0,940	0,940	0,940	0,940	0,940
Distance (km)	1000	1000	1000	1000	1000	1000
Distance*wieght (kgkm)	54,15	40,17	48,91	40,17	49,26	41,92
energy (MJ)	0,0509	0,0378	0,0460	0,0378	0,0463	0,0394
Plastic Molder	Europe	Europe	Europe	Europe	Europe	Europe
Transportation way	Truck	Truck	Truck	Truck	Truck	Truck
Transport energy (MJ/(tonne*kg))	0,940	0,940	0,940	0,940	0,940	0,940
Distance (km)	1000	1000	1000	1000	1000	1000
Distance*wieght (kgkm)	51,568	38,260	46,577	38,260	46,910	39,923
energy (MJ)	0,048	0,036	0,044	0,036	0,044	0,038
Assembling place	Amsterdam	Amsterdam	Amsterdam	Amsterdam	Amsterdam	Amsterdam
transportation way	Air fright	Air fright	Air fright	Air fright	Air fright	Air fright
Transport energy (MJ/(tonne*kg))	6,500	6,500	6,500	6,500	6,500	6,500
Distance (km)	4500	4500	4500	4500	4500	4500
Distance*wieght (kgkm)	232,055	172,170	209,598	172,170	211,095	179,655
energy (MJ)	1,508	1,119	1,362	1,119	1,372	1,168
CLC	Average CLC	Average CLC	Average CLC	Average CLC	Average CLC	Average CLC
Transportation way	truck	truck	truck	truck	truck	truck
Transport energy (MJ/(tonne*kg))	0,940	0,940	0,940	0,940	0,940	0,940
Distance (km)	200	200	200	200	200	200
Distance*wieght (kgkm)	10,314	7,652	9,315	7,652	9,382	7,985
energy (MJ)	0,010	0,007	0,009	0,007	0,009	0,008
Distributor	USA/Europe	USA/Europe	USA/Europe	USA/Europe	USA/Europe	USA/Europe
Totalt (tkm):	0,35	0,26	0,31	0,26	0,32	0,27
Totalt (km):	6750	6750	6750	6750	6750	6750
Energy (MJ)	1,62	1,20	1,46	1,20	1,47	1,25
Footprint (kg)	0,12	0,09	0,11	0,09	0,11	0,09

Figure 40: A scenario where all production and manufacturing is done in Europe instead of Asia. The transport for each plastic from the pellet factory to the distributor in USA or Europe. The type of transport, length and use of energy is specified for each step. The energy and carbon footprint has be calculated using Table 14.

Table 14: The energy usage and carbon footprint for each type of transport, as specified by EduPack[44]. The carbon footprint is based upon using fossil fuels and convert it to either thermal or electric energy.

	Transport energy (MJ/(ton*kg))	CO2 footprint (kg/MJ)
Ocean freight	0,18	0,072
Coastal freight	0,27	0,072
River/canal freight	0,4	0,072
Rail freight	0,35	0,072
55 tonne (8 axle) truck	0,71	0,072
40 tonne (6 axle) truck	0,82	0,072
32 tonne (4 axle) truck	0,94	0,072
26 tonne (3 axle) truck	1,1	0,072
14 tonne (2 axle) truck	1,5	0,072
Light goods vehicle	2,2	0,072
Air freight - long haul	6,5	0,072
Air freight - short haul	13	0,072
Helicopter	55	0,072

C Results

Figure 41: The crack of part (A) after one compression test on a subassembly.

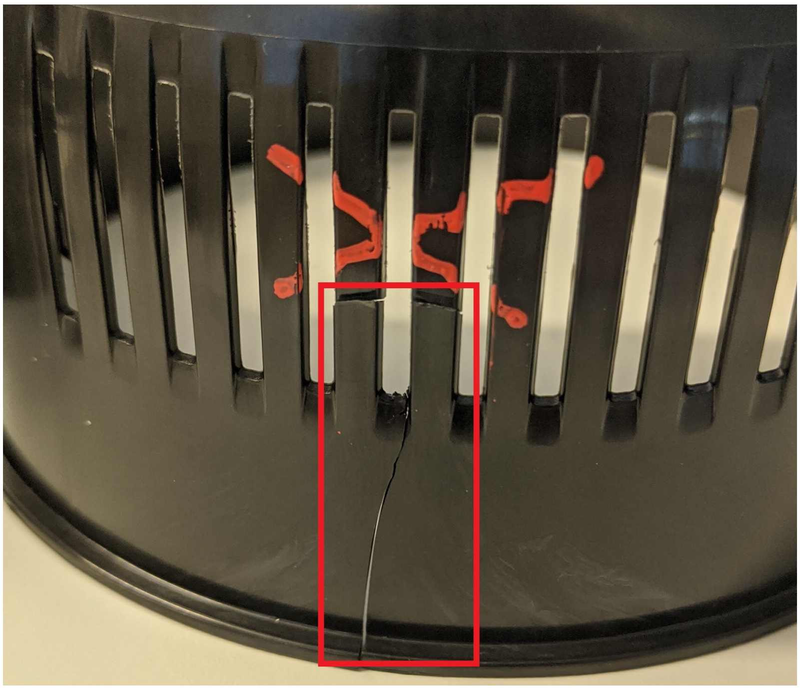
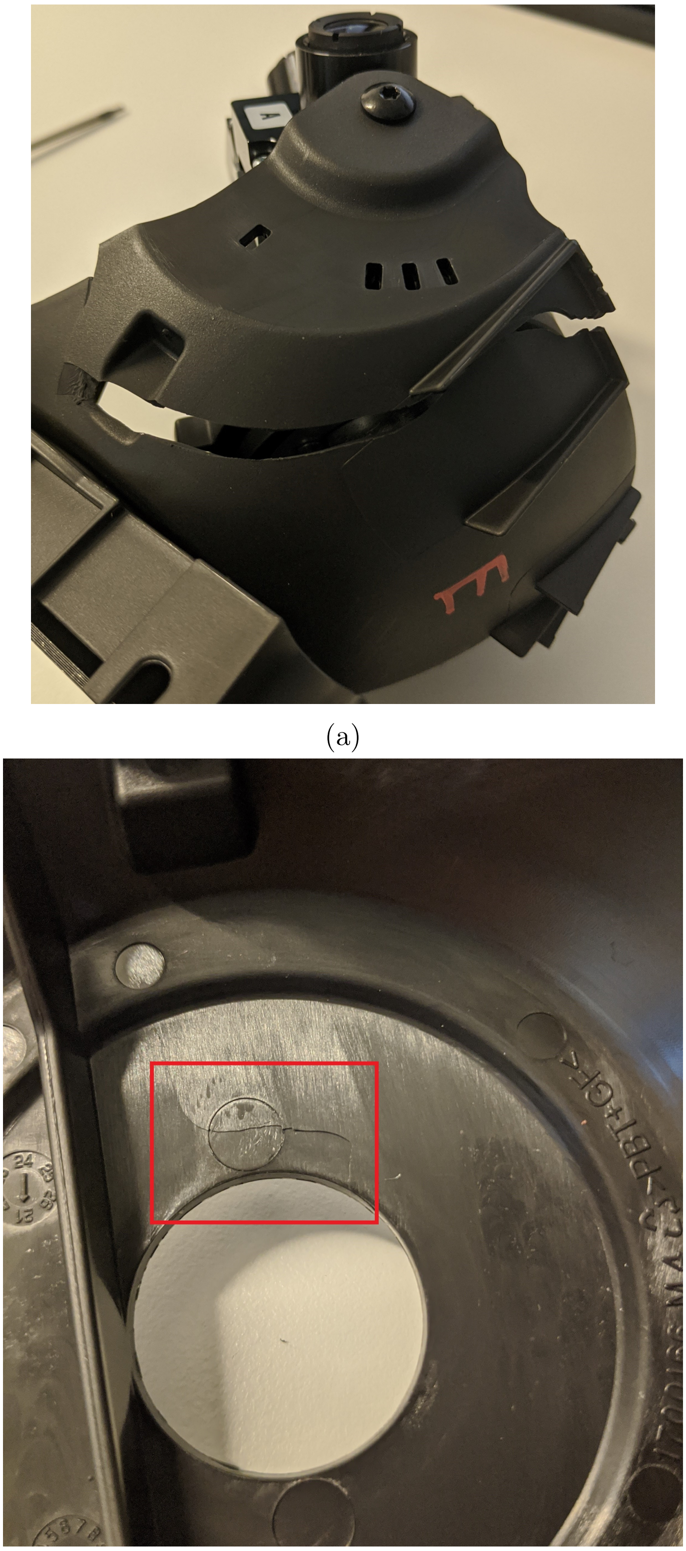


Figure 42: The image show the cracked back of part(C) in biobased plastic after a IK 8 test.



(a)

(b)

Figure 43: The images show how part (A) in biobased plastic looked after the first IK 8 test. (a) shows how part (A) cracked on the right side and (b) shows a small crack in the bottom of the part.

(a) (b)

(c) (d)

Figure 44: The four images shows the biobased parts after being subjected to a IK 8 impact test. (a) shows the cracked back of part (C), b, c and d show the damage inflicted on part (A) from different angles.

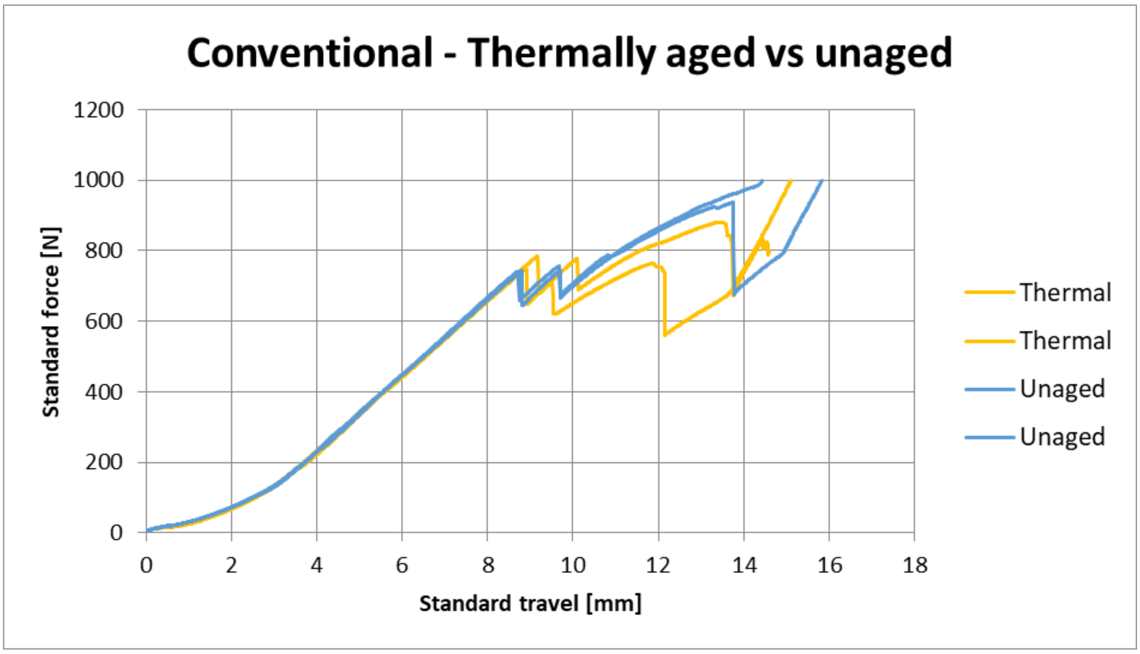


Figure 45

Figure 46: Force vs Standard travel for the conventional plastics before and after thermal aging. Two subassembly compression test were performed both before and after the thermal aging.

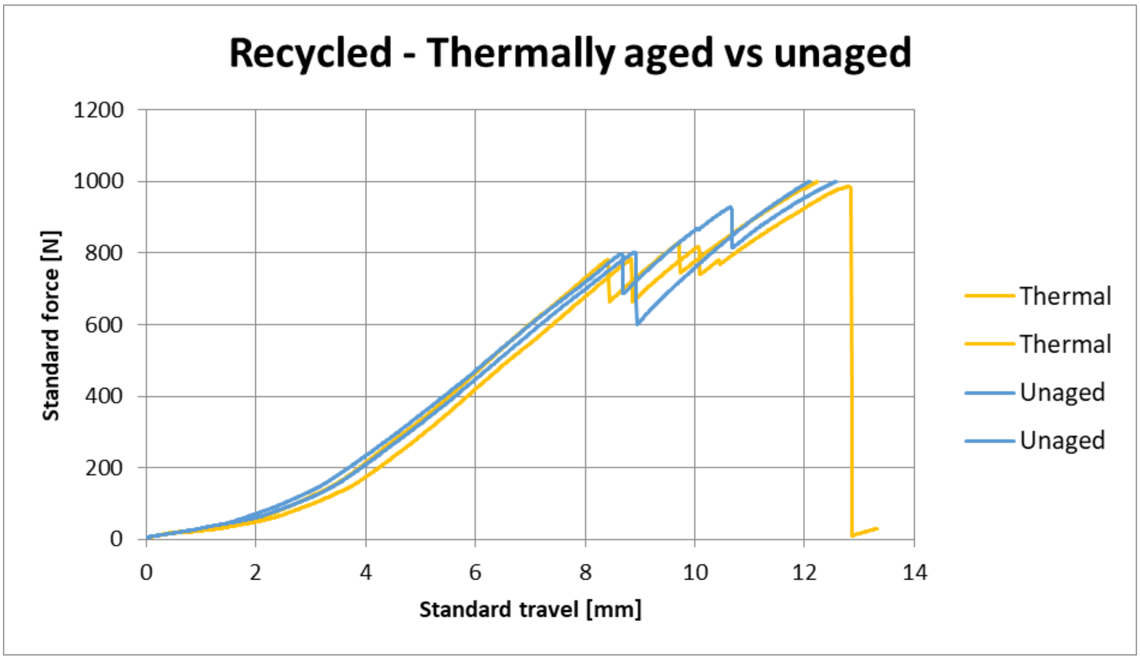


Figure 47

Figure 48: Force vs Standard travel for the recycled plastics before and after thermal aging. Two subassembly compression test were performed both before and after the thermal aging.

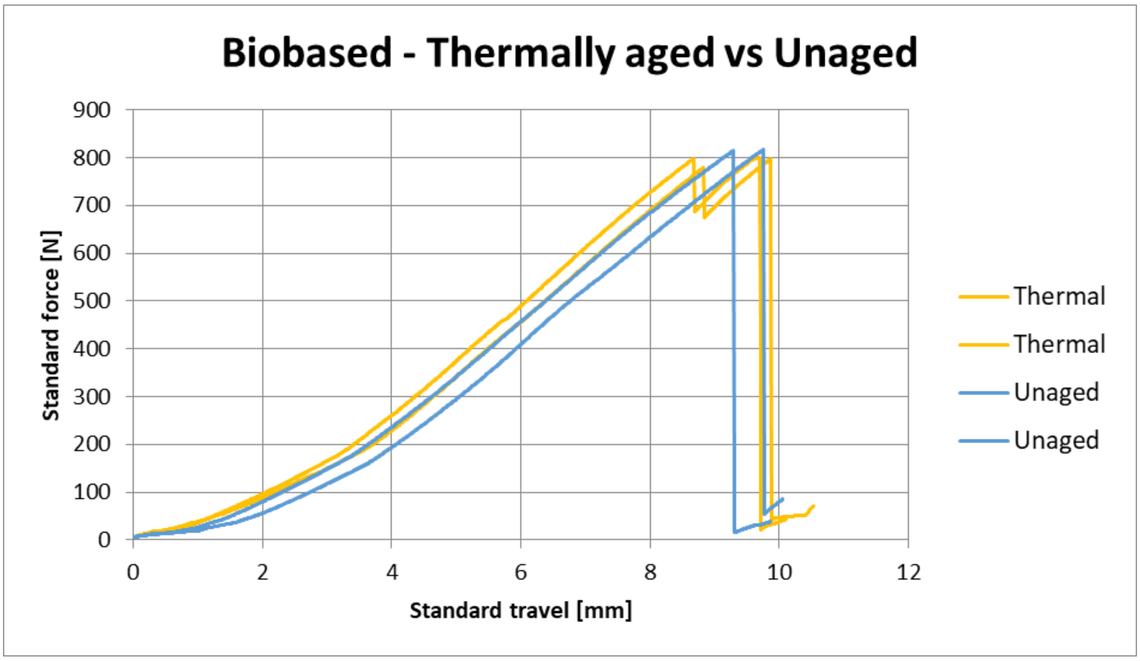


Figure 49

Figure 50: Force vs Standard travel for the biobased plastics before and after thermal aging. Two subassembly compression test were performed both before and after the thermal aging.

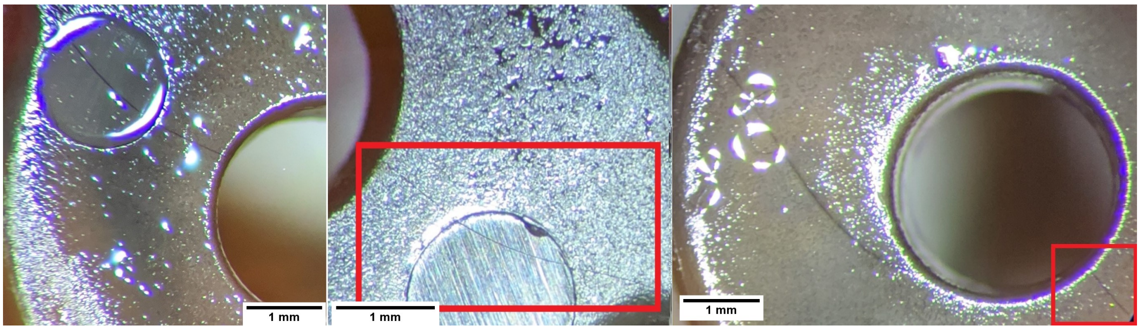


Figure 51: Cracks on part (E) in biobased plastic resulting from the organic oil test.

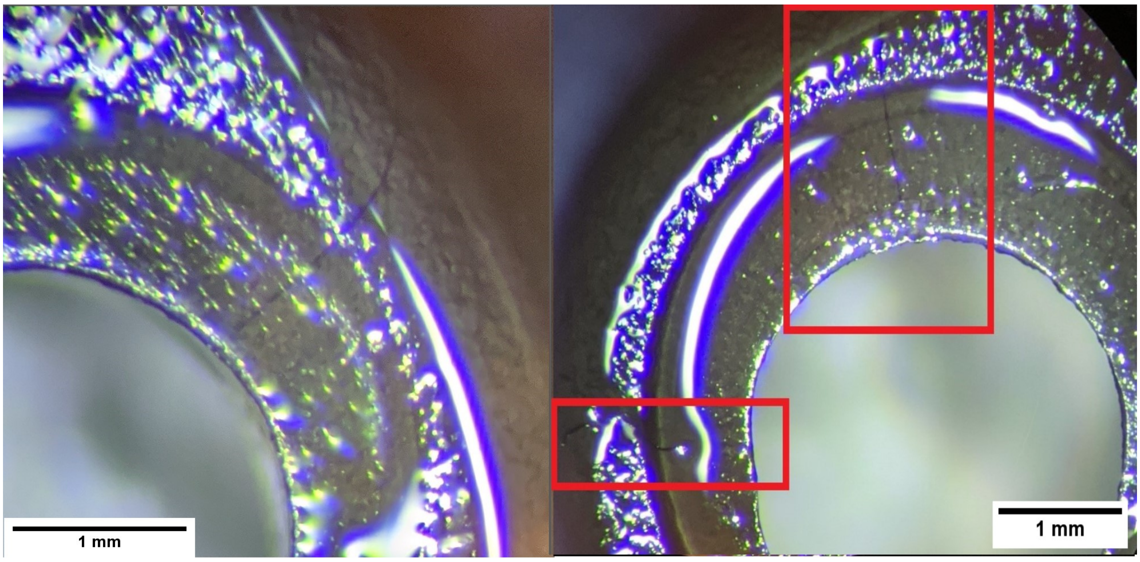


Figure 52: Cracks on part (E) in biobased plastic resulting from the organic oil test.

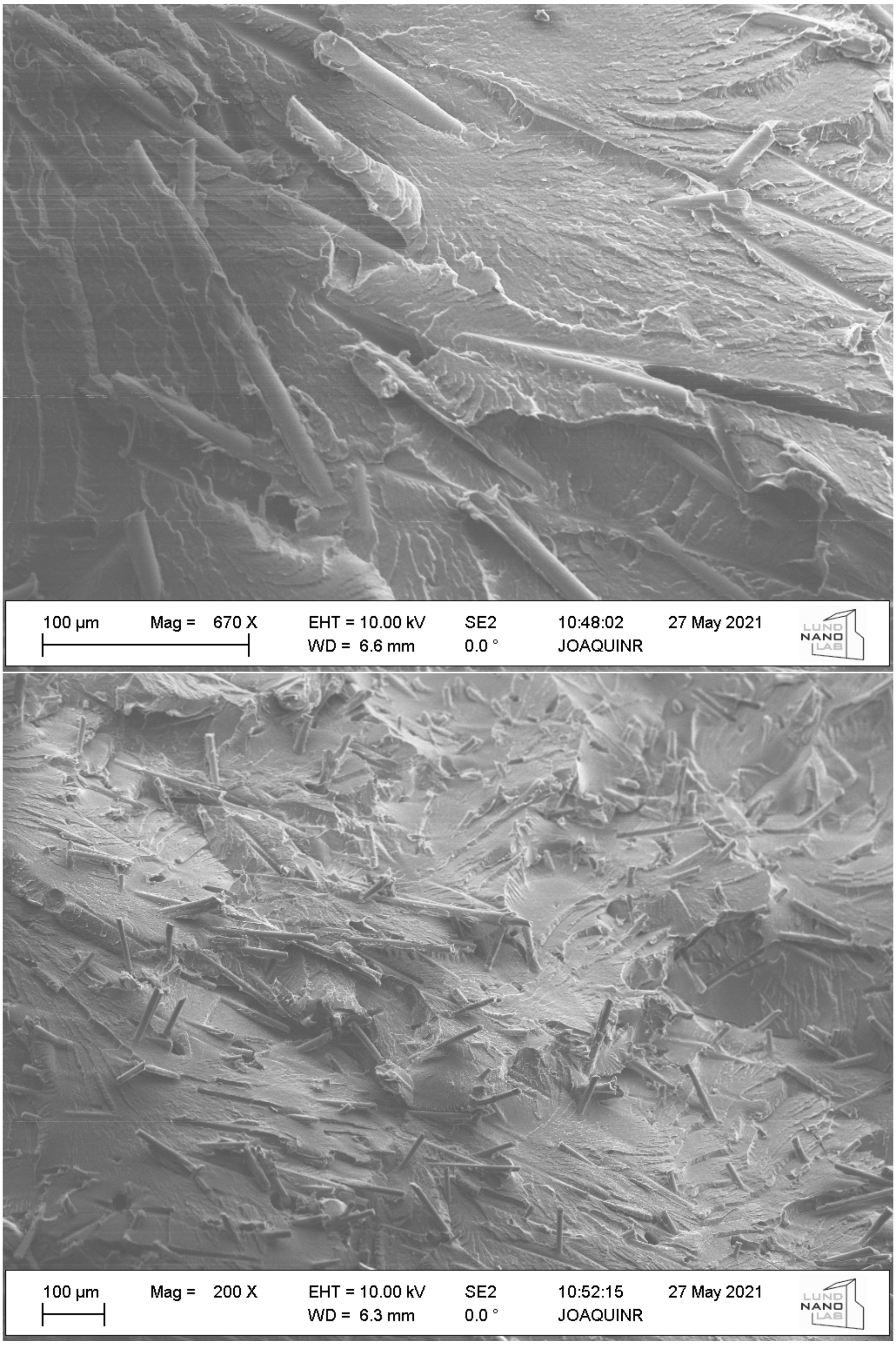


Figure 53: SEM images of a fracture surface of the conventional plastic.

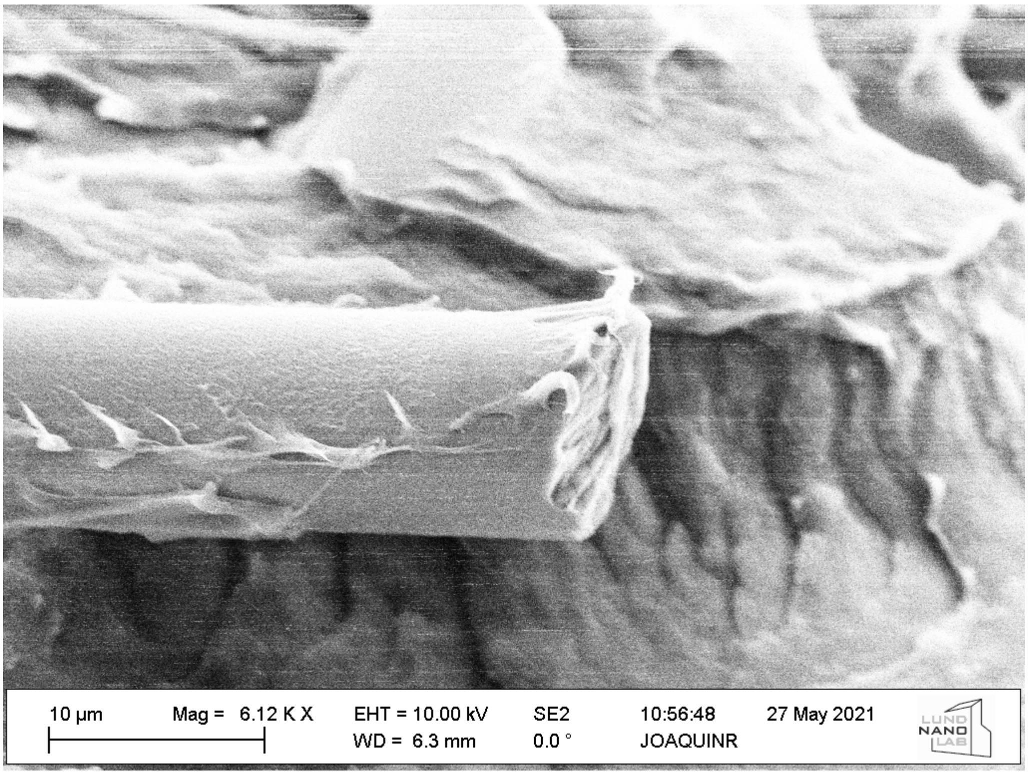


Figure 54: SEM image of a glass fiber at the fracture surface of the conventional plastic.

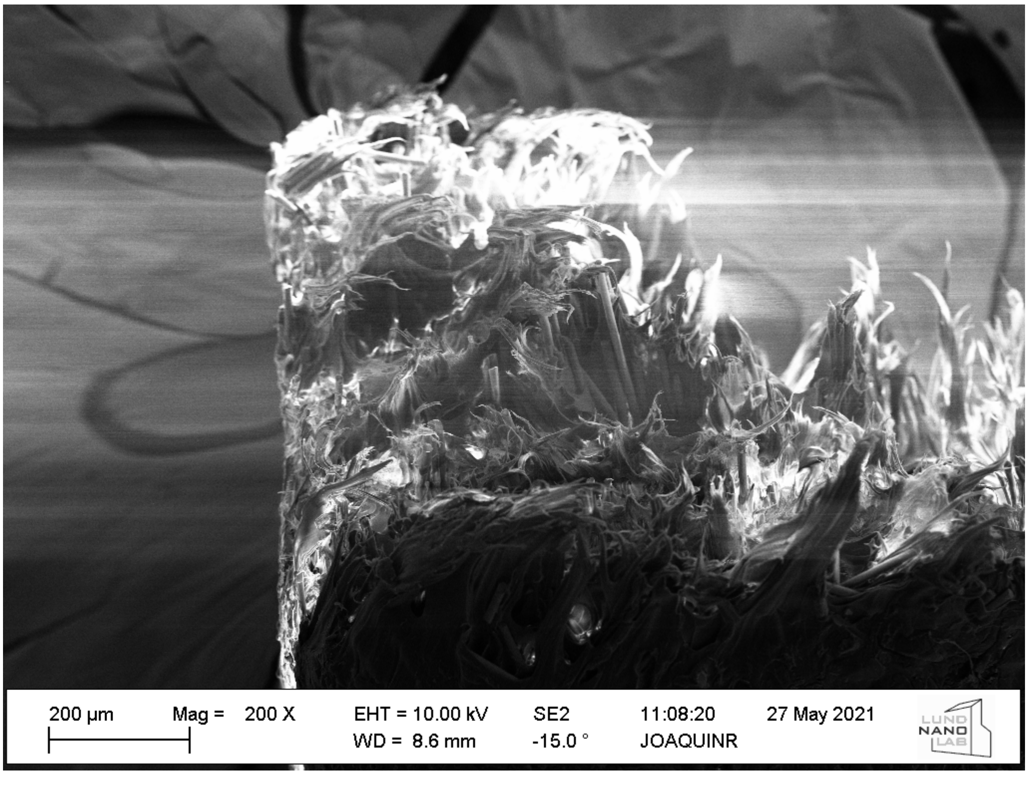


Figure 55: SEM image of the fracture surface of the recycled plastic.

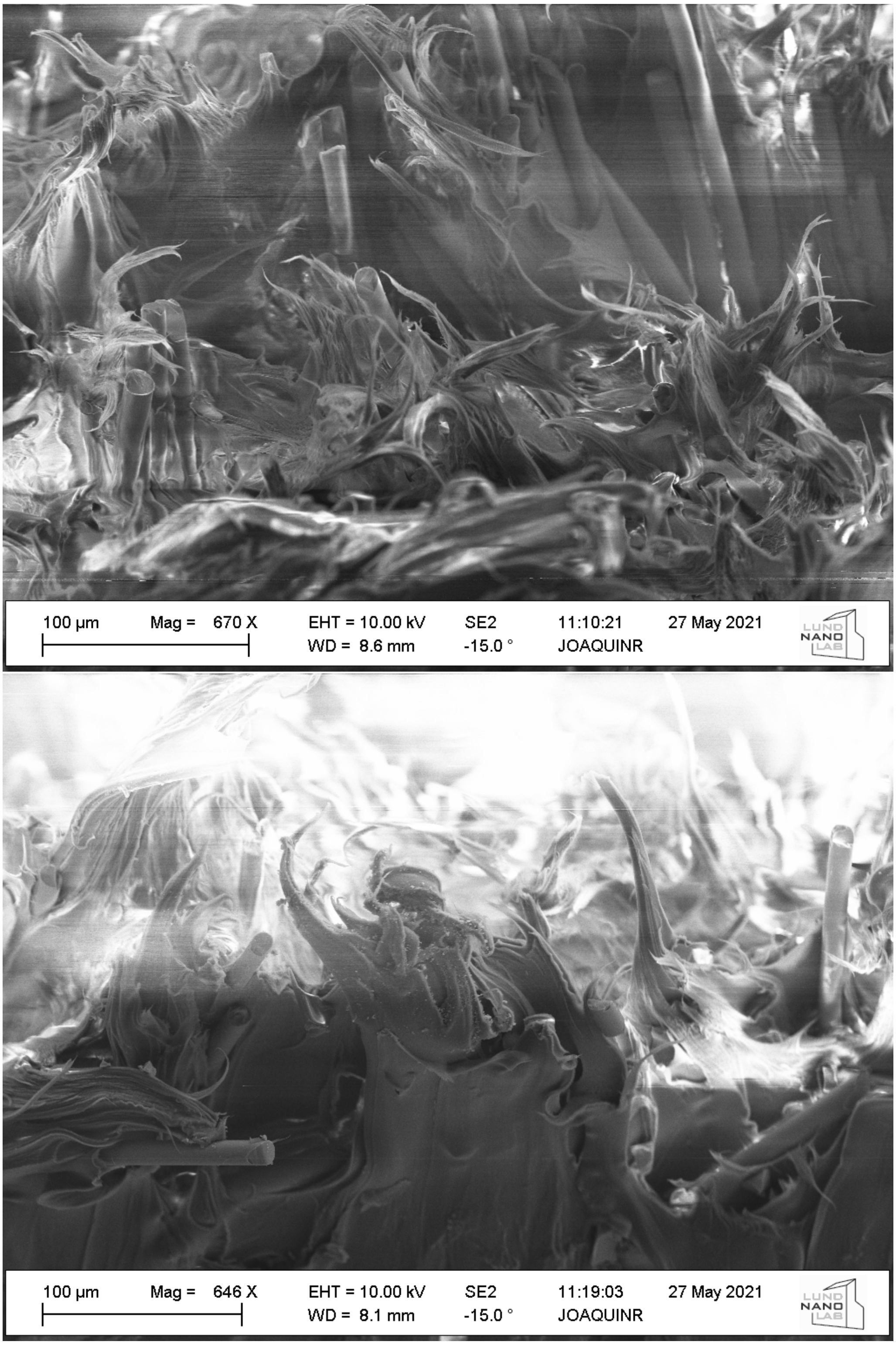


Figure 56: SEM images of a fracture surface of the recycled plastic.

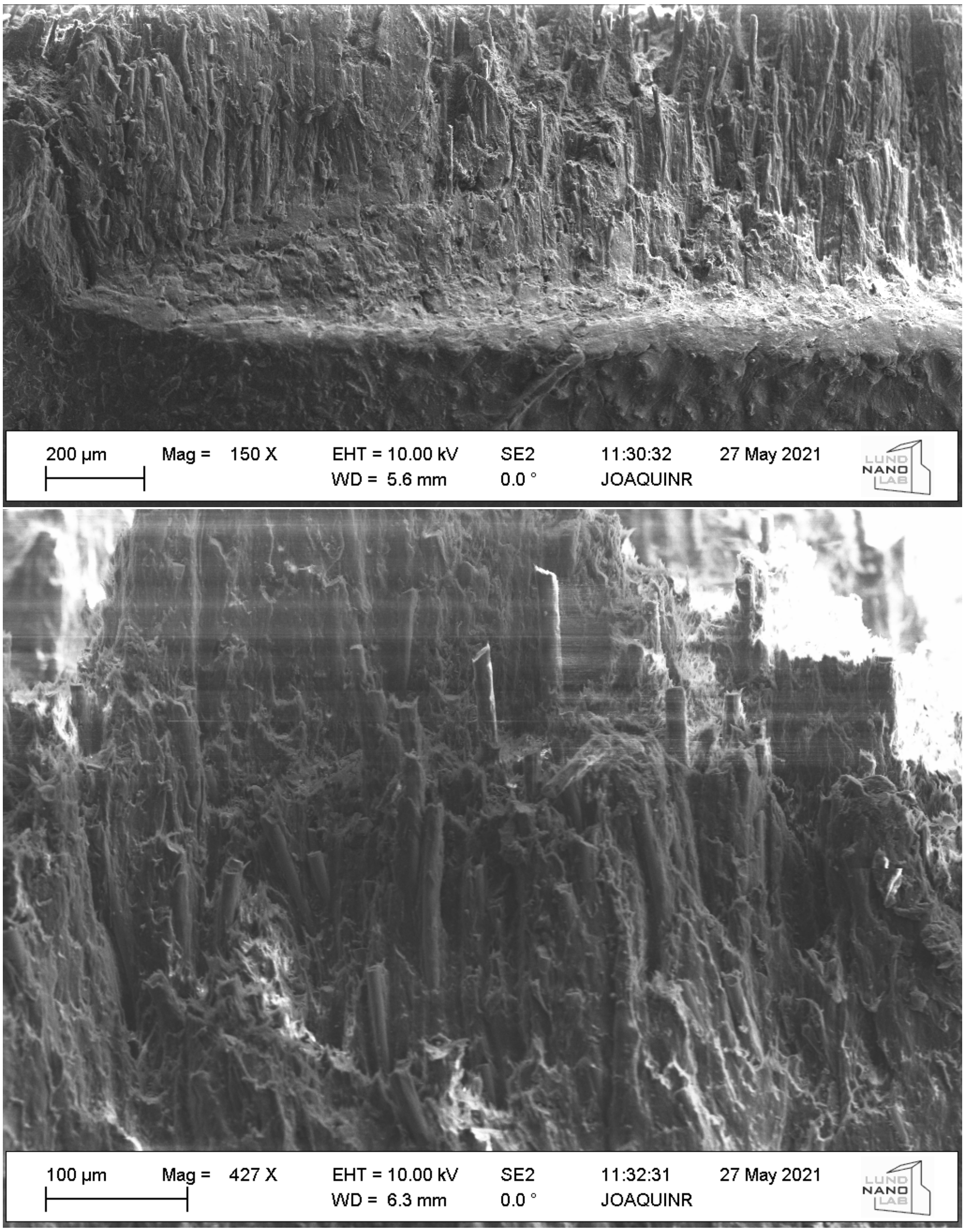


Figure 57: SEM images of a fracture surface of the biobased plastic.

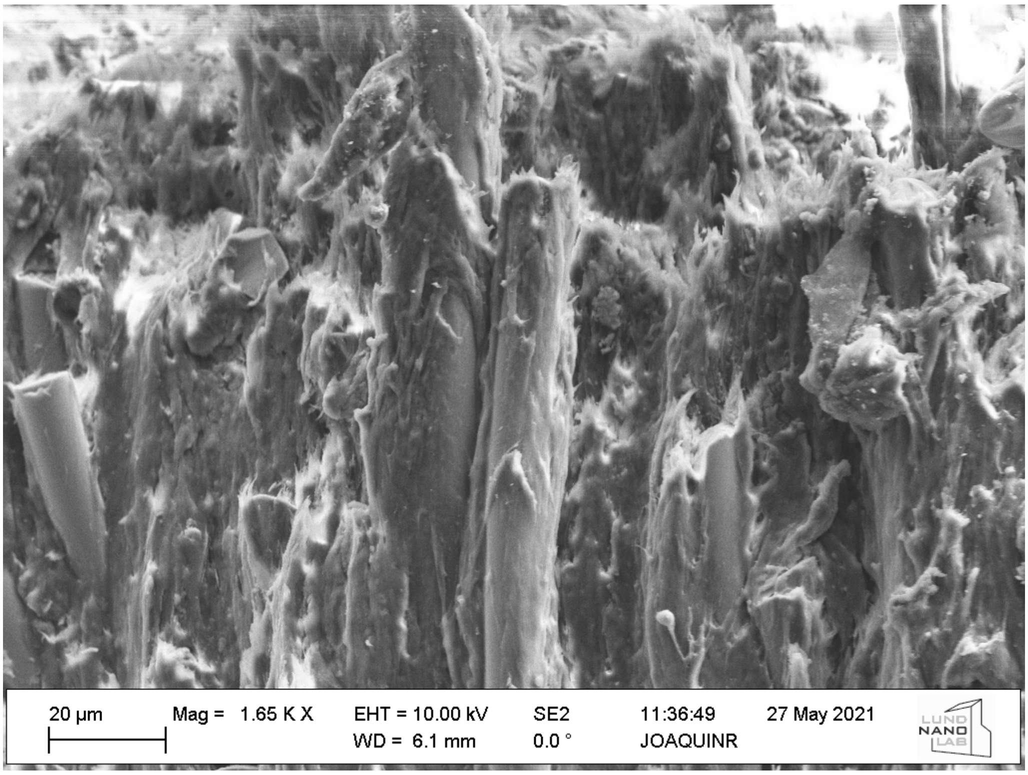


Figure 58: SEM image of glass fibers at the fracture surface of the biobased plastic.

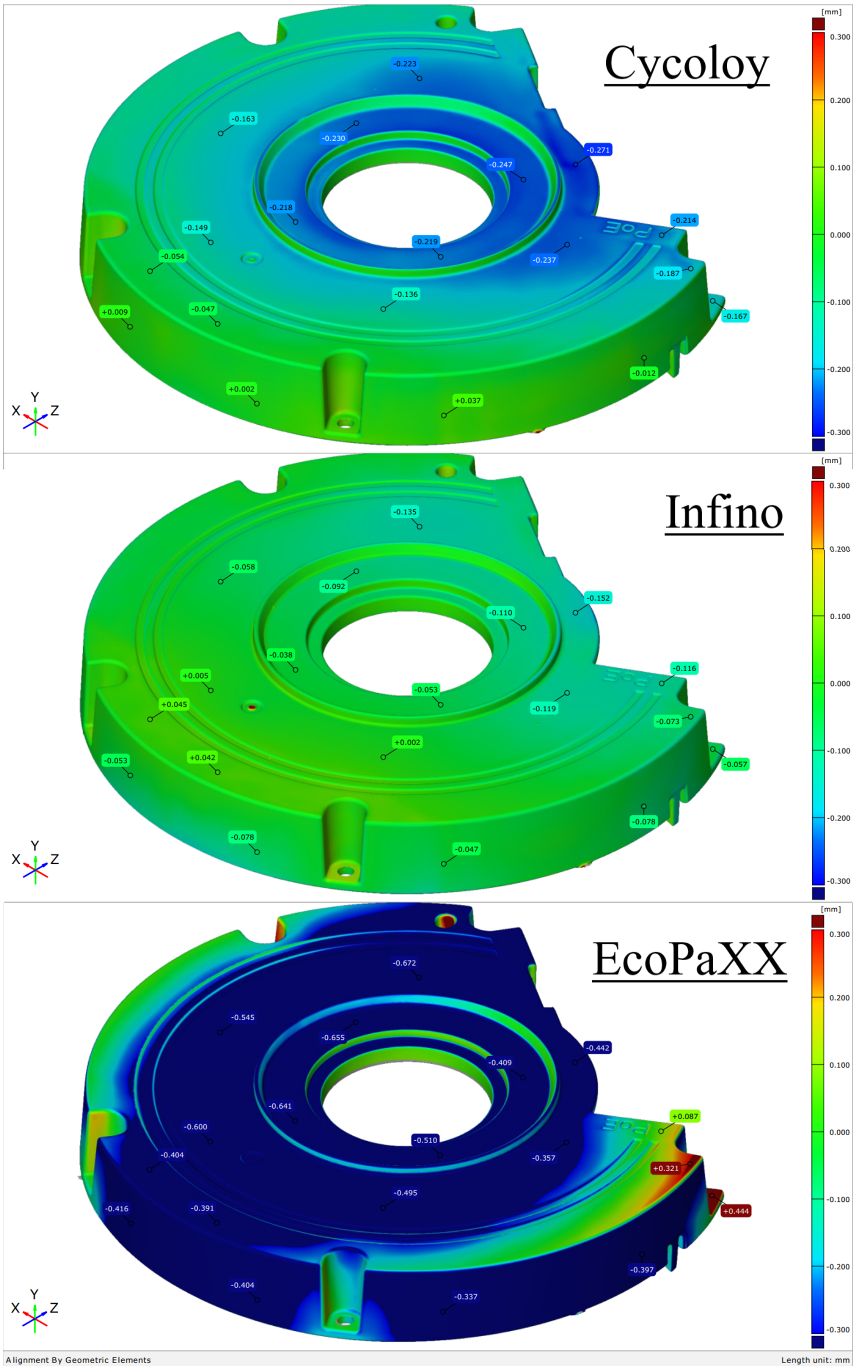


Figure 59: The 3D scanning result on part (E).

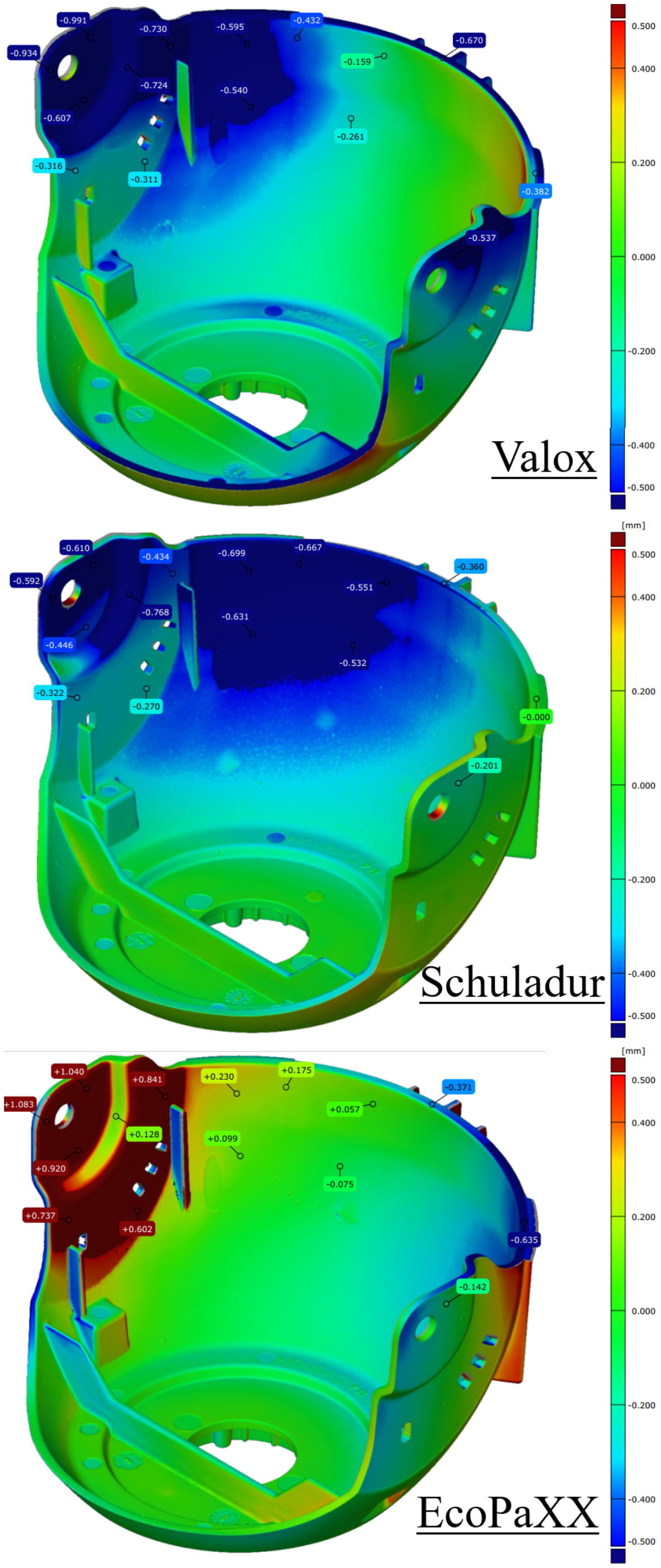
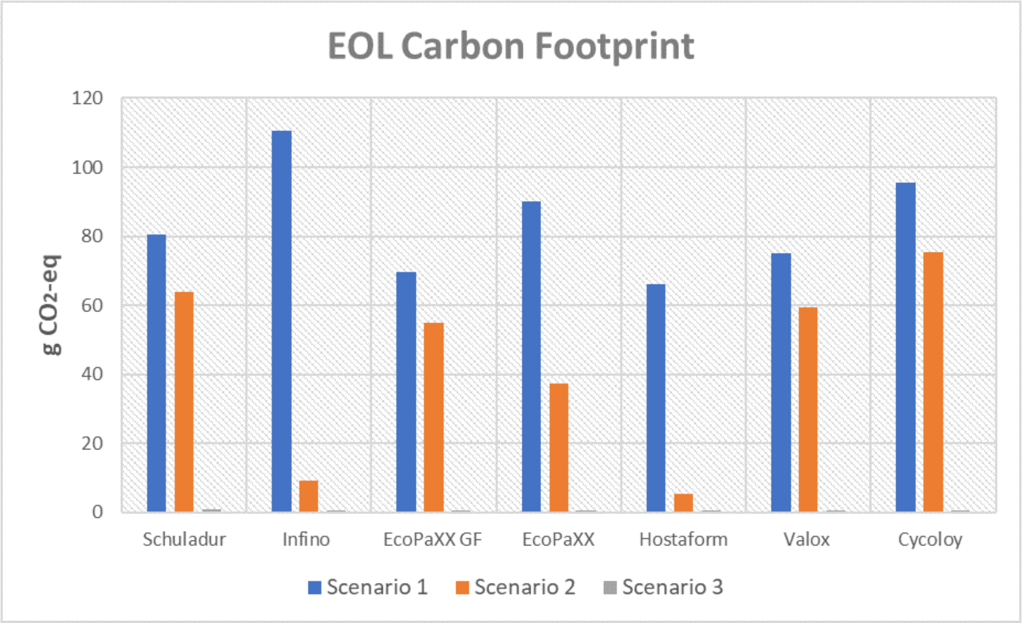
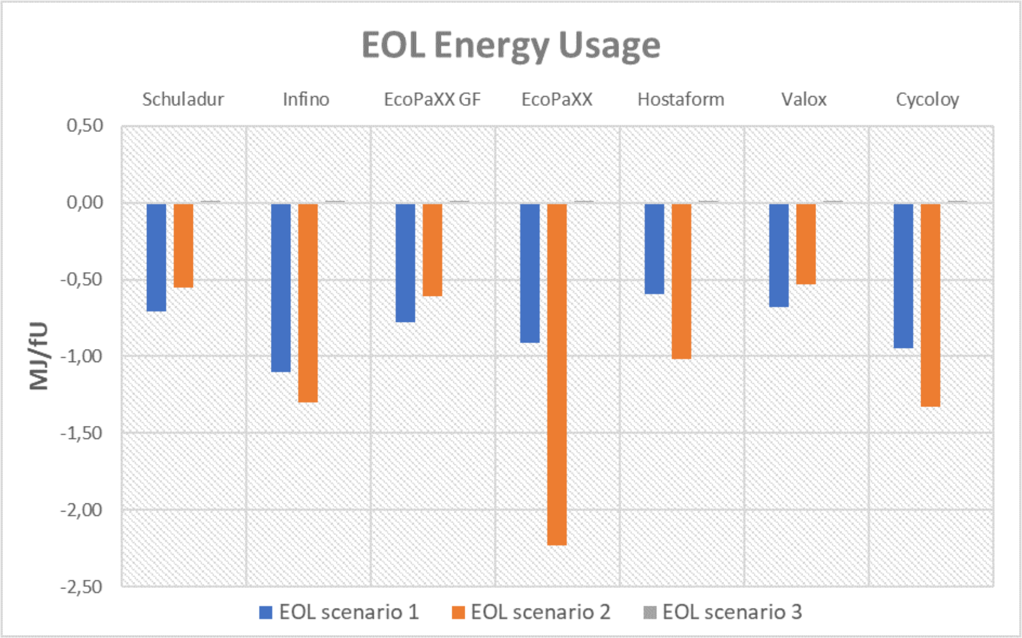


Figure 60: The 3D scanning result on part (E).



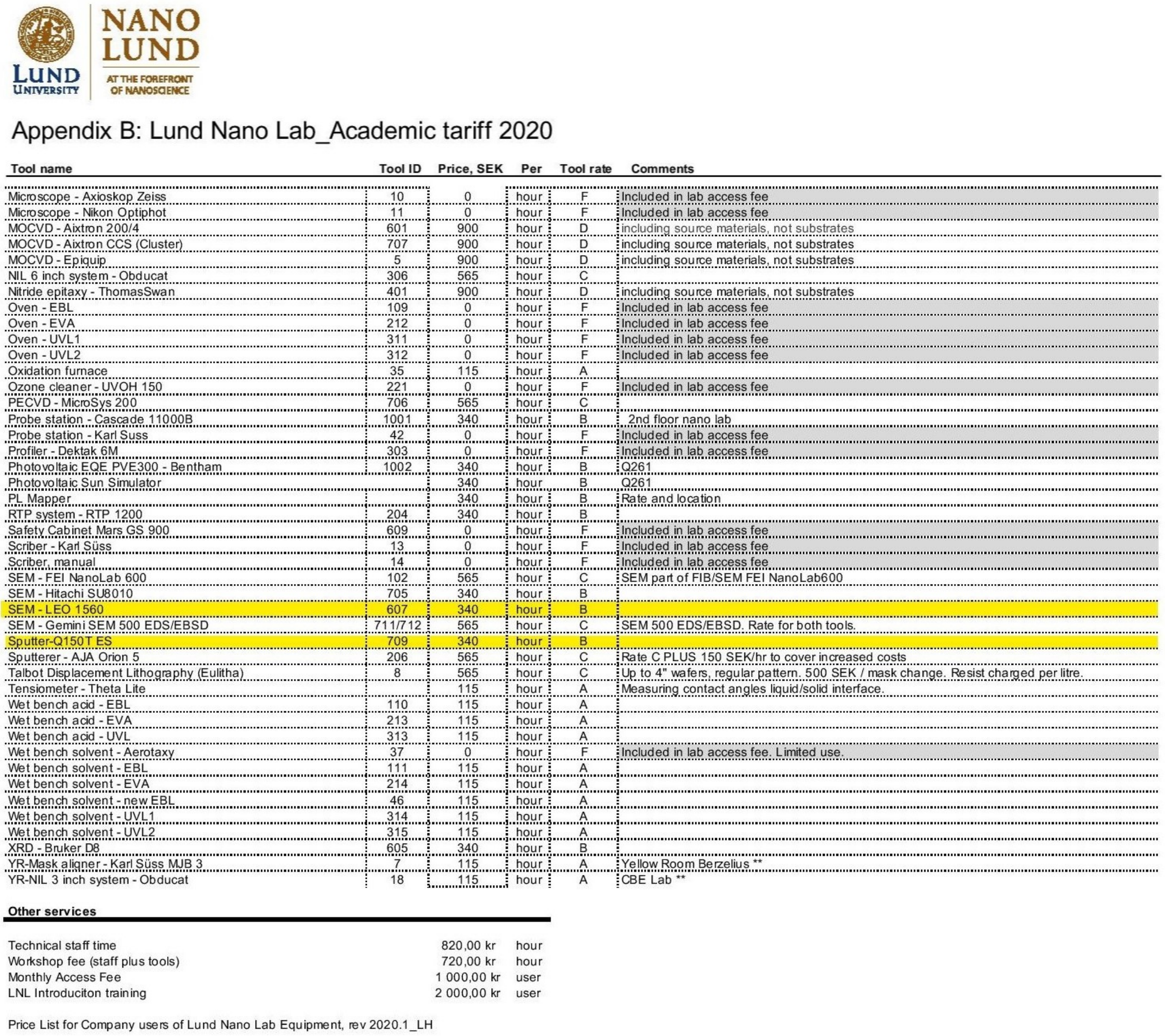
(a)



(b)

Figure 61: A visual representation of the result presented in Table 9. (a) shows the carbon footprint for each plastic in the three scenarios while (b) shows the energy usage or the energy saved in the given scenario.

D Lund Nanolab



LUND UNIVERSITY

NANO LUND

AT THE FOREFRONT OF NANOSCIENCE

Appendix B: Lund Nano Lab_Academic tariff 2020

Tool name	Tool ID	Price, SEK	Per	Tool rate	Comments
Microscope - Axioskop Zeiss	10	0	hour	F	Included in lab access fee
Microscope - Nikon Optiphot	11	0	hour	F	Included in lab access fee
MOCVD - Aixtron 200/4	601	900	hour	D	including source materials, not substrates
MOCVD - Aixtron CCS (Cluster)	707	900	hour	D	including source materials, not substrates
MOCVD - Epiquip	5	900	hour	D	including source materials, not substrates
NIL 6 inch system - Obducat	306	565	hour	C	
Nitride epitaxy - ThomasSwan	401	900	hour	D	including source materials, not substrates
Oven - EBL	109	0	hour	F	Included in lab access fee
Oven - EVA	212	0	hour	F	Included in lab access fee
Oven - UVL1	311	0	hour	F	Included in lab access fee
Oven - UVL2	312	0	hour	F	Included in lab access fee
Oxidation furnace	35	115	hour	A	
Ozone cleaner - UVOH 150	221	0	hour	F	Included in lab access fee
PECVD - MicroSys 200	706	565	hour	C	
Probe station - Cascade 11000B	1001	340	hour	B	2nd floor nano lab
Probe station - Karl Suss	42	0	hour	F	Included in lab access fee
Profiler - Dektak 6M	303	0	hour	F	Included in lab access fee
Photovoltaic EQE PVE300 - Bentham	1002	340	hour	B	Q261
Photovoltaic Sun Simulator		340	hour	B	Q261
PL Mapper		340	hour	B	Rate and location
RTP system - RTP 1200	204	340	hour	B	
Safety Cabinet Mars GS 900	609	0	hour	F	Included in lab access fee
Scriber - Karl Süss	13	0	hour	F	Included in lab access fee
Scriber, manual	14	0	hour	F	Included in lab access fee
SEM - FEI NanoLab 600	102	565	hour	C	SEM part of FIB/SEM FEI NanoLab600
SEM - Hitachi SU8010	705	340	hour	B	
SEM - LEO 1560	607	340	hour	B	
SEM - Gemini SEM 500 EDS/EBSD	711/712	565	hour	C	SEM 500 EDS/EBSD. Rate for both tools.
Sputter-Q150T ES	709	340	hour	B	
Sputterer - AJA Orion 5	206	565	hour	C	Rate C PLUS 150 SEK/hr to cover increased costs
Talbot Displacement Lithography (Eulitha)	8	565	hour	C	Up to 4" wafers, regular pattern. 500 SEK / mask change. Resist charged per litre.
Tensiometer - Theta Lite		115	hour	A	Measuring contact angles liquid/solid interface.
Wet bench acid - EBL	110	115	hour	A	
Wet bench acid - EVA	213	115	hour	A	
Wet bench acid - UVL	313	115	hour	A	
Wet bench solvent - Aerotaxy	37	0	hour	F	Included in lab access fee. Limited use.
Wet bench solvent - EBL	111	115	hour	A	
Wet bench solvent - EVA	214	115	hour	A	
Wet bench solvent - new EBL	46	115	hour	A	
Wet bench solvent - UVL1	314	115	hour	A	
Wet bench solvent - UVL2	315	115	hour	A	
XRD - Bruker D8	605	340	hour	B	
YR-Mask aligner - Karl Süss MJB 3	7	115	hour	A	Yellow Room Berzelius **
YR-NIL 3 inch system - Obducat	18	115	hour	A	CBE Lab **

Other services

Technical staff time	820,00 kr	hour
Workshop fee (staff plus tools)	720,00 kr	hour
Monthly Access Fee	1 000,00 kr	user
LNL Introduciton training	2 000,00 kr	user

Price List for Company users of Lund Nano Lab Equipment, rev 2020.1_LH

Figure 62: The price list from Lund NanoLab (LNL) for booking of tools in the lab. The highlighted rows are the tools that were used in this project.