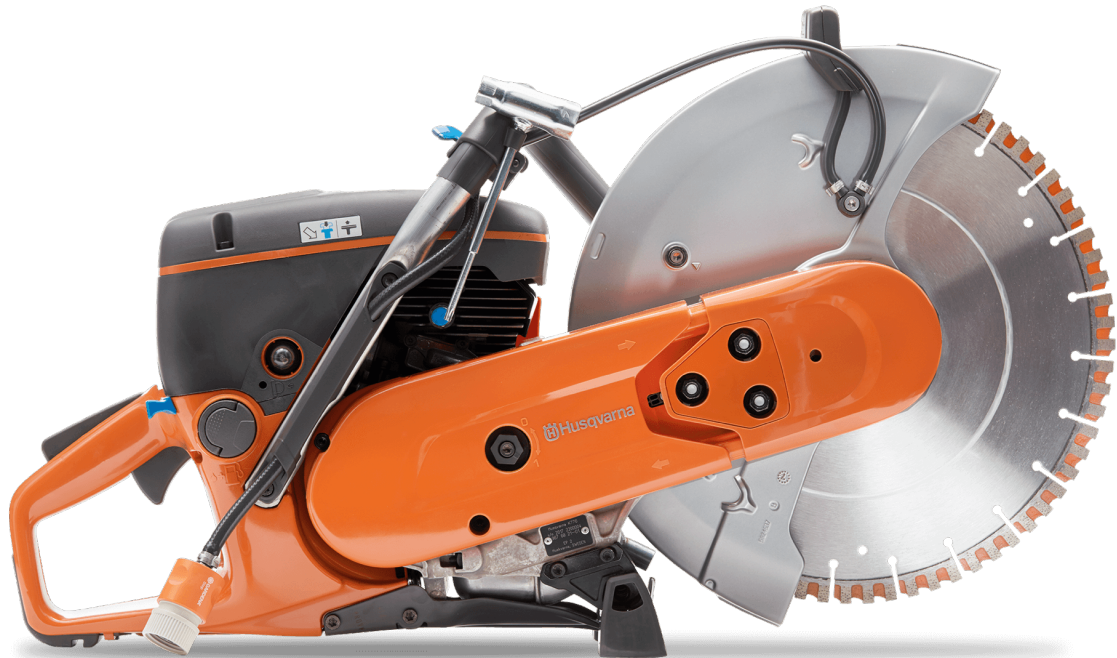




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# Alternative Plastic Materials for Increased Sustainability of Husqvarna K770

Materials selection and evaluation for the belt guard

Master's thesis in Master Programme MPAEM

FILIP ALPSTEN

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2021  
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MASTER'S THESIS 2021

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Filip Alpsten

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Supervisor: Vladimir Gutic, Husqvarna Construction Products  
Examiner: Antal Boldizar, Department of Industrial and Materials Science

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Department of Industrial and Materials Science  
Chalmers University of Technology  
SE-412 96 Gothenburg  
Telephone +46 31 772 1000

Cover: Husqvarna K770 [1]

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## Abstract

Injection molded glass fibre reinforced polyamides are widely used in various components of Husqvarna's powercutters. To increase Husqvarnas knowledge about the environmental impact of such components, and find ways to improve it, a case study on a plastic cover made of glass fibre reinforced polyamide 6 was performed. An analysis of the life cycle of the component highlights the material extraction as the major source of green house gas emissions and that there is little or no connection between end-of-life and material extraction. Based on the component demands, three material candidates with lower environmental impact was selected for prototype manufacturing; one mechanically recycled glass fibre reinforced polyamide 6, one glass fibre reinforced polypropylene and one wood fibre reinforced polypropylene. The following prototype component testing of impact strength, heat resistance and chemical resistance so far indicates that all candidates could have potential to replace the current material for increased sustainability.

Keywords: Glass fibre reinforced polyamide, Glass fibre reinforced polypropylene, Wood fibre reinforced polypropylene, Recycling, Bio-composite, Life cycle assessment



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Filip Alpsten, Jönköping, June 2021



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# 1

## Introduction

### 1.1 General background

The bulk of plastics produced today are based upon fossil feedstocks and are not biodegradable. If not recycled properly, the use of fossil fuel to produce such materials and their contribution to plastic waste accumulation in the world is not sustainable - it simply cannot continue forever. According to Plastics Europe [2], 62 million tonnes of plastics were produced in Europe during 2018. While Europe is considered among the better regions in handling plastic waste, still only 29 million tonnes were collected the same year and of those 42.6% were incinerated, 32.5% were recycled and 24.9% were put in landfills [2].

More public awareness of these problems are forcing producing companies to take action, this not only for ethical reasons but also financial. Stricter regulations are expected and customers demand more sustainable products where plastics have become a particularly sensitive subject. During 2020 Husqvarna rolled out their current sustainability strategy, called "Sustainovate 2025", with goals reaching to 2025 on several aspects. Two of the main goals are:

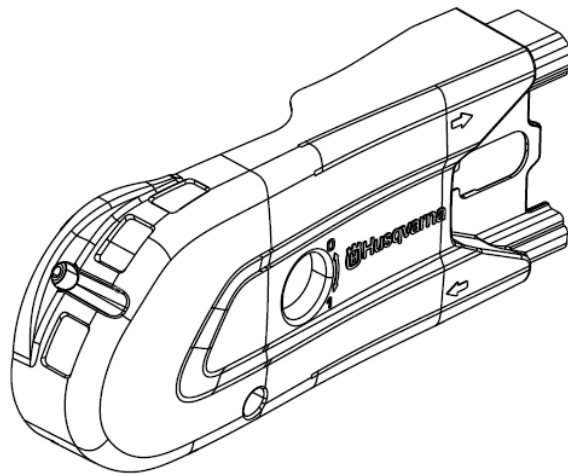
- to reduce the absolute CO<sub>2</sub>-emissions with 35% across their value chain until 2025 (baseline is 2015, a continuation of "Sustainovate 2020")
- to launch 50 circular innovations to rethink and redesign for a more resource-smart customer experience (from 2020-2025)

In a life cycle assessment of the Husqvarna K770 powercutter, conducted for Husqvarna by the company Ramboll during 2019, it was concluded that the use phase stands for the biggest portion of the products GWP (global warming potential in CO<sub>2</sub>-equivalents). This is primarily related to its consumption of gasoline and cutting blades. However, according to Husqvarnas Sustainovate progress report from 2019 [3], substantial progress is already made to this phase through electrification of their product lineup and this is expected to accelerate.

The report also highlights the material sourcing and manufacturing phases as important improvement areas. These are parts of the value chain much influenced by Husqvarna themselves and highly depending on the materials used. The Husqvarna K770 cutter is mainly consisting of, in falling order by mass; steel, plastics, magnesium and aluminum. While there are more established recycling routes for

the metal constituents, there are concerns from Husqvarna around the circularity of the plastic materials used which account for about one fourth of the product mass. Most of these parts are injection moulded fossil-based polyamide 6 (PA6), many of them with glass fibre (GF) reinforcement in varying proportions.

This thesis project aims to contribute to the sustainovate strategy by investigating possible alternative plastic materials and reinforcements with lower environmental impact than those currently used in the handheld cutter K770. To narrow down the scope, one single component of the K770 is selected for investigation; the rear belt guard. The component, seen in figure 1 and on the title page, is made of PA6 with 15 wt% GF-reinforcement (PA6-15GF).



**Figure 1.1:** ISO-view of the rear belt guard of the Husqvarna K770. Picture provided by Husqvarna.

Many of the material property demands of the PA-parts used throughout the K770 are represented in the belt guard. It must survive impacts, high temperature from the clutch, it has in-moulded metal parts and it is a long part so mould shrinkage must be considered. It is also a highly visible part that should be somewhat aesthetically appealing putting demands on surface finish and coloring. A successful implementation of an alternative material for the belt guard could potentially be used for several other components on the K770 and possibly other Husqvarna products as well.

## 1.2 Project aim

The overall aim of the thesis project is to increase the knowledge at Husqvarna about the environmental impact of glass fiber reinforced polyamide 6 parts and how it can be reduced by introduction of alternative materials. The hope is to find a more sustainable material for the belt guard, having potential to replace PA6-15GF, that can lower the CO<sub>2</sub>-emissions across the products life cycle. This without major

changes to design and manufacturing processes. To gain further experience of such material(s), the aim is to produce a small prototype series of belt guards in the alternative material(s) to conduct component tests.

### **1.3 Limitations**

The research efforts will be directed toward the rear belt guard on the K770 cutter. Even if the results of the project may be of value for other components or products at Husqvarna as well, no particular attention will be put to other components or products.

The research front on novel sustainable plastic materials and reinforcements will be investigated briefly, but the focus will be to find a material already available on the market. Husqvarna wants to improve the plastics materials life cycle on a relatively short time scale, therefore completely new material concepts not yet commercialised are of second importance.

Material selection and component design are depending on each other, altering of one of them often requires change to the other. If manufacturing and testing of prototypes show a need for design changes, suggestions might be developed if there is time after the testing phase. But there will not be possible to implement any changes to the injection moulding equipment during this project.

### **1.4 Specification of issue under investigation**

The following questions are intended to be answered through this project to fulfill the projects aim:

- How does the life cycle of PA6-15GF look? What part of the life cycle is most important to improve?
- What approaches are there to reduce environmental impact from reinforced thermoplastic materials?
- What alternative materials are there on the market that have potential to fulfill component demands, be processed in the same injection moulding equipment (with minor adjustments) and reduce environmental impact?
- How does decided material alternative(s) perform in component tests? Can it replace PA6-15GF?
- What improvement in circularity/sustainability is achieved?



# 2

## Specific background to the work

### 2.1 Husqvarna K770 and the belt guard

The Husqvarna K770 is a portable handheld cutting machine powered by a 2-stroke gasoline engine primarily sold to professionals in the construction sector. By fitting different cutting blades it can be used to cut several different hard materials, like steel, rock or concrete. It is most commonly used for concrete cutting as seen in figure 2.1.



**Figure 2.1:** A Husqvarna K770 in action. [4]

The K770 is currently the most sold of Husqvarnas powercutters, sold all over the world with the two biggest market regions being the US and Europe that together

## 2. Specific background to the work

---

constitutes about 85% of the sales. The typical customer/owner of the product is a construction company or a company renting out construction equipment. It is also commonly sold to individual contractors for multi-purpose use within construction or demolition. The machines usually last for about 100 hours of cutting operation before being discarded.

As mentioned, about one fourth of the K770's weight consists of plastics where in turn 85% (2305 grams) of those are PA6-based with various additives (all complying with the RoHS and REACH directives). This includes several rather complicated and to some extent structural or protective parts that also are exposed to elevated temperatures and chemicals.

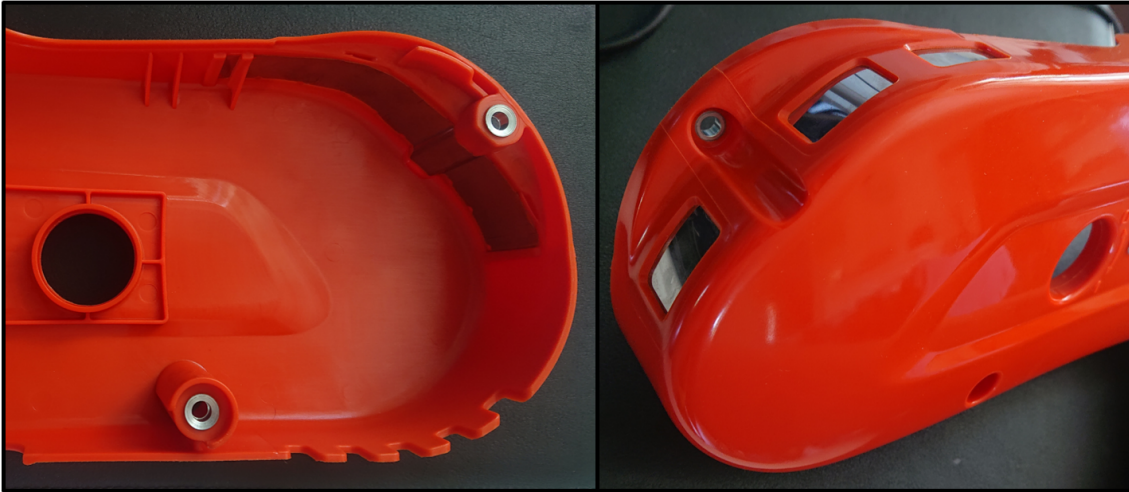
### 2.1.1 The belt guard

The main function of the belt guard is to protect the user of the machine from the moving and hot parts located behind it, a centrifugal clutch and a drive belt. But also the other way around, to protect these mechanisms from the often rough construction site environment. In figure 2.2, both the belt guard itself and the parts it covers are seen next to each other.



**Figure 2.2:** To the left, a Husqvarna K770 with the belt guard assembled. To the right, a K770 with the belt guard removed, revealing the drive belt and the centrifugal clutch behind it.

The rear belt guard, which is focused on in this project, is fastened with two bolts towards the rear of the machine. In the front part, it is also held in place by the front belt guard mounted over it, as seen in figure 2.2. The two bolts are seated against two steel bushings which are in-moulded in the belt guard. A stainless steel plate is also in-moulded in the belt guard, acting as a heat shield, in the area just over the clutch where severe temperature peaks from the friction heat can occur. These in-moulded parts are seen in figure 2.3.



**Figure 2.3:** To the left, the inside of a belt guard with visible in-moulded heat shield and bushings. To the right, the outside the belt guard with the in-moulded heat shield visible.

## 2.2 Concepts

### 2.2.1 Product life cycle and LCA

A life cycle analysis or life cycle assessment, abbreviated LCA, is a systematic analysis and survey regarding some specific measure of a whole life cycle of a product. Most often, and also in this report, it is concerning environmental impact from the inputs and outputs of mass and energy from the processes all the way from material extraction to product disposal. Embodied energy and GWP, also explained further down, are the main measures of focus in this report.

### 2.2.2 Circularity and sustainability

The concepts of both circularity and sustainability are rather freely used in the industry and in the literature, and also somewhat interconnected. But with support from the definitions from the Global Reporting Initiative [5] the concepts can be explained as follows.

Sustainable activities are of such nature that they meet a present need without compromising future generations ability to meet their needs. Or perhaps more simply expressed, activities that can be done over a very long time without causing future problems.

Circularity, or circularity measures, are measures taken to retain the value of products or materials for as long as possible, to minimise extraction of resources and waste generation. This by extending the materials/products time in use or by redirecting them back to use when discarded.

### 2.2.3 Renewable materials and renewable energy

The term renewable in this report is also used in accordance with the GRI glossary [5]. Renewable materials or renewable energy is of such nature that it is derived from resources that are replenished by agricultural processes or ecological cycles on a short time scale. This is often considered close to a human life time so that the availability of these resources are not endangered for future generations.

### 2.2.4 Biodegradable plastics

Whether or not a plastic will biodegrade depends both on the chemical structure of it and the environment it is placed in. Hence, it is not very clear how to define what is a biodegradable plastic. But the process of plastic degradation itself, is defined in [6] as a break down of the chemical structure of the plastic by microorganisms. Thus, not only into smaller pieces, so called microplastics, but to new microbial mass, carbon dioxide, methane and mineral salts.

### 2.2.5 Environmental performance measures

#### 2.2.5.1 Green house gas emissions, GWP and CO<sub>2</sub>-eq

Our emissions of so called green house gases is the major cause to the antropogenic, man-made, global warming or climate change on our planet. The most common green house gas in the atmosphere is carbon dioxide (CO<sub>2</sub>) and it is nowadays convention to relate other green house gases global warming potential to that of CO<sub>2</sub>.

The global warming potential, GWP, of CO<sub>2</sub> is defined to be 1 and for other gases the GWP is defined as how many times more mass of CO<sub>2</sub> that yields the same global warming effect. The warming effect of most green house gases change over time and this must also be considered. The most common time scale considered when comparing GWP is the green house gas warming effect over a 100 year period. [7][8] Based on this the unit used to measure green house gas emissions is the mass of carbon dioxide equivalents, abbreviated CO<sub>2</sub>-eq or CO<sub>2</sub>e.

The term GWP is also often, a bit negligent, referring to the amount of green house gas emissions, expressed in CO<sub>2</sub>e, connected to a certain activity. This both in the literature and in this report. So is also the term "carbon footprint".

#### 2.2.5.2 Embodied energy

Often expressed as the energy required, or invested, in 1 kg of material for a certain activity such as material extraction or a manufacturing process [9]. The carbon footprint is often closely related to embodied energy but does not have to be if renewable energy is used.

Regardless of coming from renewable resources or not it is always important to minimize energy use. Energy is related to costs and the renewable energy should preferably be used to displace the need of non-renewable energy.

## 2.2.6 Material property performance measures

Some maybe not so trivial material performance measures used in the report.

### 2.2.6.1 Heat Deflection Temperature (HDT)

Heat deflection temperature is a measure, often tabulated for plastics, describing the loss of stiffness related to increased temperature in the material. It is defined as the temperature at which a given deflection is reached in a three point bending load case, at a temperature increase of 2°C/minute, at stress levels of 0.45 MPa and 1.8 MPa respectively, for a specimen at standardised dimensions in accordance to the ISO 75 standard [10]. The 0.45 MPa HDT roughly corresponds to the temperature where the stiffness drops below 0.2 GPa and the 1.8 MPa HDT to when the stiffness drops below 0.8 GPa [9].

### 2.2.6.2 Specific strength and specific stiffness

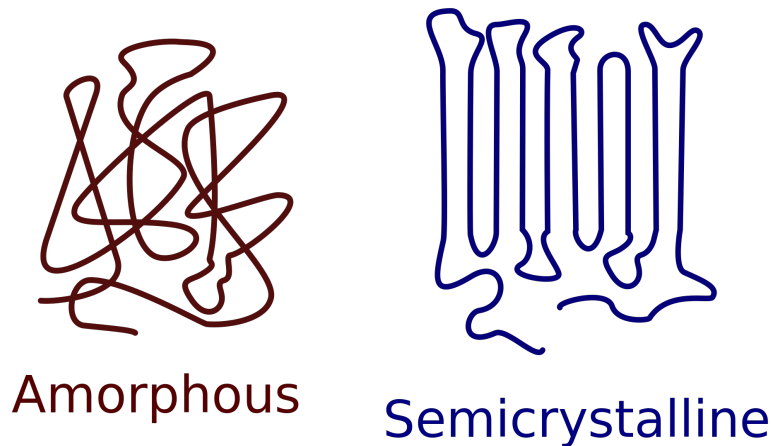
Specific strength and specific stiffness of a material is defined as the respective property divided by the materials density [9]. They can be viewed as strength- or stiffness-to-weight ratio and are useful measures to compare performance of different materials for light structures. Materials with the same specific strength/stiffness show the same performance for the same mass of material.

## 2.3 Thermoplastics and crystallinity

The base material in the belt guard, PA6, is a semicrystalline thermoplastic polymer material. When heated, such a material melts and shows a plastic behavior, hence the name thermoplastic. Upon cooling the material hardens to a solid again. The behavior is reversible and can be repeated many times, this in contrary to thermosetting polymers which do not show this reversible hardening and softening.

Thermoplastics can further be divided by their level of molecular order, or crystallinity, into amorphous or semicrystalline ones. Thermoplastic materials rarely occur fully amorphous or crystalline, but those which are dominated by random molecular arrangement are called amorphous and those with a considerable amount of regularity are called semicrystalline. A representation of both levels of crystallinity is shown in figure 2.4.

The random molecular arrangement of amorphous thermoplastics, similar to that of glasses, makes them transparent and not having a sharp melting temperature. Instead they gradually soften from their glassy state and become more liquid-like over a relatively wide temperature span when heated.



**Figure 2.4:** Representation of the random molecular arrangement in an amorphous polymer and the partly oriented, or crystallised, arrangement of a semicrystalline polymer. [11]

Semicrystalline thermoplastics on the other hand have clusters of polymer chains that are ordered in a pattern referred to as crystals. These crystals reflect and direct light in a fashion that makes the semicrystalline materials non-transparent or opaque. While there normally also are amorphous regions in its microstructure, the crystalline parts dominate the mechanical and thermal behavior. The crystalline parts, and therefore the whole material, have a sharper melting temperature similar to most other solid materials, at which the crystalline parts lose their order.

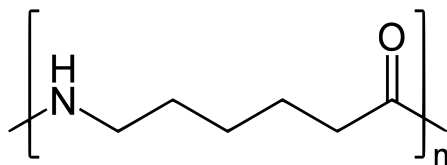
Semicrystalline thermoplastics are generally more ductile and more resistant to chemicals compared to amorphous thermoplastics [12]. They however generally show less dimensional stability and are for example more likely to warp while injection moulded due to the shrinkage related to its crystallisation.

## 2.4 Polyamides and PA6

Polyamides, also known as nylons due to the trademark name used by DuPont when first introduced in the 1930's, are a group of semi-crystalline engineering thermoplastic polymers. They are characterized by their amide-groups  $[-CO-NH-]$  which determines much of their properties like high strength, stiffness, toughness and heat resistance [13].

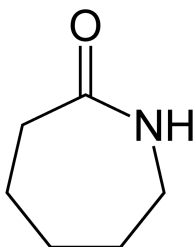
Today there are a large number of different polyamides, some examples are PA6, PA6.6, PA6.9, PA6.10, PA6.12, PA4, PA4.6, PA4.10, PA10.10, PA11, PA12 and many more. They are named after the number of carbon atoms in the backbone of the repeating unit of the polymer chains [13]. Some polyamides have two amide-groups in the repeating pattern of their molecules and are therefore named according to the number of carbon atoms between both of them like for example PA6.6.

For the case of PA6, the repeating unit, or monomer, that builds up the polymer molecule is  $[\text{NH}(\text{CH}_2)_5\text{CO}]$ , this is visualised in figure 2.5.



**Figure 2.5:** Illustration of the chemical structure of the repeating unit in the polymer chains of PA6 [14].

There are polyamide grades derived from renewable resources, but PA6 almost exclusively rely on fossil crude oil and natural gas as its feedstocks. By several steps of oxidation reactions and catalytic rearrangement of benzene and propylene the ring formed molecule caprolactam is obtained, seen in figure 2.6. This ring is then opened and polymerized to form PA6 resin [15].



**Figure 2.6:** Illustration of the chemical structure of caprolactam [14].

The polyamides, including PA6, are hygroscopic and absorb moisture from the environment. This is also due to the amide groups in their molecules and the moisture content has considerable effects on both dimensions and properties. Among the many different types of polyamides, high "amide density", meaning shorter distance between the amide groups, generally correlates to higher water absorption. The amount of water absorbed also depends on the humidity and temperature in the surroundings and it constantly changes with it.

Absorbed water in polyamides acts as a softening plasticiser, significantly reducing strength and stiffness but also increasing elongation and impact strength. For the specific material used in the belt guard, PA6-GF15, these properties can vary by roughly a factor of 2-4 between perfectly dry material and material conditioned in 50% relative humidity as seen later in table 4.1 and in the material data sheet from the supplier [16]. In even more moist conditions, causing higher water absorption, this effect is more prominent.

## 2.5 Injection moulding of thermoplastics

The belt guard is, along with most other plastic components in the K770, manufactured through injection moulding. The process allows for cheap, fast and accurate manufacturing of complex shapes for high production volume products. There is often, as for the belt guard, no need for additional manufacturing steps after injection moulding.

The basics of the process is that a thermoplastic polymer is melted to a liquid state, then injected under pressure into a mould cavity of desired shape where it is allowed to cool and solidify while kept under pressure. The solidified part is then ejected from the mould as a finished part.

The thermoplastic material feed into injection moulding machines are typically in the form of pellets or granules, an example can be seen in figure 2.7.



**Figure 2.7:** Typical plastic pellets, the raw material fed into an injection moulding machine. [17]

## 2.6 Strategies for lowered environmental impact from plastic materials

This section brings up some of the research on lowering environmental impact from plastic products life cycles that was found during the literature study in the beginning of the project.

To approach Husqvarnas goals on circularity and carbon decoupling, see section 1.1, an ideal life cycle to strive for with the belt guard could look like follows:

- Raw material comes from recycled plastic and eventual needed addition of virgin material comes from renewable sources.

- Manufacturing uses as little energy as possible, only renewable energy and waste material goes back to the circle.
- Minimal transports only using renewable energy sources.
- During use phase it lasts for a long time and is as light as possible.
- After life the belt guard comes back to Husqvarna or to the right recycling facility and waste stream. The value of the material should be kept as high as possible through mechanical and/or chemical recycling.
- If the material is mechanically recycled, it may be downgraded to a lower performing material after several cycles. After additional steps and final disposal, energy recovery or decomposing is preferred over landfilling. It might as well be upgraded again through chemical recycling.

It may be hard to live up to all these things because of lack of infrastructure or due to economic reasons. But something close to this could be aimed for under these circumstances where major design changes cannot be made. Below are some possible strategies, found in the literature, that can reduce environmental impact during the life cycle of the belt guard.

### **2.6.1 Alternative matrix materials**

Here some alternative approaches of how to lower the environmental impact from the thermoplastic composite matrix materials are brought up and discussed.

#### **2.6.1.1 Biodegradable matrix materials**

At a first glance biodegradable plastics, defined in section 2.2.4, materials can be seen as a good alternative to conventional ones considering that plastic waste management is such a big problem in the world. But the environmental performance gains can be questioned in many ways for many different applications. To begin with, the so called biodegradable plastics, are actually rarely degraded under conditions occurring in the natural environment under a reasonably short timescale. They most often require specific conditions only maintained in industrial composting facilities.

Secondly, even if composting of biodegradable plastics is a way to get rid of waste plastic, and can yield useful bi-products like biogas and fertiliser, it is still not a really desirable life cycle. Such a highly refined resource as a plastic material should be used as one for as long as possible and not just be degraded. A more accurate use of biodegradable plastics is instead in applications where it is hard to either avoid plastic fragments ending up in the environment or where it is hard to collect it from the environment. [6]

Even though there are several examples of plastics classified as biodegradable with good mechanical properties, e.g. reinforced PLA [18], most of them show to low thermal properties and resistance to chemicals for the considered application.

To conclude about biodegradable plastics as matrix material:

- Today it does not exist, at least not many, biodegradable plastics having sufficient thermal properties and chemical resistance to be used in the K770 belt guard.
- The attribute of being biodegradable is not directly related to any environmental performance gain in a product like the belt guard.

### 2.6.1.2 Matrix material from renewable feedstocks

The major advantage of producing plastic materials from renewable biomass feedstocks is the decoupling from fossil feedstock dependency. Fossil hydrocarbons are a finite resource that eventually always will bring more green house gases to the atmosphere when brought up to the surface. The crops used as renewable feedstock material instead bind CO<sub>2</sub> from the atmosphere while growing. This is most often compensating for a significant part of the remaining CO<sub>2</sub>-emissions from the extraction process.

This is not always the case though, the CO<sub>2</sub>-footprint of a renewably sourced plastic can of course also be higher than a fossil one depending on the production process. Energy use during farming of the crops and the chemical processes to convert them to polymers is often the major part of these emissions. The dependence of fossil fuels for this energy need can be expected to decrease though as efforts are made all over the world to shift to renewable energy sources.

There is a great number of possible renewable feedstocks and many different types of plastics that can be made from them. But it is in most cases preferable to use a crop that is fast growing and that require relatively small amount of land and watering. It should neither directly compete with the production of food. The ideal is residual products from crops that serve several purposes, for example waste parts of food crops or waste from wood industry.

Regarding PA6, there is research going on to produce caprolactam, the base for PA6, from renewable feedstocks through fermentation [19]. But it seems to be far from commercialisation and the world PA6 supply is still depending on fossil fuels. Winnacker and Reiger [20] have also reviewed many of the already commercial biobased polyamides and some others that are upcoming.

There are several well established fully or partly biobased polyamides extracted from castor bean oil (*Ricinus Communis*), like PA4.10, PA6.10, PA10.10, PA11 and PA12. These have all been commercially available for some time and the PA11 for

as long as 70 years. Most of them does not show any major reduction of carbon footprint compared to PA6 though, and while also being much more expensive they are mostly used where some particular properties are sought for. Composites with biobased polyamide paired with natural fibres are handled in the section for natural fibres (2.6.2.1).

### 2.6.1.3 Recycled matrix material

Thermoplastics are generally, per definition, possible to recycle mechanically (i.e. shredded, melted and reshaped). This is the most common technique used today and also the most resource and cost efficient and can roughly save 2 kg CO<sub>2</sub> per kg of plastic depending on plastic type [21]. But mechanical recycling is generally related to some degradation of the polymer chains and the material properties with each recycling step due to contamination as well as the mechanical and thermal stress it is exposed to.

They can also be chemically recycled, which can be likened to a chemical demolition and reconstruction of the material. Performance wise, chemically recycled plastics have the same properties as virgin plastics. The method can therefore be used to upgrade plastics partly degraded from mechanical recycling. It is however generally more costly, both economically and in terms of energy use, compared to mechanical recycling.

With current low recycling rates and the plastic waste accumulation seen in the world, perhaps the most responsible way to source plastic is by basing it on the plastics already existing. In most cases carbon footprint can be lowered compared to virgin materials, even though there are exceptions, and as mentioned plastic waste is reduced (or at least not increased). For certain is, that plastic waste exist in huge amounts in the world. This both in somewhat controlled landfills and out in the natural environment on land and in seas.

One example is discarded or lost fishing nets in the oceans. According to Mondragon et al. [22], it is estimated that 640 000 tonnes of discarded fishing gear ends up in the oceans yearly, which makes up about 10% of all marine plastic waste generation. The major part of the fishing nets are made of PA6 or PA66. The same study also investigates the physiochemical and mechanical properties of such waste collected from the ocean. They report that even after commercial use as fishing equipment and after floating around in the ocean for a considerable time, the properties of the PA6 from recovered fishing nets are almost indistinguishable from virgin PA6 also being thermomechanically reprocessed once. One such PA6 resin, based on recycled fishing nets, is commercially available from the company DSM under the name Akulon RePurposed [23].

Some conclusions about recycled plastics:

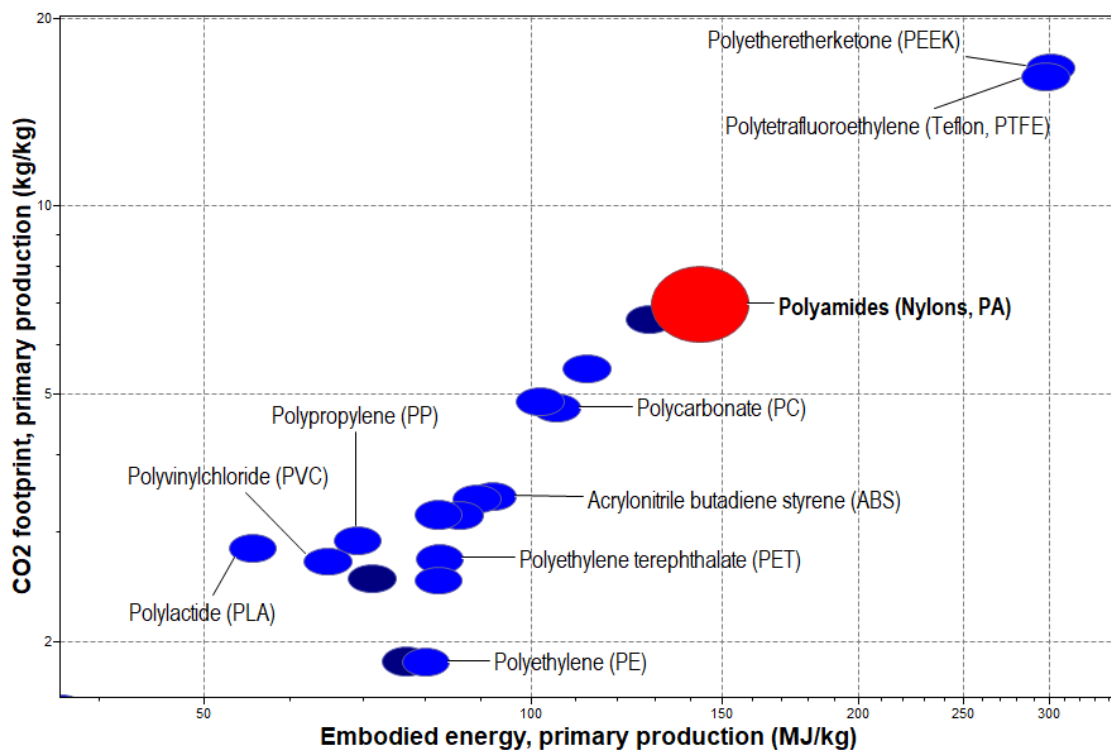
- most often savings in energy demand and carbon emissions
- no new plastics needs to be manufactured

## 2. Specific background to the work

- most often more costly and somewhat reduced performance (at least if mechanically recycled)
- at the moment the availability of recycled plastics are relatively low, but this is expected to improve and demanding recycled plastics should be a driver on plastic recycling development

### 2.6.1.4 Conventional matrix materials with lower environmental impact

As mentioned, and seen in figure 2.8, there are several other conventional fossil based thermoplastics with significantly lower CO<sub>2</sub>-footprint compared to PA6. Two of those with the lowest carbon footprint and embodied energy, while still having property profiles comparable to that of PA6, are polypropylene (PP) and polyethylene terephthalate (PET). Both PP and PET show a carbon footprint about one third of that of PA6 per kg of resin, this due to less complicated and energy demanding chemical processing. But PET have more than 50% higher density than PP and is somewhat less suitable for injection moulding compared to PP and PA6 [9].



**Figure 2.8:** Embodied energy vs. CO<sub>2</sub> footprint for some well known thermoplastics. Data taken from and diagram made in the software Granta Edupack [9]. The embodied energy is defined as energy used during material extraction from feedstock to plastic pellets. CO<sub>2</sub>-footprint are CO<sub>2</sub>-equivalents produced and released into atmosphere measured from feedstock to plastic pellets.

PP is, next to PE, the most widely used plastic today [2]. It has a simpler chemical structure and extraction process than PA6 and is therefore both cheaper and

less resource demanding. It has slightly lower mechanical performance compared to conditioned PA6 but thanks to its lower density (about  $0.9 \text{ kg/m}^3$  compared to  $1.15 \text{ kg/m}^3$  for PA6) the specific properties are similar or better. Chemical resistance is generally comparable or better but it lacks in melt temperature and HDT.

PP has generally been considered as a standard, or commodity plastic, widely used in less demanding applications, for example packaging, household products and furniture. But it is starting to be used more and more in engineering applications in the recent years. In the automotive sector a trend to shift from the more advanced engineering plastics towards PP is starting to happen even in so called "under the hood"-applications where temperature is high for extended periods [24] [25]. This is driven by savings in weight, cost and to some extent  $\text{CO}_2$ -emissions, much similar to the shift from light metal to engineering plastics in many automotive components some 30-40 years ago.

## 2.6.2 Alternative reinforcements/additives

Glass fibres have been the "go to" reinforcement for engineering thermoplastics in the industry for quite some time, and no wonders why. It provides high strength, binds well to most matrices, can withstand high temperature, is hydrophobic, not sensitive to chemicals and it is also reasonably priced. But, as analysed in section 4.1, it is non-renewable, requires much energy during manufacturing and have a big carbon footprint. Some alternatives with lower environmental impact are handled here.

### 2.6.2.1 Natural fibers

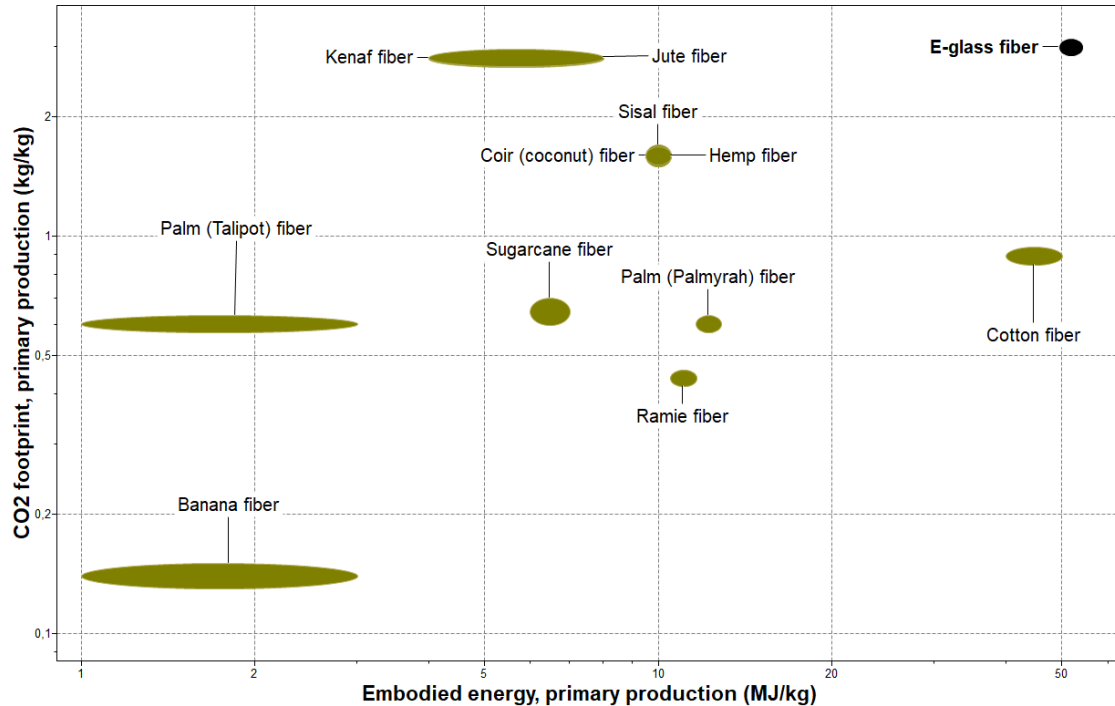
Natural fibers, abbreviated NF, in more or less processed form, have been of increasing interest for researchers as a way to reinforce thermoplastics to a lower environmental cost than with glass fibers for the last 20 years or so. Natural fibers and plastics is not a new concept, one early example from the beginning of the 20th century is bakelite, a thermosetting plastic often reinforced with cotton or paper and used for various applications such as electronics, household goods and automotive parts [26]. Today, when the use of current reinforcing additives to plastics are highly developed and high performing, the driver to introduce natural fibers in plastics is to shift towards more sustainable renewable sourcing.

There is a vast variety of natural fibres being researched on or used as reinforcement for thermoplastic composites found in the literature. A few of them, thoroughly reviewed by Faruk et al. [27] and Mohammad et al. [28], are fibers from bamboo, jute, kenaf, flax, sisal, hemp, ramie coir(coconut), abaca(banana), curaua(pineapple leaf). From their reviews one can conclude that there is good potential for increased use of natural fiber composites.

The main advantages of natural fibers, compared to GF, are lower price, lower density (most often between  $1\text{-}1.5 \text{ g/cm}^3$  vs.  $2.6 \text{ g/cm}^3$ ) and most often also a distinct

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reduction in carbon footprint, as seen in figure 2.9. Natural fiber composites are also more suitable for the more and more common incineration of plastic waste with energy recovery. This since it gives more combustion energy and less residue to landfill compared to GF-composites.



**Figure 2.9:** Diagram showing embodied energy vs. CO<sub>2</sub>-footprint for glass fibre and for some natural fibers available in the Granta data base [9].

Thanks to the significantly lower density, it is not uncommon that the specific strength (strength per unit mass) and specific stiffness of NF-reinforced plastics are on par or better than that of GF-reinforced plastics [27] [28] [29].

Santos et al. [30] reports mechanical and thermal properties of PA6 reinforced with 20 wt% caraua fibers (pineapple leaf) in a study on comparing different fiber treatment methods for increased improved bonding between fiber/matrix. The most effective method yielded a biocomposite with similar mould shrinkage, impact resistance and HDT as PA6 with 20 wt% GF. It showed lower strength and stiffness but specific values where comparable. Parts of the fibers started to show thermal degradation above 220 degrees and the material did absorb about double as much moisture over time.

As in [30], thermal degradation at high temperature, moisture absorption and interfacial adhesion seems to be the main challenges or disadvantages with NF-composites in general [31] compared to GF-composites. The natural fiber production is also most often seasonal, so availability and properties of fibers may vary during and between seasons. These challenges are likely the reasons behind why there still are

relatively few NF-reinforced plastic materials available on the market compared to the trusted GF-reinforced ones. It is also worth noting that the only commercial NF-reinforced thermoplastics found during this project have matrices of lower melting/processing temperature, e.g. PLA, PE and PP.

During 2012, the company Evonik launched a few of their fully or partly biobased polyamides reinforced with so called man-made cellulose fibers, also known as rayon or viscose [32] [33] [34]. These products were later discontinued and are no longer available from Evonik. This has been confirmed, but not further explained, in conversations with representatives from Evonik.

However, these materials, along with PA6 with man-made cellulose fiber reinforcement were also studied by Feldmann and Bledski [35] during 2013. The study reports very similar strength, stiffness and HDT performance as with GF-reinforcement in the same weight proportions and energy absorption at impact exceeding that of GF-reinforced. But they also highlight the importance of as low thermal stress history as possible, to prevent the fiber degradation, to achieve these results.

## 2. Specific background to the work

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# 3

## Method

### 3.1 Literature review

Reviewing of literature and studies relating to the project scope played an important part in the work to gain knowledge for informed decisions during the thesis project and for further work. This included searching for studies, books and other literature reviews concerning for example bio-based engineering thermoplastics, thermoplastic composites, polyamides, recycling of composite materials, circular economy for plastics etc. Searches were made on search engines like Scopus, Web of Science and Google Scholar as well as through the Chalmers Library mainly focusing on studies less than ten years old. Even some internal reports from Husqvarna, like product life cycle assessments, annual reports, etc., were studied.

In a later stage alternative materials and data was searched for from plastics suppliers websites and through third party materials selection sites or softwares including for example Granta Edupack [9].

### 3.2 Stakeholder communication

The project progress was discussed regularly with the project supervisor, a product designer at Husqvarna, to ensure the work was in line with Husqvarnas expectations and to get a good understanding of the component demands. Communication with the belt guard supplier, Essge-Plast, who manufactured the prototypes, was also important to understand the manufacturing process. Some additional persons at Husqvarna were also involved during different stages of the project, including another design engineer, the product engineer manager for handheld powercutters, a test engineer and also the product service manager. Brief discussions were also held with the recycling companies Svensk Plaståtervinning and Stena Recycling.

### 3.3 Materials selection

The initial literature study (2.6), along with the analysis of the current life cycle (4.1) and of the material property demands (4.2.1), formed the base for materials selection and directed towards a few different possible paths for lowered environmental impact of the belt guard. Several European suppliers with materials of interest

where contacted to discuss their portfolios, those with which the closest correspondence occurred where DSM, Stora Enso, Borealis, Evonik and Arkema.

With these suppliers, detailed discussions about the material property demands, environmental profiles and whether or not the materials were available in large volumes in the near future lead to a group of eight material candidates presented to Husqvarna. Together with a group of three product engineers, all working with development of the K770, three materials were decided to be tested in this project. These are presented together with motivation to the choices in section 4.2.2.

## 3.4 Evaluation of suggested materials

### 3.4.1 Prototype manufacturing

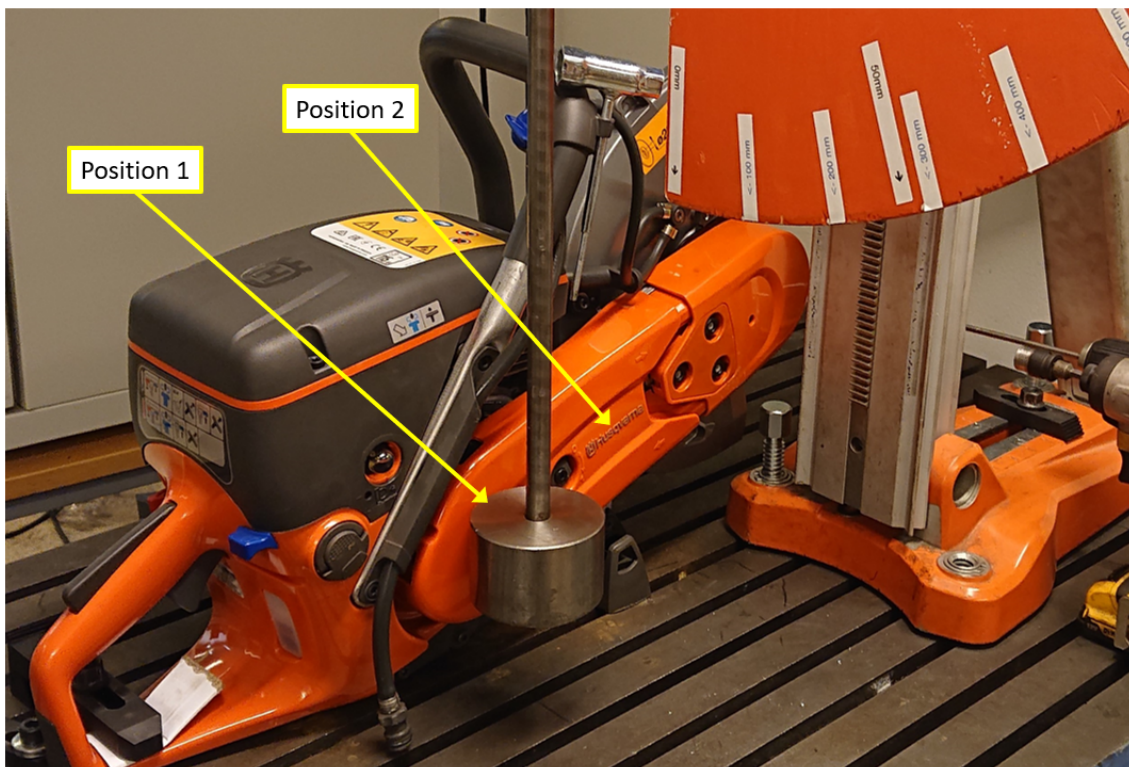
To evaluate the performance of the material candidates prototypes were manufactured. Samples of the selected materials (4.2.2), 25 kg of each, were ordered to the belt guard manufacturer Essge-Plast in Östersund for injection moulding. The prototypes were processed in the same equipment as the belt guard currently in production.

Unfortunately it was not possible for the author to be present during prototype manufacturing because of the restrictions due to the covid-19-pandemic. But Essge-Plast states that the processing parameters were chosen much alike the respective materials suppliers recommendations. 24 belt guards of each material was sent to Husqvarna for testing.

### 3.4.2 Impact testing

Husqvarna have developed a specified testing procedure for evaluating the impact strength of the belt guard as a component. This procedure was followed also for evaluation of the prototypes and is briefly described below.

With the belt guard assembled on a K770 it was hit by a pendulum, with higher and higher impact energy for each hit, until the component loses functionality. This was done on two positions on the belt guard with a new part used for each position. Prior to testing the samples were dried in a climate chamber for several days and thus tested without the possible plasticising effect of absorbed water. Hence the worst case scenario for the polyamides are captured. Two belt guards of each material was tested in each position, meaning 16 belt guards, including the current production components as reference. The test setup is shown in figure 3.1.



**Figure 3.1:** The setup for impact testing of the belt guards. A K770 is attached to the base and hit by the pendulum. The positions impacted were at the clutch (position 1) and at the cutting arm (position 2).

### 3.4.3 Heat resistance

Husqvarna have identified some situations, occasionally occurring on the field, where the centrifugal clutch behind the belt cover is slipping for extended time due to improper use of the machines. The friction heat generated can lead to severe temperature peaks at the clutch eventually also affecting the belt guard. To mimic these situations Husqvarna have developed a testing procedure which also was followed to test the belt guard prototypes. This is briefly described below. More information about the machine layout is found in section 2.1.

With the cutting blade locked to inhibit its rotation the engine is operated at full throttle for a specified time. This causes the clutch to slip and converting all power output from the engine to friction heat in the clutch. After this time the machine is shut off and allowed to cool down. This procedure was done for one belt guard of each material including a standard belt guard as reference. After this procedure the belt guard is allowed to show some damage but must still be able to protect the user from the moving parts behind the cover and must be possible disassemble and re-assemble to the machine. A picture of the setup is seen in figure 3.2



**Figure 3.2:** A K770 with a standard belt guard cooling down after extended clutch slipping.

The test was also conducted with an extended time period of clutch slip to find a limit for what the belt guards could withstand. All these runs ended with a drive belt failure, also due to overheating, this after about three times longer time than the minimum requirement. After all these extended test runs, the machine needed to be sprayed with water immediately and could not be allowed to passively cool down as in the shorter test runs. All results are presented in section 4.3.4.

#### 3.4.4 Chemical resistance

To get an idea of how the different materials react to some of the chemicals the machines commonly encounter a simple chemical test was performed with a following impact test.

After four days of drying in a climate chamber, four belt guards of each material was first covered with a basic solution of water and calcium hydroxide for one day to mimic the alkalic concrete/water-slurry commonly obtained when cutting. Thereafter the belt guards were cleaned with four different chemicals often used by customers to remove the slurry from the machines; two types of acidic detergents, one alkaline degreaser and one so called "multispray" based on hydrocarbons. The belt guards were covered also in these chemicals for a few days before the impact testing was performed according to the same test procedure described in section 3.4.2 except the drying. The results are presented in section 4.3.5

# 4

## Results and Discussion

### 4.1 Current life cycle with PA6-GF15

Here the analysis of the current life cycle of the belt guard will be presented and discussed, mainly concerning environmental aspects as energy use and carbon footprint. Some conclusions about this is summed up in section 4.1.6.

#### 4.1.1 Material extraction

The material currently used in the belt guard is a polyamide 6 with 15% glass fibre reinforcement provided by the supplier DSM under the name Akulon® K224-G3. Both the PA6 matrix from fossil oil feedstock and the GF-reinforcements are to be considered as non-renewable materials.

Looking at the PA6 resin alone, it contains no recycled content and uses fossil oil and natural gas as feedstock. This is a non-renewable resource that eventually also brings more green house gases to the atmosphere, simply not sustainable. The extraction process from this feedstock is also quite resource intensive due to a rather complex extraction process [15].

Energy and water consumption is high during resin production and so is therefore generally also its green house gas emissions. This was seen in figure 2.8, a diagram showing embodied energy vs. CO<sub>2</sub>-footprint for PA6 and other common thermoplastics. DSM themselves claim a 6 kg carbon footprint per kg of Akulon K224-G3 resin while the Granta database reports 7 kgCO<sub>2</sub>/kg and 125 MJ/kg embodied energy for PA6-GF15. [9]

Since PA6 is a relatively highly refined plastic material, with much energy invested in it, there is great potential to reduce the energy use and CO<sub>2</sub>-emissions by using recycled material, instead of virgin, if possible. There are also several other types of plastics with significantly less energy intensive extraction process than PA6 worth considering.

It is not known what glass fibre type that is used in Akulon® K224-G3, but the base materials are usually the minerals alumina (Al<sub>2</sub>O<sub>3</sub>, calcia (CaO) and silica (SiO<sub>2</sub>) [9], which are not considered as a renewable resources. However, the potential problems of using these common minerals are less prominent compared to the fossil oils since they do not lead to a direct increase of green house gases and exist in greater

quantities compared to fossil oils.

The carbon footprint of the most common glass fibre type for thermoplastic composites, so called E-glass, is around 3 kgCO<sub>2</sub>/kg according to Granta [9]. As seen earlier in figure 2.9 there is a potential reduce this down to one tenth with some of the natural fibres. While on the other hand, the also occurring carbon fibres, have a drastically higher carbon footprint of around 20 kgCO<sub>2</sub>/kg instead.

### 4.1.2 Manufacturing

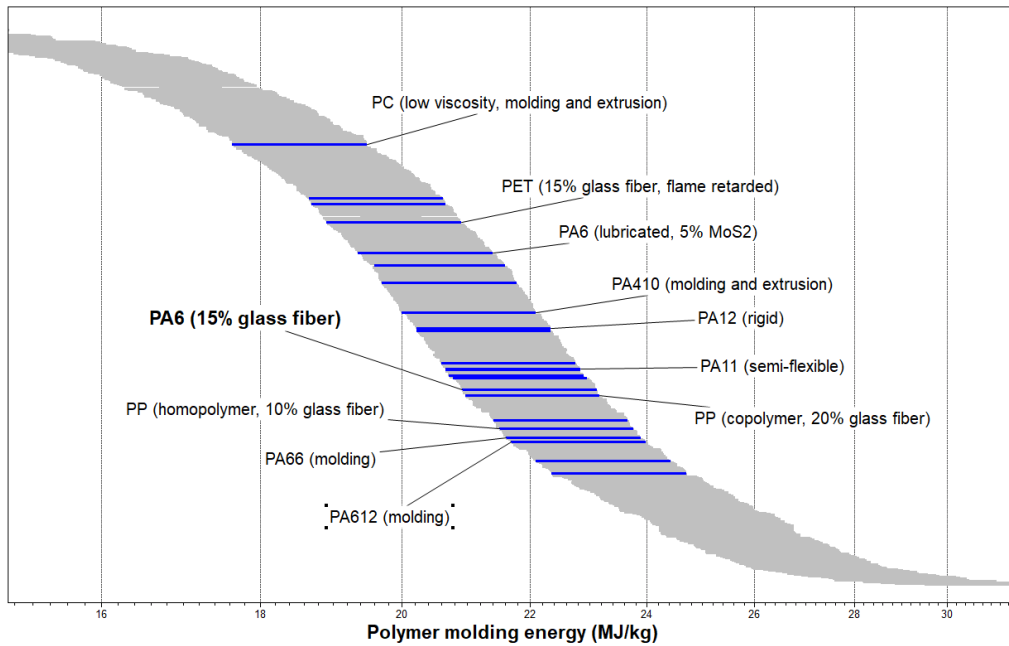
The belt guard is injection moulded in one piece and gets its final shape in this single step (except from the heat shield and the bushings). This is a fast and cheap process that produce very little waste, but it is actually quite energy demanding. Both the energy use and the CO<sub>2</sub>-emissions connected to the injection moulding process stands for some 15% of the totals from feedstock to finished belt guard as seen in figure 4.4.

Expressed in CO<sub>2</sub>-footprint per kg material and embodied energy per kg material the moulding process accounts for about 22 MJ/kg and 1.65 kgCO<sub>2</sub>/kg [9]. The carbon footprint from the moulding process might though be lower than reported from Granta. The moulding occurs in Sweden and the swedish electricity mix have a high portion of renewable electricity sources. The energy demand of 22 MJ/kg should however be quite accurate regardless location.

To put this in relation to some other process, it can be compared to the die casting process of Al and Mg which also is widely used by Husqvarna for other components. The processing for these materials both requires about 11 MJ/kg of energy and 0.8 kgCO<sub>2</sub>/kg [9], so roughly half the values of PA6. Even though these are very different materials, not straight off comparable with PA6-GF15, and with about 120% and 40% higher density respectively, the comparison might be surprising.

The energy requirement for the injection moulding process does not vary particularly much between different polymer resins. But the differences occurring are mainly depending on melt temperature and melt viscosity of the material. When looking at plastics with similar mechanical properties, thermal properties and price, a variation between approximately 18 and 25 MJ/kg is found. PA6-GF15 lays somewhere on the middle of this scale which is visualised in figure 4.1.

To conclude, the injection moulding process is with the current material a minor part of the total GWP and energy demand. Without totally changing the design of the belt guard there is no real alternative to injection moulding as forming method. There is neither much potential to decrease energy demand, and by so also the GWP, by altering to other materials with similar performance as PA6-GF15. The moulding process emissions did therefore not play a big part in the materials selection process.



**Figure 4.1:** Polymer moulding energy for plastic materials in the GRANTA database. The grey lines are all plastic materials available in the database and the highlighted blue lines represent some materials with similar mechanical and thermal properties as PA6-GF15. Data taken from and diagram made in the software Granta Edupack [9].

### 4.1.3 Distribution

Husvarna themselves identify distribution and transportation of materials, components and products as a very small part of their total carbon footprint, and also as something they have little influence of [3]. The transports coupled to the material selection is a minor part of the life cycle energy demand and carbon footprint for the belt guard. The raw material (plastic pellets) is produced in the Netherlands, shipped to northern Sweden for injection moulding then back to south of Sweden for assembly before shipping to a customer.

Excluding final shipping to customers the transports contribute to about one percent of the total life cycle energy demand according to the simplified LCA performed in Granta, presented in 4.1.6. Even if the material supplier, injection moulder and assembly plant would be located as far away from each other as possible on the planet, the relative contribution of energy demand from transports are likely to stay below 5% according to the Granta LCA.

The software also provides a cost analysis over the life cycle, and this shows that the transports stands for about a three times larger portion of the life cycle cost as the life cycle energy demand and carbon footprint. It is thereby likely that economic incitements to shorten transport routes occur before the transports would stand for a significant portion of total emissions.

### 4.1.4 Use

During the use phase, the belt guard does not have any considerable interaction with its environment and the component is also fairly weight optimised. The component also seems to be durable, there are few warranty errands related to it and the spare part sales are also quite low compared to production volume. The conclusion is that the component normally outlast the life time of the complete machine and that the room for improved sustainability in this life cycle phase is small.

### 4.1.5 End of life

Being a thermoplastic material, PA6 is perfectly suitable for both mechanical and chemical recycling. As for most additives, the GF-reinforcements makes recycling more challenging and often also narrows the area of use of the recycled material to some extent. But even with the GF-reinforcement in the belt guard the material is possible to recycle though it demands more accurate recycling streams.

The owners manual for the K770 [36] says, about disposal of the product, that "When the product is no longer in use, send it to a Husqvarna dealer or discard it at a recycling location.". Husqvarna does neither keep track of to what extent disposed machines are collected by dealers, nor what happens to the machines if it is done. Even if the machines would be collected by dealers, based on the further analysis in this section, it is assumed that this still not would increase the chances for the material to be recycled.

As Husqvarna themselves have identified in the Sustainovate report [3], they do not have much control over what happens to disposed products. Instead it is mostly depending on current practice and regulations on the respective markets where the products are sold. USA and Europe are the biggest markets both for Husqvarna Construction Products in total and for the K770. Of the K770 cutters sold during 2019, the two regions together made up around 85% of the sales according to Husqvarna. Looking at plastic waste handling in these two regions can give a good indication of what happens to the discarded belt guards. Waste management statistics for the regions are seen in in figure 4.2 and 4.3.

Considering the statistics for US, figure 4.2, around 75% of collected plastic waste goes to landfill, and as little as 8% is recycled to new materials. The numbers presented only considers collected plastic waste, production is higher. It also seems likely that even less portion of discarded PA6-GF15 gets recycled due to the complications introduces with the added glass fibres. A rough but not implausible assumption is to consider all discarded belt guards to be put in landfills on this market.

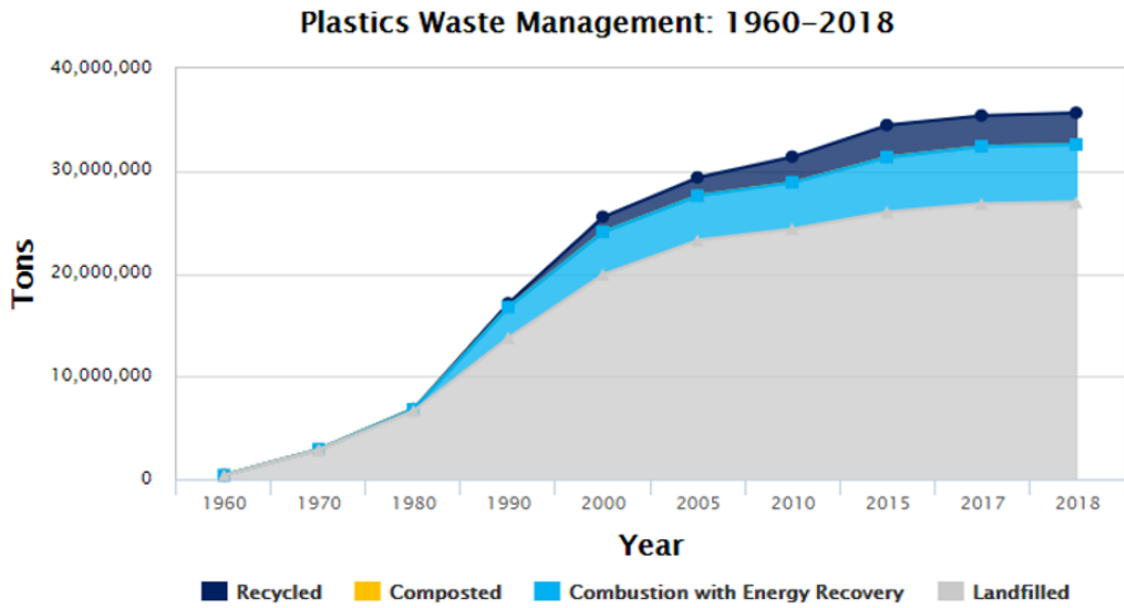


Figure 4.2: Plastic waste management in US between 1960-2018 [37].

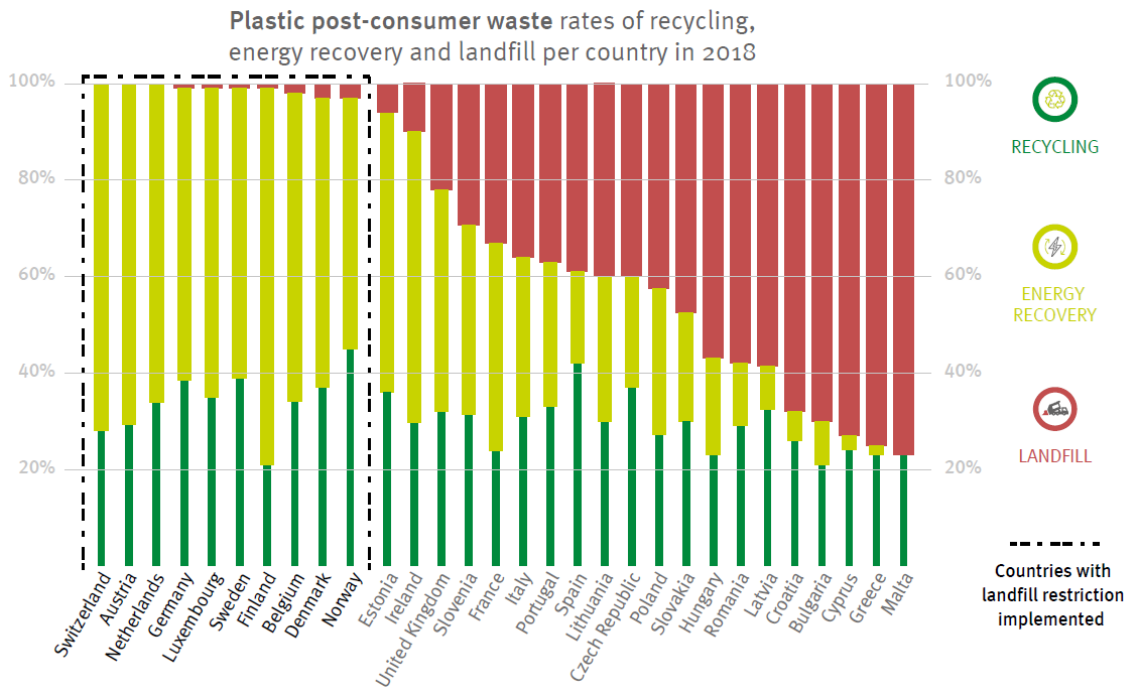


Figure 4.3: Plastic waste management in Europe 2018. These numbers are for the 29 million tons collected, the same year the European production reached 61.8 million tons. Source: *PlasticsEurope - all rights reserved* [2]

The European market handles plastic waste a bit different compared to the North American. On average during 2018, 42.6% of the collected plastic waste was energy

recovered (incinerated), 32.5% was recycled and 24.9% was put in landfill [2]. Figure 4.3 shows how these three end of life treatments are portioned in respective country. Also here, considerable portions of plastic waste are landfilled even though it is far away from the US statistics, and there is also a big variation between the European countries. Even though about one third of collected plastic waste is recycled in the region, Plastic Europe also state that the bulk of that portion comes from packaging material and not engineering plastics.

It should be clarified though, that even in Europe, less than half the amount of the 61.8 million tons of plastics produced in the region where collected as waste. This is probably due to several reasons, for example that plastic raw material and products are being exported and that plastics still in use in products increase. But also because plastic is lost to municipal or industrial solid waste or lost to the environment in some other way.

While the recycling statistics presented in figure 4.2 and 4.3 considers all types of plastics, some indicators more closely related to PA6 specifically might also be worth to mention. One indicator is that the Granta database [9] reports that the recycled fraction in material production (world) is about 0.7% for plain PA6 and around 0.1% for PA6-GF15. The same values for the other three main constituents of the K770 powercutter, steel aluminum and magnesium, are around 50%, 45% and 35% respectively.

In conversations with Stena Recycling in Sweden, they say that for complex products like the powercutter, the plastics are most likely to be incinerated and that eventual GF-residues are landfilled. Discarded cars are also of a somewhat similar complex material composition, mainly consisting of different metals and plastics, where polyamides also are commonly used. During 2019, Sveriges Radio [38] revealed that even though the car industry have a legal requirement to recycle 85% of the mass of discarded cars to new materials, still virtually nothing of the plastics where recycled in Sweden. Regarding products like powercutters, there does not seem to exist such legislation.

It is reasonable to assume that there is almost no chance that the belt guards are recycled to new high value materials at the moment. Most of them will probably either be incinerated in Europe or end up in landfills in the US. Both these waste treatment methods are to be considered as unsustainable. While incineration with energy recovery is to prefer over landfilling, the energy recovered is very small compared to what is invested in the material. According to the LCA results presented in section 4.1.6, incineration of 1 kg PA6-GF15 material causes 1.5 kg of extra carbon emissions to get back as little as 6% of the energy invested in the material. Something that within economics, would be expressed as an ROI (Return On Investment) of -94%. The glass fibres do not add to the recovered energy and the residues still needs to be landfilled.

#### 4.1.6 Summary and conclusions about the current life cycle

Based on conclusions drawn about the belt guard life cycle in the analysis above, a simplified LCA was performed in the software Granta EcoAudit [9]. The LCA is performed for 1 kg of injection moulded PA6-GF15, including 2600 km of road transports on truck with incineration with energy recovery as potential disposal method. The main results are summarised in the diagrams seen in figure 4.4 and 4.5. The incineration with energy recovery (EoL potential) is not included in the values of relative life cycle phase contribution in figure 4.5, instead it shows what the potential impact is.

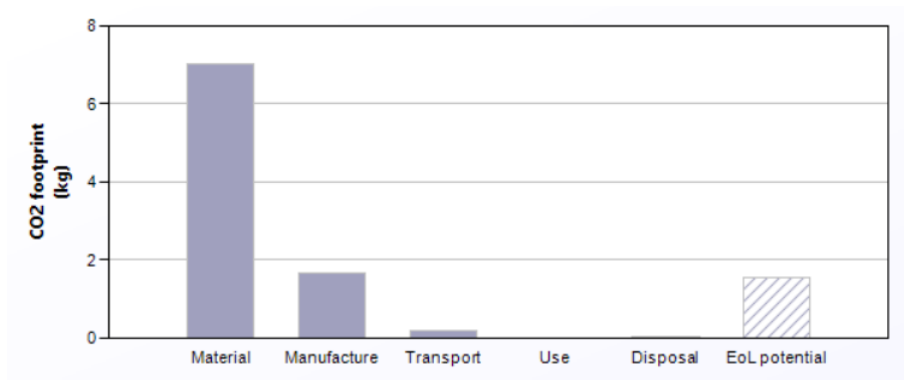


Figure 4.4: GWP-data calculated with Granta EcoAudit [9] for 1 kg of PA6-GF15.

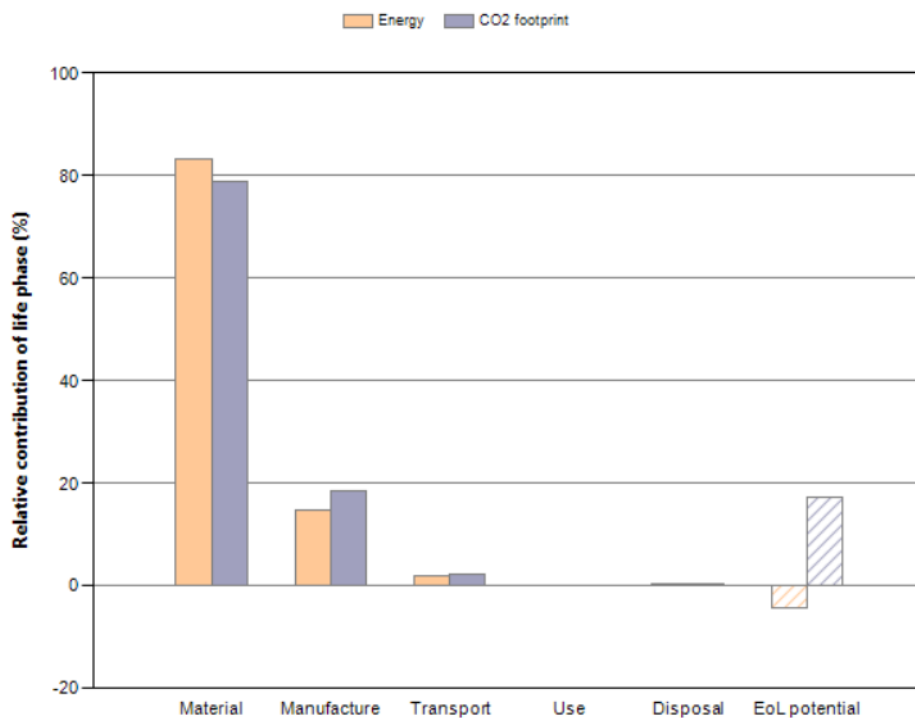


Figure 4.5: Relative contribution from each life cycle phase for 1 kg of PA6-GF15 considering energy use and CO2 footprint calculated in [9].

Further conclusions about the current life cycle of the PA6-GF15 used in the belt guard are that:

- the current life cycle is far away from a desirable circular life cycle. The connection between end of life and material extraction is basically non-existing.
- PA6-GF15 in the belt guard consists of 100% non-renewable material. In addition, the extraction process of both PA6 and GF are very energy consuming. This both in relation the total energy demand over its own life cycle and compared to possible alternative matrix and reinforcing materials. As seen in figure 4.5, the material extraction stands for some 80% of total energy demand and GWP.
- the injection moulding process is also quite energy demanding, but there is no real competing technique available and there is not much savings to gain by using other similar polymers. With the current high environmental impact from material extraction this process makes up a relatively small portion, about 15%, of the total energy demand and GWP.
- the distribution of the material and the moulded belt guards stands for an almost neglectable part of the energy demand on CO<sub>2</sub>-emissions from feedstock to manufactured belt guard. Material supplier, injection moulder and assembly plant is by today's standards located close to each other. Even if they were not, this would still make up a small portion of life cycle energy demand and CO<sub>2</sub>-emissions.
- during the use phase, the belt guard does not have any considerable interaction with its environment. The component is fairly weight optimised and by looking at warranty errands and spare parts sales it normally seems to outlast the life time of the complete machine.
- it can be assumed that nothing, or at the most a still neglectable fraction, of the belt guard material is recycled to new high value materials. Based on the market sales distribution it can further be assumed that the major part of the produced belt guards ends up in landfills and that a somewhat smaller part is incinerated with energy recovery. If energy recovered, only about 6% of invested energy can be recovered. This while about 1.5 kg of CO<sub>2</sub> is produced per 1 kg incinerated material, see figure 4.4 and 4.5. The glass fibres yield no energy recovery while incinerated and the residues are normally landfilled.

## 4.2 Materials selection

In section 4.1 about the current life cycle of the belt guard, it is concluded that the material extraction phase is most important to improve and also that this life cycle phase shows more room for improvement than the others. It is also desirable to establish some connections between EoL and the material extraction phase. Either by basing the material on renewable resources or on recycled materials.

The main focus during materials selection was thereby to find materials that reduce GWP and energy demand from material extraction and/or connects this with EoL. Material candidates must of course also fulfill component requirements and be available on the market in high volumes. Some more details about the selection method can be found in section 3.3.

### 4.2.1 Understanding material demands on the belt guard

The selection of PA6-GF in the belt guard is, according to Husqvarna, is basically based on experience and developments evolving during an extended time period. This material have been widely used, with success, throughout this and other products for many years. But with more ambitious environmental goals it is time to asses the materials selection for the belt guard once again. This section will discuss what properties of the current material that is of particular importance and what properties that can be compromised with alternative materials.

To understand the effect of the glass fibre reinforcement, some important properties are presented in table 4.1, both for the current GF-reinforced PA6 and similar resin from the same manufacturer but without reinforcement. Both unreinforced PA6 and PA6-GF30 has been used in the belt guard of the K770's predecessors K750 and K760.

Noticeable is that both materials are absorbing a significant amount of moisture, which have a dramatic impact on the mechanical properties. "Dry" typically means moister content equivalent to when the material was moulded (some 0.1%) and conditioned ("cond") refers to moister content obtained when stored in 50% relative humidity [39]. Probable moisture content for the belt guard when in use is around the level when the material is conditioned. Tensile modulus and tensile strength are both almost halved when conditioned compared to dry samples. But on the other hand Charpy impact strength can be almost doubled while the elongation increases by four times. This must be remebered when comparing these materials to others that are less moisture sensitive.

**Table 4.1:** Properties of PA6-GF15 (DSM Akulon K224-G3) [40], currently used in the belt guard, and a similar unreinforced PA6 from DSM (Akulon F223-D) [23].

	<b>PA6-GF15</b>	<b>PA6</b>	
<b>Property</b>	<b>dry/cond</b>	<b>dry/cond</b>	<b>unit</b>
Tensile modulus	6000/3500	3200/1000	MPa
Tensile strength	125/70	87/45	MPa
Strain at break	3/12	4/25	%
Charpy notched impact strength (+23°C)	7/15	4.5/35	kJ/m <sup>2</sup>
Charpy notched impact strength (-30°C)	6/6	2.5/5	kJ/m <sup>2</sup>
Charpy impact strength (+23°C)	45/80	no break	kJ/m <sup>2</sup>
Charpy impact strength (-30°C)	40/40	no break	kJ/m <sup>2</sup>
Melting temperature	220/-	220/-	°C
Temp. of deflection at load (0.45 MPa)	215/-	160	°C
Temp. of deflection at load (1.8 MPa)	195/-	60/-	°C
Moulding shrinkage (parallel to melt flow)	0.32/-	1.1/-	%
Moulding shrinkage (normal to melt flow)	0.96/-	1.1/-	%
Humidity absorption (50% rel. humidity)	2.3/-	2.8/-	wt%
Density	1230/-	1130/-	kg/m <sup>3</sup>

This comparison between reinforced/unreinforced PA6 show that the glass fibre reinforcement have a very large impact on almost all of the properties. The most significant differences of importance for this application is probably that without the addition of the GF-reinforcement, stiffness and strength is reduced almost by half, greater mould shrinkage in the parallel direction and temperature of deflection is dramatically lowered. GF-reinforcement seems to be of particular importance for dimensional stability at elevated temperature and also makes the material slightly less sensitive to moisture.

#### 4.2.1.1 Mechanical properties

The addition of glass fibers are, as mentioned, significantly increasing both the tensile modulus and the tensile strength of the material. But since the belt guard is not a structural part, not supporting anything more than itself, these two properties are only considered of moderate importance and might be able to be compromised.

The GF also increases the wear resistance of the part which is of importance in a construction site environment. But even unreinforced PA6 offers good abrasion resistance [12] and Husqvarna actually reports that they rather have had problems with GF-reinforced parts wearing down the metal components they are attached to due to vibrations.

The toughness and impact resistance are considered to be of higher importance though. The part should not fail by brittle fracture during typical use and expose the user to the moving parts (clutch and drive belt), and it is very likely to suffer many impacts during use and transportation. The addition of glass fibers is actually

decreasing the impact strength, compared to unfilled PA6, for all tabulated conditions except for in the least favourable when the sample is dry and very cold.

Husqvarna have a specified impact testing procedure, which is described in section 3.4.2, to evaluate the impact strength of the belt guard as a component. These tests show that the belt guard can withstand impact energy levels more than twice as high as the minimum requirement. This indicates that there should be room to compromise with the impact strength of an alternative material compared to PA6-GF15.

#### 4.2.1.2 Thermal properties

The polyamides are in general capable of handling relatively high temperatures among other thermoplastics. This is true also for PA6 and it is often the case why they are used. The service temperature interval, the temperature span at which the material can be used for an extended period without significant deterioration of its properties, is around -50°C to 110°C [9].

The 2-stroke internal combustion engine is generating heat that is transmitted both by the surrounding air and by the metal parts close to. The engine crank case, which the belt guard is mounted to, is maintaining about 100°C during normal continuous operation according to Husqvarna. The air behind the cover is not that hot though, this since the area is quite well ventilated thanks to the fan-like design of the rotating clutch. A rough estimate is that the air behind the cover maintains some 60-80°C under the same circumstances, something that the PA6-GF15 handles well.

Severe temperature peaks can however occur behind the belt guard. As further explained in section 2.1, and seen in figure 2.2, there is a centrifugal clutch engaging mechanical connection between the engine and the cutting blade at a certain rotational speed of the engine. There are cases when the clutch is slipping for a much longer time than intended, which can lead to very high build up caused by the friction.

One example is if the operator, typically an inexperienced one, tries to use the cutter in a too "gentle" manner, continuously keeping the engine speed to low for proper clutch engagement and hence inducing extended clutch slip and friction heat. The other example occurs when the cutting blade is stuck during cutting without the operators attention, forcing the engine speed down to a point where it starts to slip and continues to do so until the operator releases the throttle trigger. The engine delivers up to 3.7 kW, so in such a case the clutch quickly reaches temperatures well above the melting temperature of the plastic.

To mimic these situations, Husqvarna have developed a testing procedure, described in section 3.4.3, where the clutch is slipping during extended time resulting in heat build up. The current material handles this demanding test well but there is not much margin.

### 4.2.1.3 Chemical resistance

While in use, the machine is exposed to several different chemicals, and so also the belt guard. The most apparent is the the water/concrete slurry that machines used for concrete cutting regularly are exposed to. The cutting blade is normally sprayed with water during concrete cutting, both to cool the blade and to minimise dust, which results in this basic (high pH) slurry as a bi-product.

After or between uses, the slurry dries to the surface of the belt guard. Many different chemicals are used by customers to clean this off the machines, some examples being acidic detergents, alkaline degreasers and so called "multisprays" based on hydrocarbons. Since the machines run on gasoline, spillage while refueling can occur and the material should not deteriorate from that kind of exposure either.

PA6-GF15 is handling these chemicals reasonably well and Husqvarna does not report any major issues related to exposure of these. Semicrystalline thermoplastics, as PA6, are generally highly chemical resistant. But among those, PA6 is not particularly resistant though. It is generally outperformed by for example polyethylene and polypropylene, particularly concerning acids, alkalis and organic solvents. [9].

### 4.2.1.4 Conclusions about current material utilisation

- As discussed in section 4.1, the belt guard seems to hold good quality/performance, this is indicated by warranty errands and spare parts sales. No major weaknesses are reported.
- Mechanical properties are probably better than enough. Strength and stiffness are not of particular importance. Impact resistance is though, but the impact resistance testing indicate a big margin.
- Thermal properties are probably more maxed out according to testing. But the test is very tough and mimics a case of severe misuse of the machine. It is also hard to judge on forehand how a material with lower thermal properties could perform.
- Chemical resistance is assumed to be acceptable with the current material since no major problems are reported. Among other semicrystalline thermoplastics, PA6 is not particularly resistant to chemicals though. So many other such materials should also handle the considered chemicals sufficiently.

## 4.2.2 Selected materials for prototyping

The following materials where selected for prototyping:

- DSM Akulon® RePurposed RE15 BK00003 (mechanically recycled PA6-GF15)
- Borealis Fibremod™ GB205U (PP-GF20)
- Stora Enso DuraSense® Prime 30 Impact O (PP with 30% wood fibers)

These three materials are all quite different and represent three of the different strategies for lowered environmental impact from plastic materials handled in 2.6, one being based on recycled plastic, one conventional fossil-based with lower carbon footprint than the current material, and one with renewable fibre reinforcement. They are further described in this chapter and an overview of their properties are shown in table 4.2.

**Table 4.2:** A compilation of some selected properties of the current belt guard material and the three material candidates. The full specification sheets provided by the manufacturers are found in appendix. Both polyamides are hydroscopic and moisture content have significant impact on properties, they are therefore shown both in dry and conditioned state. When in use, the moisture content is most likely close to the conditioned state. PP is hydrophobic and not much affected by moisture, hence dry and conditioned properties are not separated.

\* value not provided by supplier, instead the author's estimation based on data for similar material in Granta [9] is presented.

\*\* the manufacturer does not provide a grade-specific GWP-value, but refers to the eco-profile from Plastics Europe for an unreinforced fossil based PP [15] which is presented.

Property	dry/cond Current	dry/cond RePurposed	cond Fibremod	cond DuraSense	unit
Density	1230/-	1240/-	1040	1050*	kg/m <sup>3</sup>
Tensile modulus	6000/3500	5800/-	4850	3600	MPa
Tensile strength	125/70	120/-	80	76	MPa
Strain at break	3/12	2.9/-	3.8*	8.5	%
Charpy notched(+23°C)	7/15	6/-	11	22	kJ/m <sup>2</sup>
Charpy notched (-30°C)	6/6	-/-	6.7*	-	kJ/m <sup>2</sup>
Charpy unnotched(+23°C)	45/80	35/-	33*	94	kJ/m <sup>2</sup>
Charpy unnotched(-30°C)	40/40	-/-	21*	-	kJ/m <sup>2</sup>
Melt temperature	220/-	220/-	173*	170*	°C
HDT (0.45 MPa)	215/-	200/-	154	-	°C
HDT (1.8 MPa)	195/-	190/-	137*	120	°C
Max service temp.	108*/-	108*/-	115*	110*	°C
Moulding shrinkage(parallel)	0.32/-	0.35/-	0.47*	-	%
Moulding shrinkage(normal)	0.96/-	1/-	-	-	%
Humidity absorption(50% rel.)	2.3/-	2.5/-	<0.01*	<0.5	wt%
Material GWP (suppliers info)	6	2.3	1.63**	2.6	kgCO <sub>2</sub> e/kg
Material GWP (Granta)	7.02*	-	2.03*	-	kgCO <sub>2</sub> e/kg
Price indication	X	X*1,2	X*0,8	~33	SEK/kg

#### 4.2.2.1 DSM Akulon® RePurposed

This material is based on mechanically recycled PA6 from abandoned fishing nets, so called "ghost nets", gathered from the Indian Ocean and Arabian Sea by local fishermen. The gathered nets are cut up, cleaned and extruded locally before being shipped to DSM for compounding in Europe. DSM claims [41] that over 3000 tonnes of nets are collected yearly by their suppliers and that over 300 people are employed in the local recycling chain.

The polymer part, 85wt%, of the particular grade tested in this project, is fully based on the recycled fishing nets. The remaining 15wt% are virgin, non-renewable, short glass fibres. As expected, and seen in table 4.2, the mechanical and thermal performance of the material is slightly worse compared to the virgin equivalent from DSM. Less data is presented by DSM for the recycled grade, but from the available data it generally reaches around 95% of the performance of the virgin one.

As a consequence of varying color of fishing nets and contamination from the mechanical recycling, Akulon RePurposed is only available in black. The price indication given from DSM is that the grade is about 20% more expensive than the current grade they provide for the belt guard.

### 4.2.2.2 Borealis Fibremod™

The Fibremod-series from Borealis are their glass fibre or carbon fiber reinforced polypropylene grades for high performing solutions aiming to compete with conventional engineering plastics, like PA6, within automotive as a lighter and cheaper alternative with smaller carbon footprint. [42]

The particular grade tried in this project is GB205U. It is a fossil-based PP with 20 wt% short glass fibre reinforcement and is hence considered fully non-renewable, but nevertheless it shows a big reduction in carbon footprint compared to the current material. It is stabilised for long term heat exposure and is intended for under-the-bonnet components in cars, washing machine parts and other technical components exposed to high loads and heat.

As seen in table 4.2 it is the strongest and stiffest material of the candidates and also show higher Charpy impact strength than the two polyamides. It should handle long term heat exposure about as well or better than the two polyamides, but have melting temperature and HDT some 50°C lower than them, so should be more sensitive to very high temperature peaks.

To achieve a shorter delivery time of the sample the Fibremod GB205U was ordered in black for this project. It is also available in "natural color" for possibility to color with a wanted colorant. Borealis claims a typical 20% cost reduction compared to PA6-GF.

### 4.2.2.3 Stora Enso DuraSense® Prime

During the last few years the Swedish/Finish forest, pulp and paper company, Stora Enso, have developed and launched a series of wood fibre reinforced biocomposite materials with matrices of PE, PP or PLA under the trademark DuraSense®. The plastic matrices have been either fossil-based, based on renewables or on recycled plastics and compounded with different types of wood fibres.

They have earlier been used in less demanding applications like furniture, consumer good handles, car interior parts etc. But the latest addition in their biocomposite

portfolio, DuraSense Prime, are a series of wood fibre reinforced polypropylenes for injection moulding, aiming to compete with engineering plastics like PP-GF and PA in more demanding applications. Among the three candidates, the material type is however the least proven for this type of application. It is recently launched and there are not many similar competitors on the market.

DuraSense Prime is available with three different types of fibres, or a mix of them. Two of them are of simpler nature derived from residues of spruce from sawmills in two different lengths, called "S" and "L". These two fibers are visible in the composite and gives some texture to it. The third type, the so called "impact-fiber" is a more processed wood fibre. It not as visible and gives higher strength, impact strength but also considerably higher GWP compared to the S- and L-fiber.

The particular grade selected for this project is DuraSense Prime 30 Impact O. It is a PP matrix with 30% wood fiber of impact-type. This fibre was selected because it was expected to work best in the current moulding tool, which is designed for the low melt viscosity of PA6, without changes. The S- and L-fibers are still considered to give a material with sufficient strength and impact strength but to a carbon footprint of about 1.3 kgCO<sub>2</sub>e/kg compared to the 2.6 kgCO<sub>2</sub>e/kg for the DuraSense Prime 30 Impact O.

PP is hydrophobic and absorbs less than 0.01 wt% of water in 50% RH (relative humidity) [9]. The wood fibers however do absorb some moisture. Stora Enso claims, about the composite, around 0.5% humidity absorption of in six in 50% RH and some 1-1.5% after six weeks of submersion depending on fiber fraction and fiber type. At 0.5% moisture level the change in properties are barely measurable and at 1-1.5% strength and stiffness decrease by a few percent. The properties are thereby not at all as moisture dependent as for the polyamides.

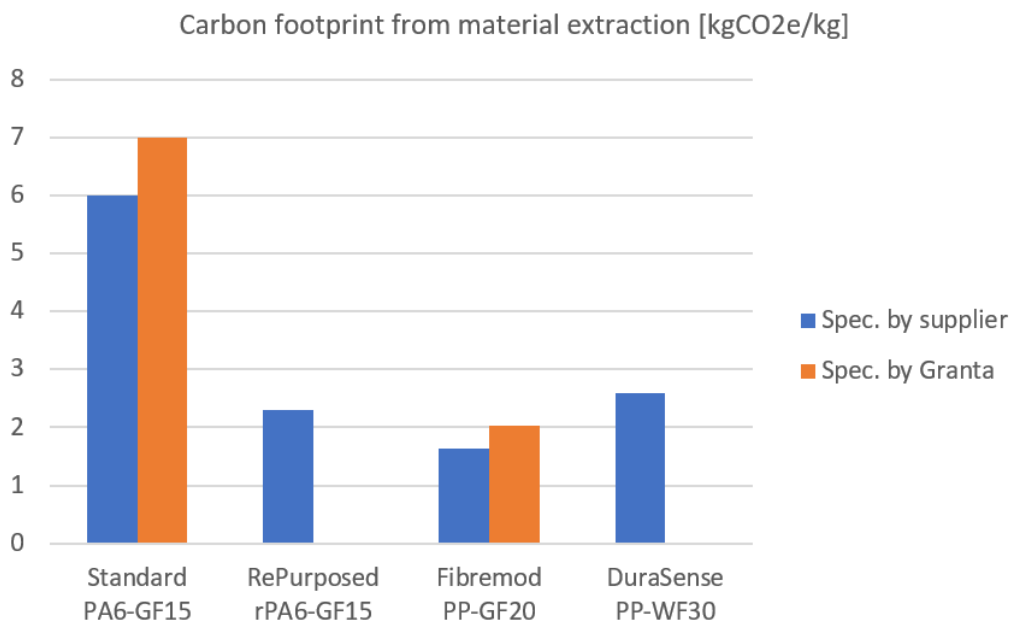
The feedstock for the PP matrix is a mix of fossil oil and vegetable oil residues from food industry. The total mass balance of fossil/renewable content is adjusted to what is sold to the customers whom can choose between a fossil PP and a renewable PP. The total volume delivered to all customers is guaranteed to contain a fraction of renewable PP at least corresponding to the fraction of what is sold.

The sample of the DuraSense Prime 30 Impact O came uncolored from Stora Enso for possibility to be colored in orange. The manufacturer Essge-Plast did not stock a so called "masterbatch" of orange colored PP suitable for the material, so instead a grey color was tried. The price indication for the selected material is about 3.3 €/kg with fossil PP. Renewable PP would raise the price a bit and switching to the "S" or "L" fibers would make it cheaper.

### 4.2.3 Sustainability of the material candidates

As earlier discussed, the goal was to find materials with reduced carbon footprint from material extraction and preferably also with some connection between mate-

rial disposal and extraction. Even though different sources report slightly different values, the carbon footprints are relatively straight forward to compare and those are visualised in a diagram in figure 4.6. It is clear that all material candidates give a significant reduction to around one third of the current material. The more subjective sustainability aspects concerning how the different materials are sourced are discussed below.



**Figure 4.6:** A diagram of the carbon footprint of the standard material and the three candidates. These are the same values also presented in table 4.2 and include both the respective material suppliers information and what the Granta [9] reports for those included in the database.

Even though the Fibremod shows the lowest carbon footprint of the candidates, the life cycle also share the same drawbacks as the current material used of being based entirely on non-renewables and not containing any recycled content. Switching to this material still does not decouple the the material extraction from the fossil fuel dependency. Although the material is possible to recycle, both mechanically and chemically, it is as for the current material not likely to happen in the near future.

The RePurposed, made from discarded fishing nets recovered from the ocean, is an impressive example of how a mechanically recycled plastic material can reduce the carbon footprint and also perform capably. Increasing the demand of recycled plastics is likely the best way to speed up development of technical innovations and infrastructure for future material recycling. The chances of being recycled again is currently as low as for the standard material, the glass fibres are still non-recycled and considered non-renewable. Whether fishing nets are a renewable resource or not can be discussed. But as mentioned in section 2.6, about 640 000 tons of such discarded fishing gear are added to the oceans every year [22] and so far this resource does not seem to be overexploited.

The particular grade of DuraSense that was selected for this project have a slightly higher carbon footprint than the two other candidates. But as discussed in section 4.2.2.3, and concluded by the results in section 4.3.3, it would probably be possible to use one of the lower performing fibre types with lower carbon footprint. This would make it have the lowest carbon footprint of all candidates. This material is also claimed to be recyclable, both mechanically and chemically. But the chances of being mechanically recycled, at least in the near future, is perhaps even lower than for the other candidates which material types are more commonly available. The wood fibre reinforced material is though more suitable for the very commonly applied incineration with energy recovery. Compared to the GF-reinforced plastics, more energy can be recovered, it leaves no residues to landfills, and if paired with the renewable PP matrix it is all a part of the natural carbon cycle.

## 4.3 Evaluation of prototypes

### 4.3.1 Manufacturing

According to the belt guard manufacturer, Essge-Plast, the prototype manufacturing went on well without major issues with any the three material candidates. After first tuning of the process for each material they all were produced with the same cycle time as the current material. But Essge-Plast estimates that the cycle time could be slightly reduced with the PP-grades if the process was further fine tuned. The prototypes are seen in figure 4.7. Also the in moulded heat shield and bushings, seen earlier in figure 2.3, seems to be well integrated with all the different materials.



**Figure 4.7:** One belt guard in each of the materials. From left to right: DSM Standard Akulon, DSM Akulon RePurposed, Stora Enso DuraSense, Borealis Fibremod.

### 4.3.2 Fitment, finish, feel and weights

The recycled Akulon RePurposed parts showed, except from the color, a very similar surface finish and feel as the standard material. Both have a very glossy finish with almost invisible glass fibres. Dimensions of the belt guards manufactured in Akulon RePurposed seem very close to the standard and while assembling it on a machine the fitment was no different compared to the standard belt guard.

The DuraSense part feels noticeably lighter compared to the two polyamides and the surface feel is also a bit different. Very apparent, at least when dried, is that the sound and feel from handling the belt guard is very different between DuraSense and the polyamides. The DuraSense gives a much more damped or dull sound when knocking on it compared to the polyamides which gives a more hard or brittle and high pitched clang. This difference should however be less prominent when the polyamides have absorbed more moisture over time which makes its stiffness decrease.

The 30% of wood fibres added to the DuraSense are barely visible but can be noticed as streaks coming out from the central hole where the mould inlets are located. Figure 4.8 shows the appearance of two belt covers manufactured in the DuraSense material, one with added color and one without.



**Figure 4.8:** Two belt guards of the DuraSense Prime 30 Impact O. One uncolored as the material came from Stora Enso and one with grey color added.

The belt guard made from Borealis Fibremod both feels like and gives a clang much alike the other PP-candidate, DuraSense, when handling it. The Fibremod material came colored in black so no other color could be tried. It shows the most visible fibers of all material candidates with quite visible fibre streaks from the central hole with the mould inlets and is therefore maybe more suited for a mould with more textured surface. This is seen in figure 4.9.



**Figure 4.9:** A Fibremod belt guard with visible streaks of glass fibres.

Both the PP belt guards, Fibremod and Durasense, showed slightly different shape, or warpage, compared to the polyamide ones. This was best seen when they were assembled on the machine which revealed a slightly bigger gap between the belt guard and the cutting arm visualised in figure 4.10. It was however no difficulty to assemble the front belt cover which is mounted over the rear one and also holds it in place.



**Figure 4.10:** Two belt guards mounted to the crank case/cutting arm on a K770. To the left a standard belt guard and to the right a prototype made in Fibremod. The gaps considered are highlighted with the yellow lines.

Nine prototypes of each material, as well as three standard belt guards, were also weighed after drying before prior to impact testing. The average weights of them are listed in table 4.3.

**Table 4.3:** Average weights of the standard and prototype belt guards after three days of drying in a climate chamber at 70°C and relative humidity of 0%. The scale used had a 0.05 g resolution and the standard deviation was less than 0.2 g for each material type.

	<b>Standard</b>	<b>RePurposed</b>	<b>FibreMod</b>	<b>DuraSense</b>
Average weight [g]	140,2	139,1	117,0	118,4

Both PP-based materials would thereby give a component weight reduction of roughly 15-20% depending on the moisture content in the polyamides which can reach up to 7-8% [40].

### 4.3.3 Impact testing

The belt guards were hit with several hits with increasing impact energy between each hit. According to Husqvarnas test protocol, expressed as a percentage of the minimum requirement, the impact energy in each hit was ramped up in the following sequence: 4%, 16%, 36%, 64%, 100%, 144%, 196%, 256%, 324%, 400%.

Minor cracks are allowed for a passed impact test but the the functionality, to protect the user from the moving parts behind the cover, must not be impaired. The last impact energy level passed for the tested belt guards are presented in table 4.4 and more details about the test method is found in section 3.4.2.

**Table 4.4:** Impact energy at the last passed impact expressed as a percentage of the minimum requirement set by Husqvarna. All samples were tested in dry condition.

	<b>Standard</b>	<b>RePurposed</b>	<b>FibreMod</b>	<b>DuraSense</b>
At clutch part 1	400%	400%	400%	400%
At clutch part 2	400%	400%	400%	400%
At cutting arm part 1	256%	196%	256%	400%
At cutting arm part 2	196%	196%	256%	400%

The two PP-based materials, FibreMod and DuraSense, both performed better than the polyamides in this test. This was expected considering the declared impact properties seen in table 4.2. The polyamides are though expected to withstand higher impact energy with increasing moisture absorption, while the PP-based materials will perform about the same regardless of humidity.

The wood fibre reinforced DuraSense showed a particularly high impact resistance under the premises of the results showed in table 4.4. At the clutch position no cracks at all appeared at the maximum impact energy of the rig (400%). At the cutting arm position only minor cracks appeared at the maximum impact energy level, similar to those starting to appear at the 64% or 100% level for the polyamides and the 144% level for the FibreMod.

The difference between the virgin and the recycled polyamide was not very prominent. A slight tendency towards easier crack growth was observed for the RePurposed but a larger sample size and finer resolution of impact energy levels would be required to consider it determined.

To also get a rough perception of the cold temperature behavior of the belt guard prototypes, one of each material was impact tested after being stored in a freezer at about  $-20^{\circ}\text{C}$ . These samples were not dried prior to freezing and the same parts were used for both positions, hence it is not to be judged against the results showed in table 4.4. The impacts where made at room temperature within one minute after being removed from the freezer. They were first impacted at the clutch position after three days in the freezer, then put in the freezer for one day again before impacting the cutting arm position. The results are shown in table 4.5.

**Table 4.5:** Impact energy at the last passed impact. This expressed in a percentage just like in table 4.4.

	<b>RePurposed</b>	<b>Fibremod</b>	<b>DuraSense</b>
At clutch	400%	400%	400%
At cutting arm	144%	196%	400%

To sum up the impact tests, all the materials passed the minimum requirements in the impact test procedure specified by Husqvarna and none of the candidates performance was dramatically worsened as cold. The DuraSense performed particularly well which indicates that it probably would have performed good enough in this test even with the lower performing fibres, described in section 4.2.2.3, that further reduces carbon footprint and cost.

#### 4.3.4 Heat resistance

Two belt guards of each material were tested for heat resistance with the clutch slip test method described in section 3.4.3. So one belt guard of each material was first exposed to clutch slip during the time span corresponding to Husqvarnas test protocol, referred to as 1 time factor. Husqvarna then allows some damage to the belt guard but the function of protecting the user from the moving parts behind the cover must not be compromised and it must be possible to disassemble and reassemble the belt guard. The results can be seen in the upper and lower left the figures 4.11, 4.12, 4.13 and 4.14

With new belt guards another test run, outside the scope of Husqvarnas regular test protocol, was also performed to investigate the limit of the materials. All these runs resulted in belt failure after 3-3.6 time factors which made it impossible to maintain clutch slip for any longer. The results can be seen in the upper and lower right of the figures 4.11, 4.12, 4.13 and 4.14

As seen in figure 4.12 and 4.11, the Akulon RePurposed behaved very similar to the standard Akulon in both test situations as expected. Both of them handled the test

#### 4. Results and Discussion

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of one time factor almost without any damage at all. The slight bubbling seen on the inside of the standard belt guard was not seen in the RePurposed, but the small difference between might as well only be due variations between the test runs. Both of them were severely affected by the long test runs, with the heat shield starting to float away and major distortion, but they are not melted through.

The Fibremod belt guard is however more affected, than the polyamides as seen in figur 4.13. It is on the limit of pass/fail in the one time factor run. The part was not melted through, the in moulded metal part are in its places, it could be removed and reassembled and would still protect the user after this run, but it is visibly affected and locally distorted also on the outside. After the extended run it melted through and was far from usable. But the extended test case was also way more severe than the short test run.

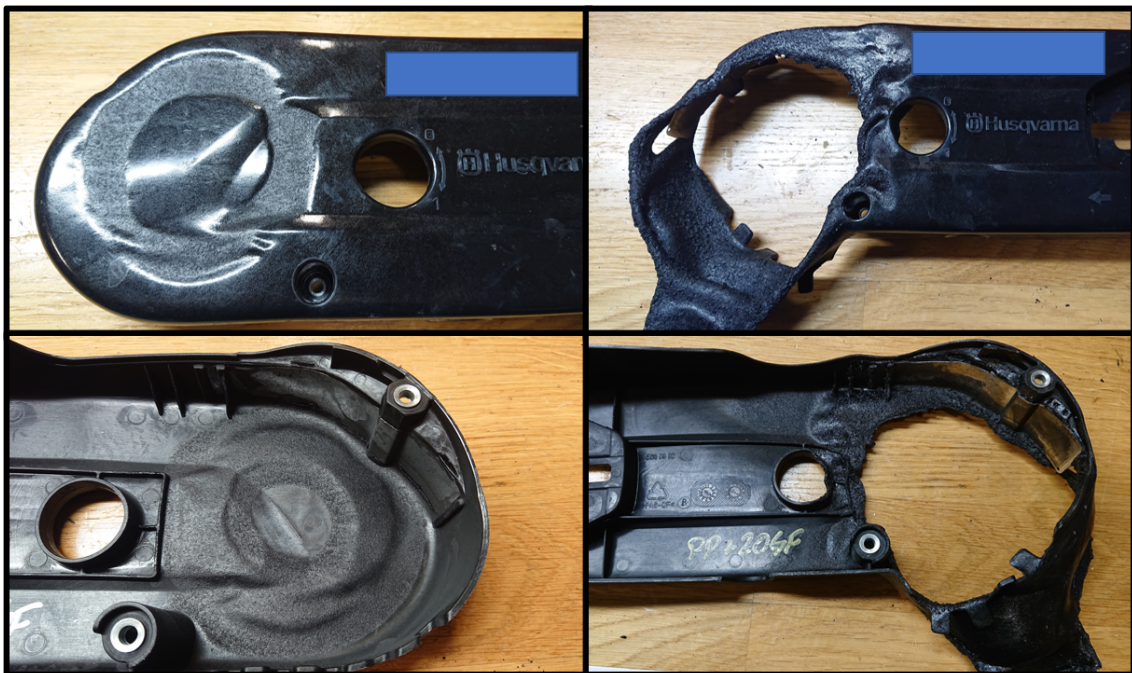
The DuraSense surprised by not showing any visible damage at all on the outside of the belt guard in the short test, as seen in figure 4.14, and was definitely usable afterwards. Also in the long test run it performed surprisingly well compared to the Fibremod which have a similar PP matrix. It was severely affected and distorted but did not melt through and was actually possible to remove and reassemble without any issues. The fiber type seems to do a better job of keeping the material together than the glass fibres in the Fibremod which might be explained by its presumable lower thermal conductivity.



**Figure 4.11:** Two standard belt guards showed on outside and inside after heat resistance test. The left one was exposed to clutch slip for 1 time factor and the right one was exposed to clutch slip for 3.1 time factors.



**Figure 4.12:** Two Repurposed belt guards showed on outside and inside after heat resistance test. The left one was exposed to clutch slip for 1 time factor and the right one was exposed to clutch slip for 3.6 time factors.



**Figure 4.13:** Two Fibremod belt guards showed on outside and inside after heat resistance test. The left one was exposed to clutch slip for 1 time factor and the right one was exposed to clutch slip for 3.2 time factors.



**Figure 4.14:** Two DuraSense belt guards showed on outside and inside after heat resistance test. The left one was exposed to clutch slip for 1 time factor and the right one was exposed to clutch slip for 3 time factors.

### 4.3.5 Chemical resistance

The impact testing performed after exposure of some different chemicals often encountered by the machines gave the following results presented in table 4.6. More details about the test procedure is found in section 3.4.4.

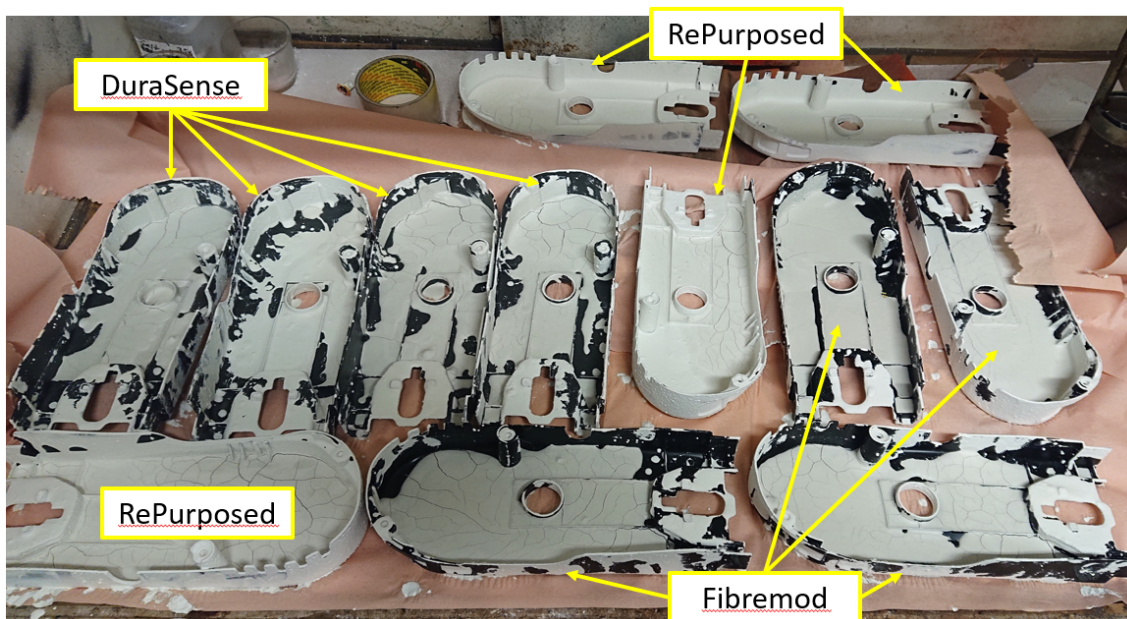
**Table 4.6:** Impact energy at the last passed impact. This expressed in a percentage just like in table 4.4.

<b>Impact at clutch</b>	<b>RePurposed</b>	<b>Fibremod</b>	<b>DuraSense</b>
Calcium Hydroxide + alkaline degreaser	400%	400%	400%
Calcium Hydroxide + acidic detergent 1	400%	400%	400%
Calcium Hydroxide + multispray	400%	400%	400%
Calcium Hydroxide + acidic detergent 2	400%	400%	400%
<b>Impact at cutting arm</b>	<b>RePurposed</b>	<b>Fibremod</b>	<b>DuraSense</b>
Calcium Hydroxide + alkaline degreaser	100%	100%	400%
Calcium Hydroxide + acidic detergent 1	144%	144%	324%
Calcium Hydroxide + multispray	100%	100%	400%
Calcium Hydroxide + acidic detergent 2	100%	144%	400%

These results indicates a reduction of impact strength for all the three material candidates at the cutting arm position after exposure to these chemicals. No standard belt guards were tested as reference but a reduction of impact strength is expected

also from that material according to Husqvarna. All materials did however still pass the minimum requirement for non-treated belt guards and at the clutch position all materials still maxed out the test rig.

Also noticed during the testing of chemical resistance was that the two PP-based materials, DuraSense and Fibremod, showed a different wetting behavior compared to the polyamide. This is seen in figure 4.15. The water/calcium hydroxide solution did not adhere as much to the surface when it was drying on the PP as on the polyamide which stays completely covered in slurry after immersion. It is possible that the PP materials would be easier to keep clean for the customers.



**Figure 4.15:** For belt guards in each of the prototype materials some time after immersion in a solution of calcium hydroxide and water. Both PP-based materials show a different wetting behavior, being more hydrophobic, than the polyamide.



# 5

## Conclusion

The aim of this masters thesis project was to increase the knowledge at Husqvarna about the environmental impact of plastics in their products, particularly PA6-based, and how this impact might be reduced. This was approached as a case study of one particular component of the K770 power cutter, the rear belt guard, which is manufactured in PA6-GF15. The following research questions were investigated:

- How does the life cycle of PA6-15GF look? What part of the life cycle is most important to improve?
- What approaches are there to reduce environmental impact from reinforced thermoplastic materials?
- What alternative materials are there on the market that have potential to fulfill component demands, be processed in the same injection moulding equipment (with minor adjustments) and reduce environmental impact?
- How does decided material alternative(s) perform in component tests? Can it replace PA6-15GF?
- What improvement in circularity/sustainability is achieved?

The analysis of the belt guard life cycle highlights the material extraction as the most energy demanding life cycle phase also responsible for the major part of the components carbon footprint. It was further concluded that little or no connection between the product disposal and material extraction exists. Both composite constituents are extracted from non-renewable feedstocks and, most probable, later disposed of in a plain linear manner through landfilling or incineration.

Husqvarna does currently not have much influence over what happens to their products after disposal and are rather bound to the common practice on the respective market where the products are sold. Material sourcing was thereby identified as the main focus area and possibility for improved sustainability of their plastic components.

Through a literature study of research conducted on the topic, several approaches for lowered environmental impact of plastic components were discovered and analysed. Based on the requirements of the component, the currently common plastic waste treatment methods, and material availability on the market today, it was concluded that the most promising approaches are either to;

- base the matrix on recycled material to reduce energy consumption and carbon footprint while preventing plastic waste generation

- base the matrix material on renewable plant-based resources and thus connect end-of-life and material extraction through the natural carbon cycle
- base the matrix on a conventional plastic with less energy consumption and smaller carbon footprint
- replace the glass fibre reinforcement with renewable plant-based fibers

or a combination of the above stated approaches.

To gain further experience of such materials, prototypes were manufactured in three different material candidates available on the market today. One mechanically recycled PA6 with 15% glass fibre reinforcement (DSM Akulon RePurposed), one conventional fossil based PP with 20% glass fibre (Borealis Fibremod), and one fossil- or renewable-based PP with 30% wood fibre reinforcement (Stora Enso DuraSense).

The material candidates have very different life cycles but all give a similar reduction of carbon footprint, considering material extraction, to around one third of the current material. Only minor difference in carbon footprint from manufacturing, use phase, transports and end-of-life are estimated between the candidates.

Prototype belt guards of each material were successfully manufactured and tested for impact strength, heat resistance and chemical resistance. The recycled PA6-GF15 performed very much alike the virgin PA6-GF15 but with slightly lower impact strength. Both PP-based materials gave a 15-20% component weight reduction and higher impact strength compared to the standard material, the wood fibre reinforced one showed a particularly high impact strength. The PP-based materials were at least as resistant to the chemicals tested as the polyamides but both showed a lower heat resistance.

Based on the component testes performed in the project, all the material candidates reached the minimum requirements in each of the tests. Hence they all could have potential to replace virgin PA6-GF15 for improved sustainability in the belt guard or other components. Further evaluation, including long term testing, is however needed before a potential introduction.

### 5.1 Recommendations for further work

- The long term testing of the alternatives that was initially planned could not be done in this project due to delays. It is recommended for Husqvarna to proceed these tests to find out if any of the material candidates actually function well over time in the component. This could also provide valuable experience that can be applied to other components aswell. As mentioned, only the K770 contains about 2.3 kg of PA6-GF, what more components could be replaced?
- No attention was put to the potential need for design changes, this since both manufacturing and testing went on without major issues appearing. It is possible though, especially for the PP-based materials which differs most to the

current one, that design changes could further improve the performance of the material.

- The cost of the material candidates are relatively close to the current one. The Fibremod is estimated to be a bit cheaper while the DuraSense and RePurposed a bit more expensive, but the estimates in the report might not be very accurate. This is also for Husqvarna to further investigate.
- No recommendation about which of the material candidates that should be selected is given. The work is rather to be seen as a demonstration of different strategies to reduce the environmental impact from plastic materials in the K770 or similar products. What kind of material types to promote and how this for example also can create marketing benefits is for Husqvarna to further investigate.



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