Master's thesis

NTNU
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Life cycle assessment (LCA) and life cycle cost (LCC) analysis of a housing assembly

Master's thesis in Sustainable Manufacturing
Supervisor: Angela Daniela La Rosa
June 2022

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Abstract

Reducing the environmental and economic impacts on a big company is a very important task to be more sustainable. The purpose of the thesis is to identify the environmental and economic impacts of a product, called product 474, from GLN, a dynamic group mainly based in Portugal and also try to find a suitable and more sustainable solution for the company's rejected product problem. Using Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis was possible to identify the environmental impacts and the cost for the company to produce one unit of the product 474. A possible solution to solve the rejected product problem is a reversible adhesive, which using induction or microwave technology can be disbanded and therefore the material of the rejected product can be reused, not only this solution solves the rejected product problem, but also avoid environmental and economic impacts, turning the Life Cycle of product 474 more sustainable.

Sammendrag

Å redusere de miljømessige og økonomiske konsekvensene for et stort selskap er en svært viktig oppgave for å bli mer bærekraftig. Hensikten med oppgaven er å identifisere de miljømessige og økonomiske konsekvensene av et produkt, kalt produkt 474, fra GLN, en dynamisk gruppe hovedsakelig basert i Portugal og også prøve å finne en passende og mer bærekraftig løsning for selskapets avviste produktproblem. Ved å bruke Life Cycle Assessment (LCA) og Life Cycle Cost (LCC) analyse var det mulig å identifisere miljøpåvirkningene og kostnadene for selskapet å produsere én enhet av produktet 474. En mulig løsning for å løse problemet med avvist produkt er et reversibelt lim , som ved hjelp av induksjons- eller mikrobølgeteknologi kan oppløses og derfor materialet til det avviste produktet kan gjenbrukes, løser ikke bare denne løsningen problemet med avvist produkt, men unngår også miljømessige og økonomiske konsekvenser, og gjør livssyklusen til produkt 474 mer bærekraftig.

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List of Abbreviations (or Symbols)

LCA	Life Cycle Assessment
LCC	Life Cycle Cost
PBT GF30	70% polybutylene terephthalate and 30% glass fibre
PA6	Polycaprolactam
G	Gram
Kg	Kilogram
Km	Kilometer
ODP	Ozone Layer Depletion
CO_2	Carbon dioxide
GWP	Global Warming Potential
DA	Diels–Alder

1 Introduction

A life cycle is a series of events that initiates the creation of a new product and continues until it reaches the end of its useful life. The most common steps in the life cycle of a product include product development, market launch, growth, maturity, usage, and end of life.(Hargrave, 2021)

According to Centre et al. (2011), Life Cycle Assessment (LCA) is a structured, comprehensive and internationally standardized method (ISO 14044 and 14040). It calculates all relevant emissions and resource consumption, as well as the associated environmental and health implications and resource depletion concerns. that are associated with any products. A Life Cycle Assessment considers a product's full life cycle, from resource extraction to manufacture, consumption, and recycling, up to the disposal of remaining waste. As a result, Life Cycle Assessment is an important and strong decision-making tool that complements other methodologies, which are equally necessary to help effectively and efficiently make consumption and production more sustainable.

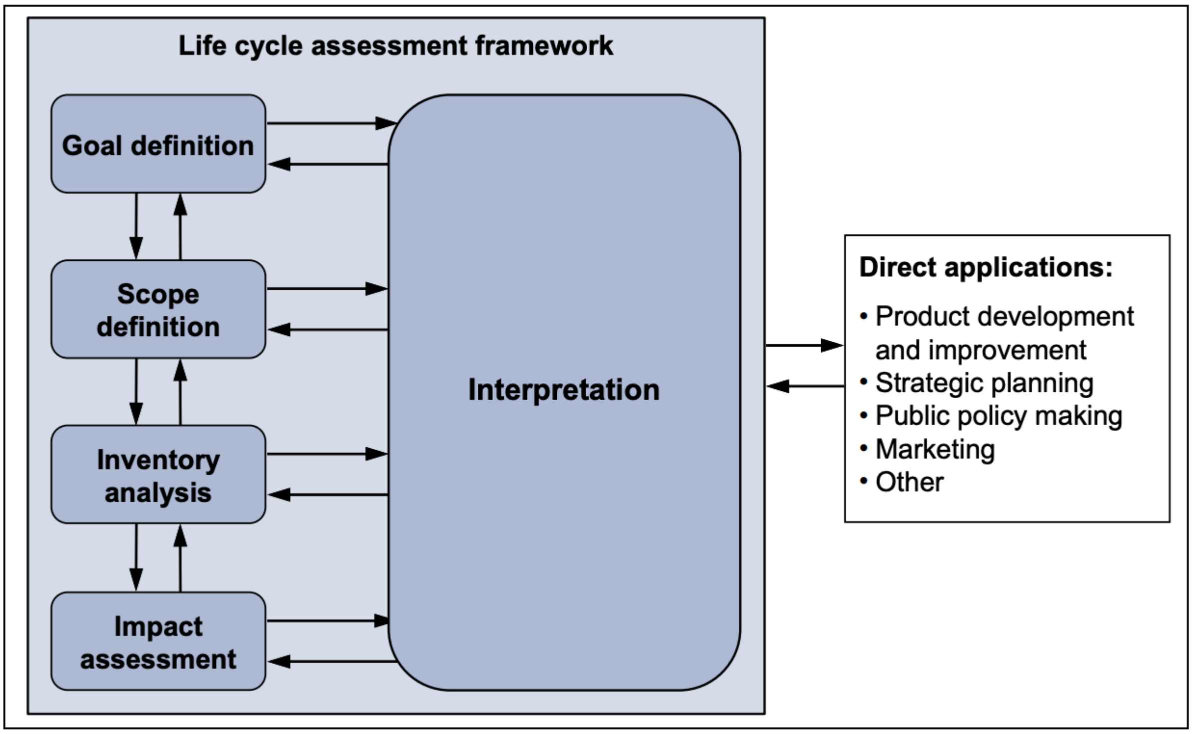

Figure 1. Framework for life cycle assessment. Source: Centre et al. (2011)

Life Cycle Cost (LCC) is the study of all cost involved since the beginning until the end of life of a product. The "*LCC analysis helps engineers justify equipment and process selection based on total costs rather than the initial purchase price*"(Barringer et al., 1995)

This master thesis is about LCA and LCC study of a product from GLN, which is a dynamic group, mainly based on the district of Leiria in Portugal. The group is well known by its high precision molds production and plastic injection. Divided in 5 business the group describe itself as:

> GLN MOLDS A modern production unit, where the latest generation of equipment engineering and manufacturing is used to guarantee the accuracy of a micron and the implementation of more complex pieces. Internationally recognized as one of

the molds producers of reference at European level. We work in close partnership with our customers to fully understand the requirements of each mold, proposing the best solutions for the design and manufacture.
FAMOLDE Unit specialized in the design and production of high technical molds, particularly in micro-molds for thermoplastic injection of small and medium dimensions. Equipped with the latest technology such as high speed machining centers, erosion centers Electro-Robotic and Laser Technology for Micro-Milling. With its own injection department, we can test molds of 50t to 450t machines.
GLN PLAST Geared toward the injection of plastic parts, guarantees the execution of projects of injection of thermoplastics. Supported by more than 15 years of experience covers the most demanding industries, such as electronics, automobile, electrical and food packaging. We offer a range of value-added services (e.g. assembly, packaging) thus increasing the value chain of the customer.
GLN INNOV Unit that is leading the development of new products and solutions, promoting innovation oriented to creativity. It combines the skills of Engineering, Design and Development as a unit designed to promote innovation and technological developments in the service markets. We promote the sharing of wisdom, the attainment of practical knowledge, as well as the development of talent. We believe in cooperation with centers of knowledge, organizations and external institutions and in Creativity as the right attitude to address daily challenges.(GLN, 2022b)
GLN MÉXICO began the internationalization process through the opening of the new facilities in Querétaro, Mexico. This unit is devoted to the repair and maintenance services of technical molds for thermoplastic injection. Investment in GLN Mexico improves the viability of facing new challenges in the production and injection of molds.(GLN, 2022a)

As mentioned above the main procedure of GLN is plastic molding. In summary plastic molding is an industrial process where a polymer is heated until liquefied, inserted into a mold and rapidly cooled so it solidifies on the desire shape of the mold.
The product of this study is a housing assembly for the automotive industry made through the plastic molding process at GLN, where 87% of the product is made of polymers and 13% of inserted metals.

1.1 Problem domain

Seeking to be more sustainable, GLN is committed to reduce the environmental impact of its products. One of the biggest problems that the company faces with the housing assembly, also known as product 474, is the final disposal of the rejected products. For this reason, the GLN accept the study of this master thesis, which is focused on a Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) study of a housing assembly product from GLN and also on finding a solution to make the process more sustainable.

1.2 Research questions

The following research questions are formulated:
1- What are the impacts caused by product 474 on the environmental?
2- What are solutions to make product 474 more sustainable?

1.3 Thesis Outline

The rest of this master's thesis is divided into the following sections:

Chapter 2 presents the Life Cycle Assessment (LCA) study on the focus product of the thesis.
Chapter 3 presents the Life Cycle Cost (LCC) study on the focus product of the thesis.
Chapter 4 shows possible solutions and conclusion of the thesis.

2 Life Cycle Assessment (LCA)

2.1 Goal

The purpose in the analysis of the life cycle of 1 product of housing assembly, known as piece 474, from GLN is to seek for the critical processes seeing how it affect the environment.

2.1.1 Context

One of many products made from GLN is the object of this study, which is a 385,5g product made of PBT GF30 – 70% polybutylene terephthalate and 30% glass fibre – and an additional 12 inserted metal pieces made of copper, zamac and brass.
GLN wanted to know how can this product process be more sustainable, and also find a solution to the scrap products that is not being recycle due the inserted materials.

2.1.2 Objectives of the study

The objective of this LCA and LCC study is to identify the environmental and economic impacts that piece 474 of GLN company causes, and find a solution which reduces these impacts.
The target audience is the production and waste management sectors within GLN, since the results will help the group be more sustainable. The study is for a technical and internal audience.
The results are not foreseen to be disclosed to the public

2.2 Scope

The studied product is housing assembly produced by GLN in Portugal, and for this study the functional unit is 1 product – since is this function unit already used on the company that produces the housing assembly. The boundaries on this paper will be the production process and the scraps, all the data collect will be provided by GLN, with the objective of know the environmental impacts (local and reginal impacts).

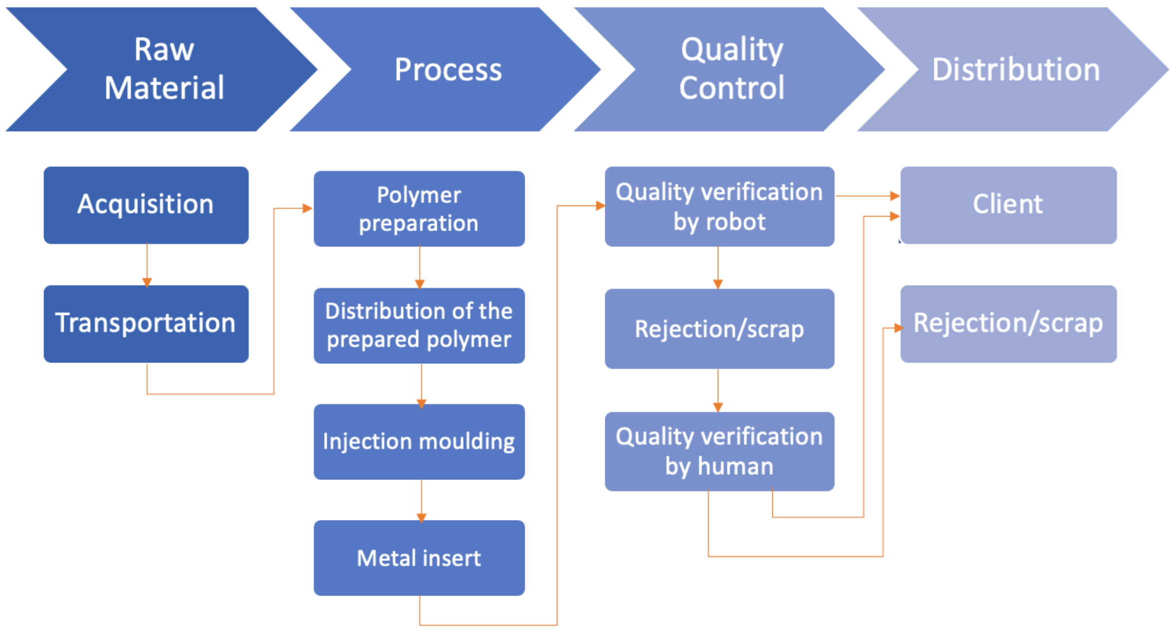

Figure 2. Flowchart showing the main process of the production of housing assembly.

Raw Material
This first step is when GLN buys the raw material, the polymer and metals come from different parts of Europe, such as Germany, Belgium and England. On the acquisition is only considering the process of buying the material, that is why there is no environmental input nor output. On the other hand, the transportation of these raw materials from their origin until it gets to GLN based in Portugal, has environmental costs, the input its fuel, since it is not clear on the data given how the materials are transported, but whether the mean of transportation it needs fuel and also as the output there is air emission.

Process
On this step is where the product is made, first the polymer goes through a preparation, that means that the polymer is heated and dry to be in the perfect way to go to injection molding. After the preparation the prepared polymer is distributed by pipes that goes from the preparation station until the injection molding machine. The third step of the process is the injection molding itself, the polymer is heated one more time inside the machine and injected into the mold. After cooled down and being extruded from the mold the metal parts are inserted into the housing by a robot by a process called press fit. All these processes have an input in common, electrical energy.

Quality Control
When the housing is done its time for the verification, first is the robot verification, the robot collects the housing and scan/take pictures to see if the product is in perfect shape, dimension and condition. If approved by the robot the product goes to the distribution for the client, if the robot considered that the product it is not perfect, it put on a box of "scrap" and this box will be verify by a human to make sure if the product can go to the client or should be rejected. Electrical energy is the input on the quality control by robot.

Distribution
The last phase is distribution, if the product is in conditions it goes to the client, if it is not, it is rejected, and the rejection/scrap goes to landfill since the company cannot recycle the product due to the metal insertions. The client distribution is out of the system boundaries because the aim of this study is to understand the environmental impact of the product that is rejected and find a more sustainable solution for the rejected product.

2.2.1 System Bouderies

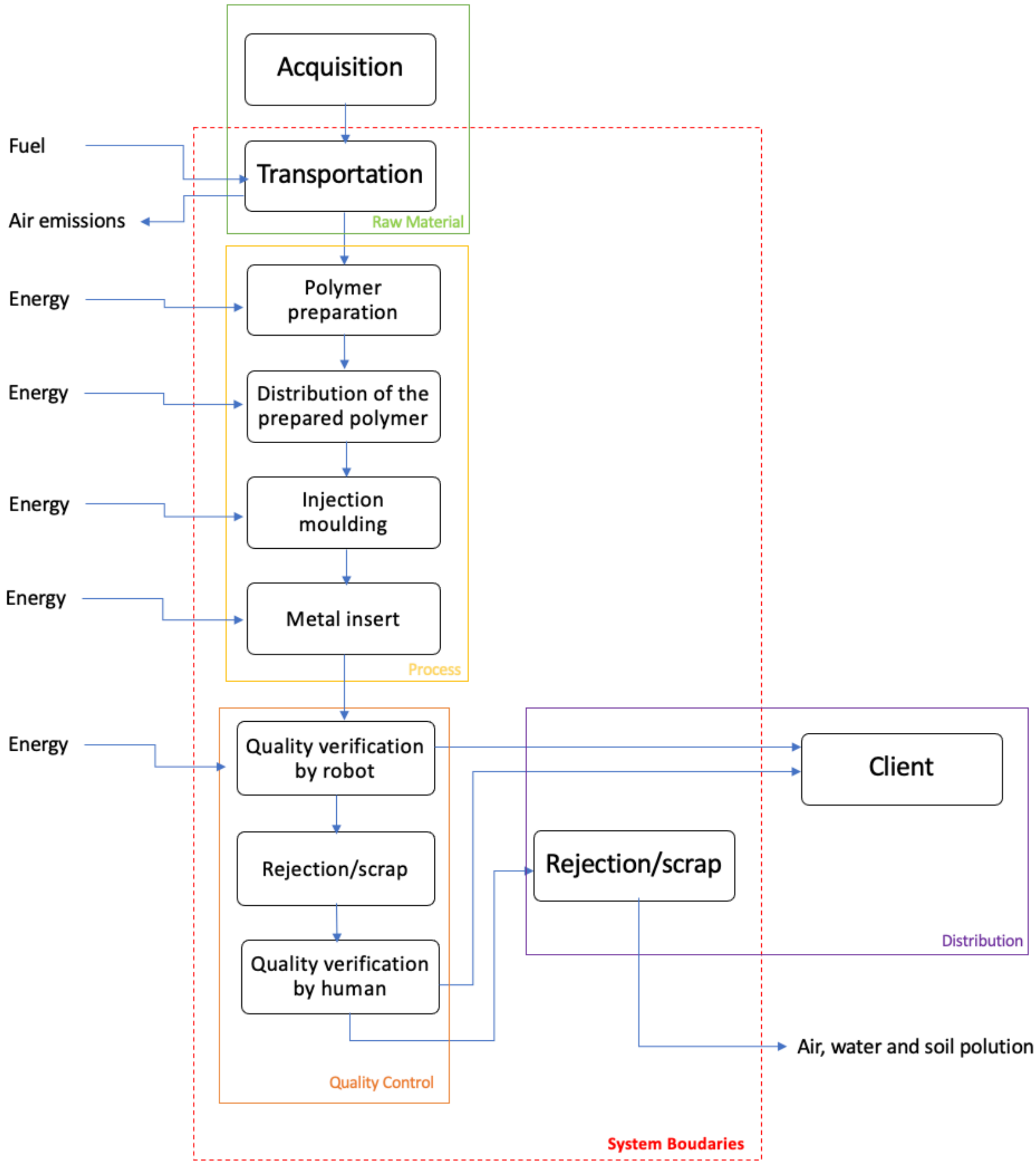

Figure 3. System boundary, unit process, inputs and outputs of the process of a housing assembly

2.2.2 Methodology

The data used in this LCA was collected from GLN and in the database in the software Simapro, specifically Ecoinvent3 - allocation, cut-off by classification – System and unit. The chosen database in Simapro was European (RER) obtained as an average of inputs from European countries, being possible to use in this study as Portugal is located in Europe.
The method used was CML-IA Baseline V3.07 with a normalization/weight EU25, which is a characterization method.
The data given from GLN was the processes of the final material, since the acquisition of raw material until the final product. The material used in these processes, and where these materials come from.
After collecting all the information needed, the data was inputted on the software SimaPro, as mention above. In the software a new material category was created, named "0Housing" and 5 processes were created: PBT GF30, Household, MP17010022, MP17010023, MP17010025, MP17010026 and Housing assembly. Each process needed information such as input and quantities.

- **PBT GF30 –** In order to create this process, the composition of the material (70% Polybutylene terephthalate and 30% Glass fibre) were inputted on the software, since SimaPro did not has the component polybutylene terephthalate(PBT) on its library, the closest component was polycaprolactam (PA6) which is described as Nylon 6, therefore there were a substitution on the components. As the data given from GLN mentioned that its used 335,3 grams of PBT GF30, to produce this amount is needed 234,71 grams of Nylon 6 (70%) and 100,59 grams of glass fibre (30%) combined by injection moulding process.
- **Household –** To build the housing, 335,3 grams of PBT GF30 is needed through a process of injection moulding. But since the PBT GF30 supplier is from Germany, it was added transportation, 0,3353Kg x 2171Km = 728KgKm. All this data were added as inputs of the housing in the software.

Figure 4. Household

- **MP17010022** – For this insert, 1 gram of brass was added on SimaPro, also the supplier is from Germany but the manufacturer is from England, so transportation was also added, 0,001Kg * 3450Km = 3,45KgKm

Figure 5. MP17010022

- **MP17010023** – The main material of this insert is carbon steel, so 7 grams of carbon steel was added on the software, for the transportation, the supplier is from Germany, so transportation was also added, 0,007Kg * 2100Km = 14,7KgKm

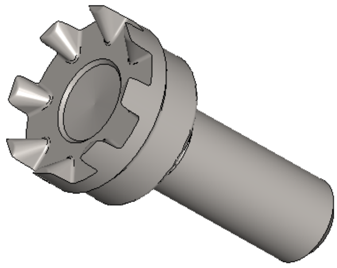

Figure 6. MP17010023

- **MP17010025** – For this insert, 2 grams of carbon steel was added on SimaPro, also the supplier is from Belgium, so transportation was also added, 0,002Kg * 2055Km = 4,11KgKm

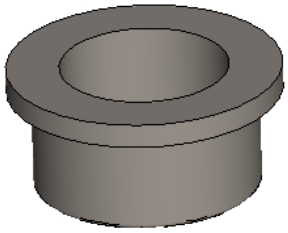

Figure 7. MP17010025

- **MP17010026** – On this piece of insert, 2 gram of carbon steel was added on the software, also the supplier is from Germany, so transportation was also added as 0,002Kg * 2730Km = 5,46KgKm

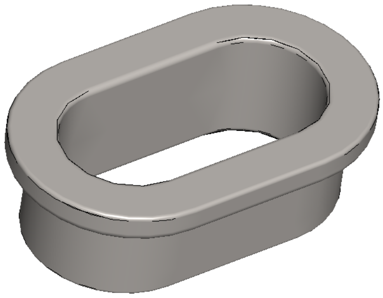

Figure 8. MP17010026

- **Housing assembly –** The housing assembly is all the above process together, the only difference is the quantity, the inputs added on SimaPro are: 3345,3 grams of housing + 4 grams of MP17010022 + 42grams of MP17010023 + 2 grams of MP17010025 + 2grams of MP17010026 + press fit process (which due to SimaPro library was substituted to "Deep drawing steel 38000kN press, automode").

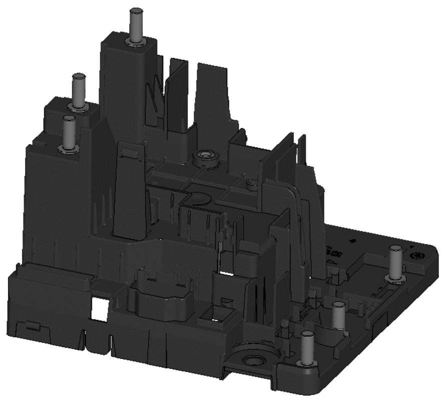

Figure 9. Housing Assembly

After adding all the data mention above the software provided the results of environmental impacts that each of the process cause, this will be discussed on "2.4 Impact Assessment"

2.3 Inventory Analysis

In order to have the final product (Housing Assembly) there is a need of 5 materials: household, and 4 metal inserts (MP17010022, MP17010023, MP17010025 and MP17010026) these materials are considered inputs. As its table 1 shows. It was also added the Deep drawing steel 38000kN press, automode on the inventory table, which is the closest process in SimaPro with the insertion of the metal parts in the household

Housing Assembly	
Input	Quantity
Household	335,3 g
MP17010022	4 g
MP17010023	42 g
MP17010025	2 g
MP17010026	2 g
Deep drawing steel 38000kN press, automode	50 g

Table 1 - Inputs of Housing Assembly

But every input of the housing assembly has its own inputs as it can be seen in the tables bellow:

In order to get a housing as an output there is a need of inputs such as the raw material, PBT GF30, the transportation of the raw material to GLN and the process, which in this case is, injection moulding. The product comes from Germany which is 2171 Km from GLN so to calculate the transportation it is needed to multiply the distance (Km) and the weight of the product (Kg) therefore, is 2171Km x 0,3353Kg = 728KgKm

Household	
Imput	Quantity
PBT GF30	335,3 g
Injection Moulding	335,3 g
Transportation	728 KgKm

Table 2 - Inputs of Household

The raw material (PBT GF30) is made of 70% of polybutylene terephthalate and 30% of glass fibre which is combined by injection moulding process, as mention before, the polybutylene terephthalate was substituted for Nylon 6, due the limitations of the Software.

PBT GF30	
Imput	Quantity
Nylon 6	234,71 g
Glass Fibre	100,59 g
Injection Moulding	335,3 g

Table 3 - Inputs of PBT GF30

The inputs of the metal inserted parts are only the metal and the transportation from the supplier to GLN as the tables 4, 5, 6 and 7 shows.

MP17010022 is a metal insert made of brass, this product is produced in England and the supplier is from Germany, the total distance until arrive at GLN is 3450 Km, to calculate the transportation it is needed to multiply the distance (Km) and the weight of the product (Kg) therefore, is 3450Km x 0,001Kg = 3,45KgKm

MP17010022	
Imput	Quantity
Brass	1 g
Transportation	3,45 KgKm

Table 4 - Inputs of MP17010022

MP17010023 is a metal insert made of carbon steel, this product is produced Germany, the distance to arrive at GLN is 2100 Km, to calculate the transportation it is needed to multiply the distance (Km) and the weight of the product (Kg) therefore, is 2100Km x 0,007Kg = 14,7KgKm

MP17010023	
Imput	Quantity
Carbon Steel	7 g
Transportation	14,7 KgKm

Table 5 - Inputs of MP17010023

MP17010025 is a metal insert made of carbon steel, this product is produced Belgium, the distance to arrive at GLN is 2055 Km, to calculate the transportation it is needed to multiply the distance (Km) and the weight of the product (Kg) therefore, is 2055Km x 0,002Kg = 4,11KgKm

MP17010025	
Imput	Quantity
Carbon Steel	2 g
Transportation	4,11 KgKm

Table 6 - Inputs of MP17010025

MP17010025 is a metal insert made of carbon steel, this product is produced Germany, the distance to arrive at GLN is 2730 Km, to calculate the transportation it is needed to multiply the distance (Km) and the weight of the product (Kg) therefore, is 2730Km x 0,002Kg = 5,46KgKm

MP17010026	
Imput	Quantity
Carbon Steel	2 g
Transportation	5,46 KgKm

Table 7 - Inputs of MP17010026

To have a clear understand of the inputs and outputs the figure 2 will show that the final output is the Housing assembly which has several inputs, each input of the housing assembly is an output of other processes.

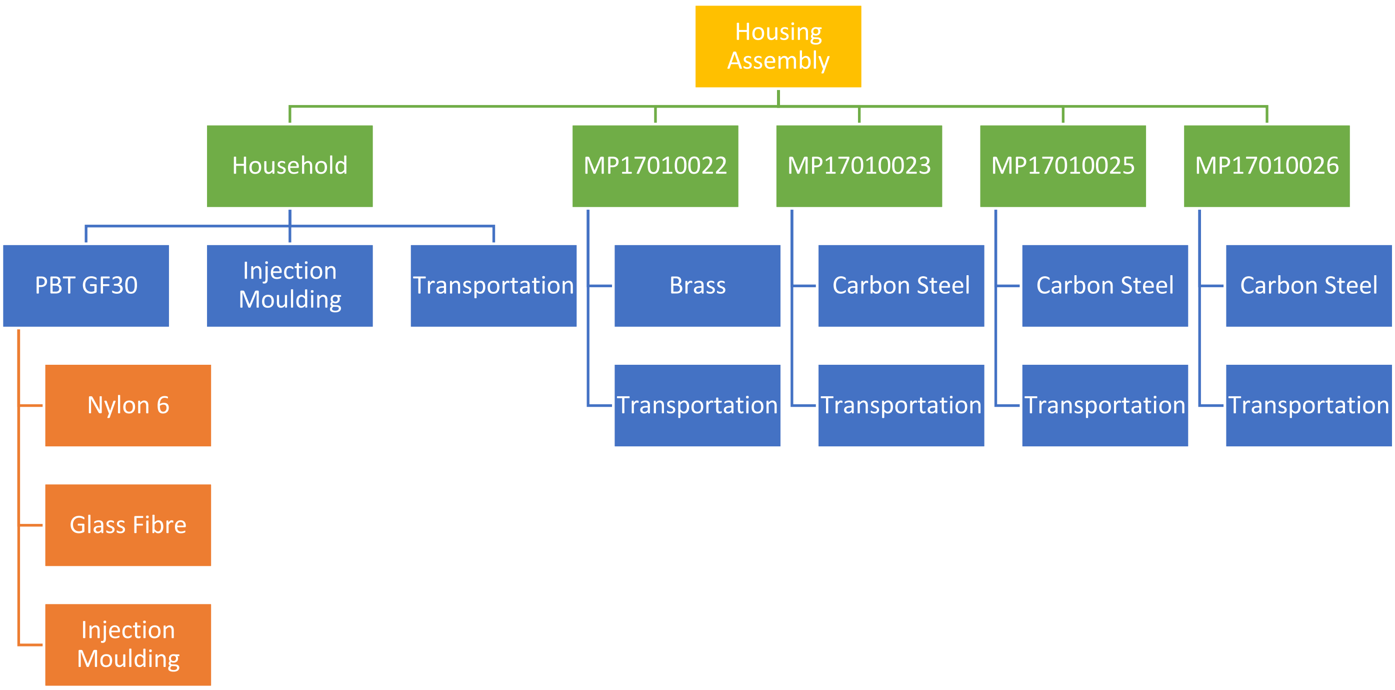

Figure 10. Input and outputs.

2.3.1 Inventory Flows

The inventory flows show the inputs and outputs of the processes and the contribution and impact that each input has on the specific output.

In the figures bellow it is possible to see the inventory flows on the process described on the "2.3 Inventory Analysis".

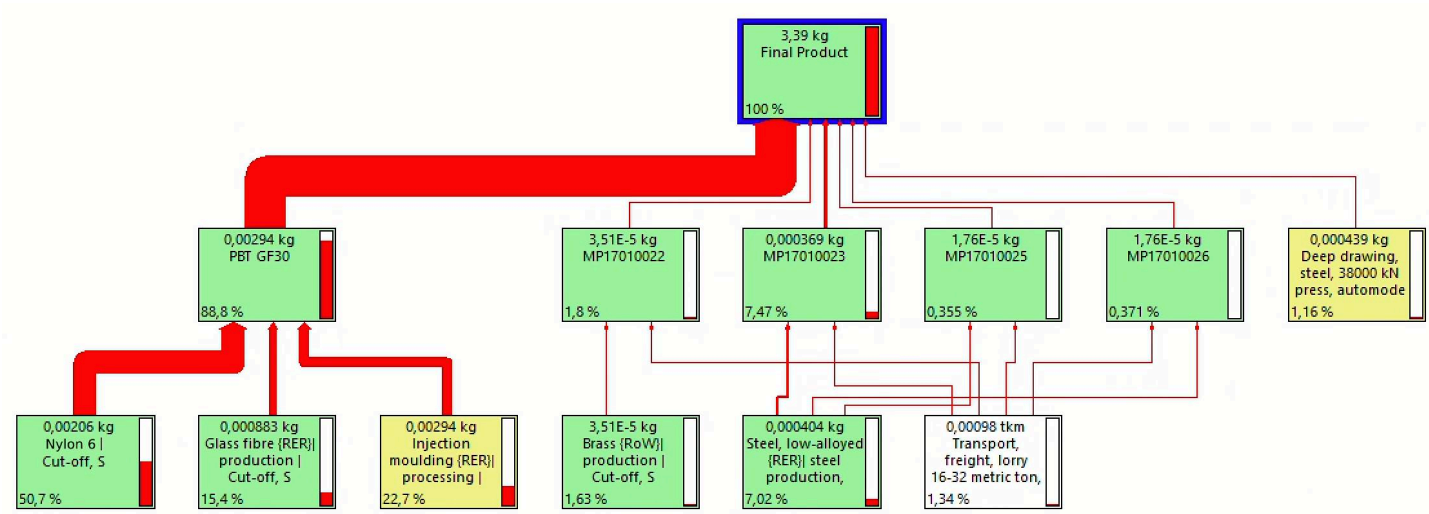

Figure 11. Network results of Housing assembly

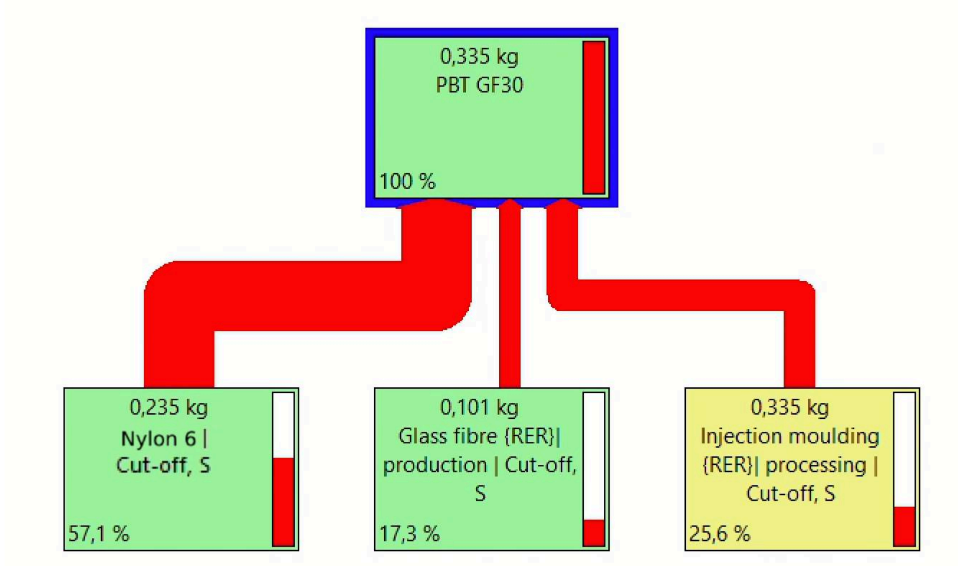

Figure 12. Network results of PBT GF30

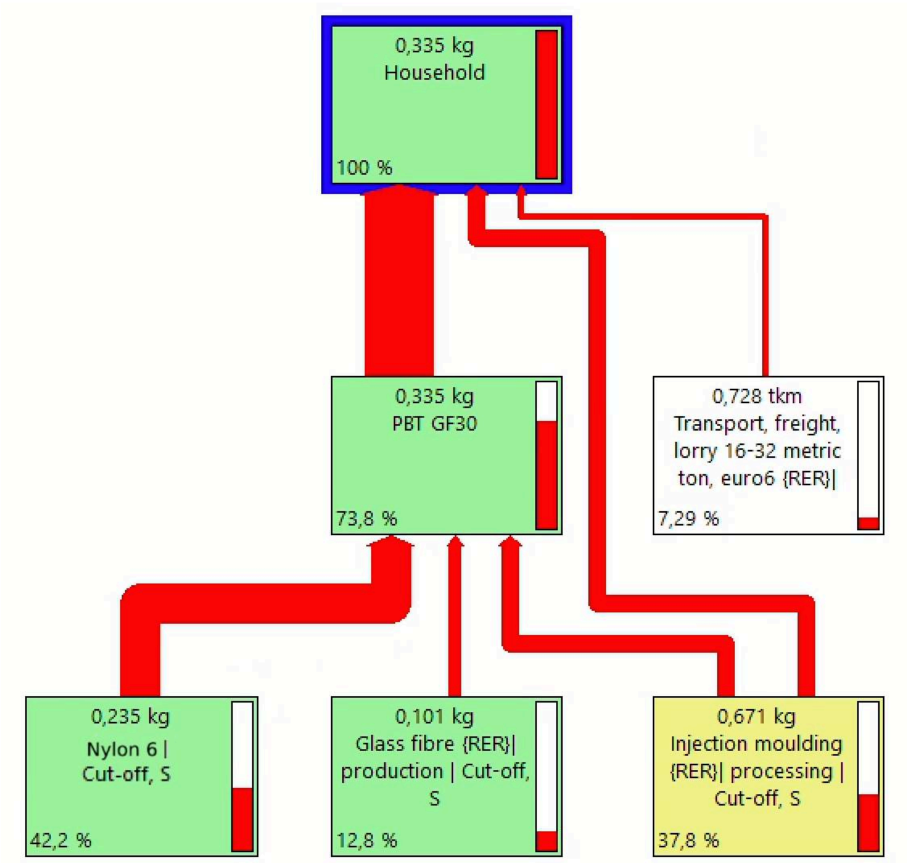

Figure 13. Network results of Household

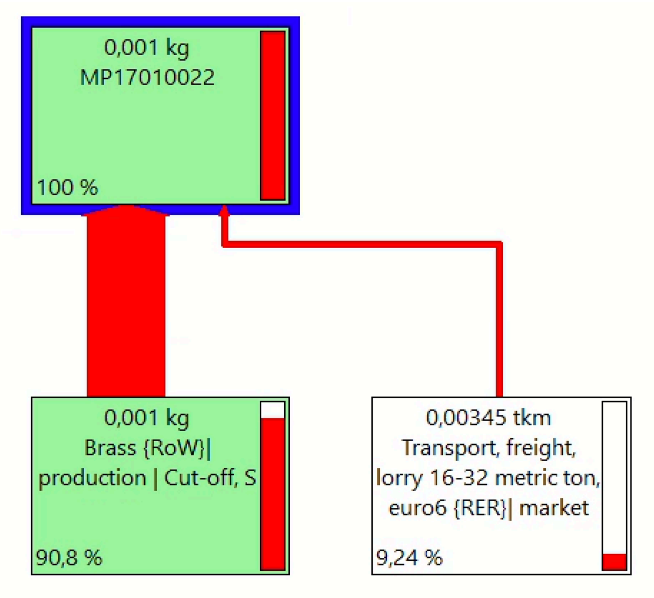

Figure 14. Network results of MP17010022

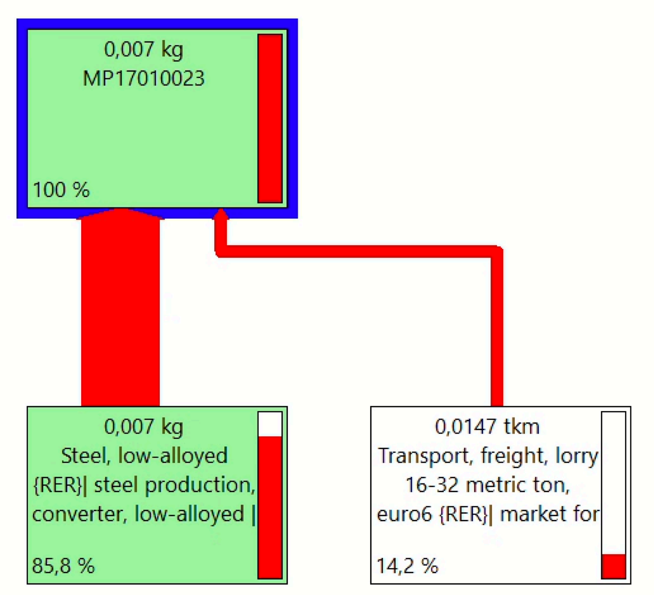

Figure 15. Network results of MP17010023

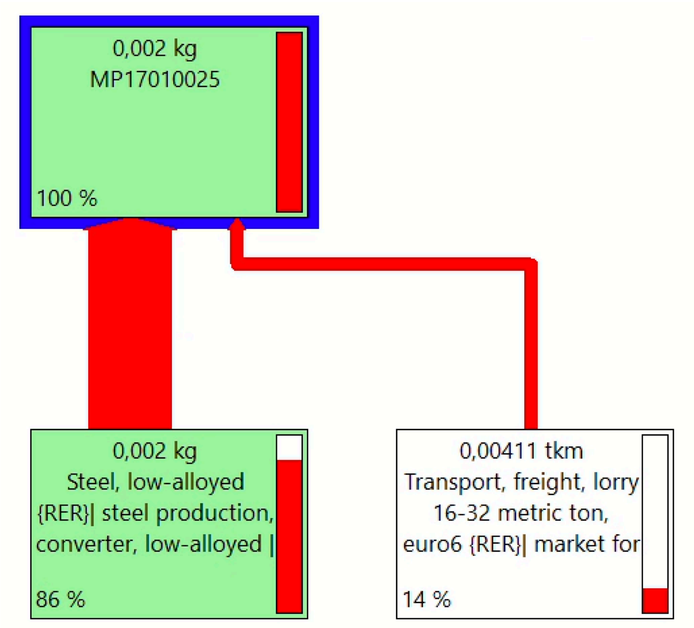

Figure 16. Network results of MP17010025

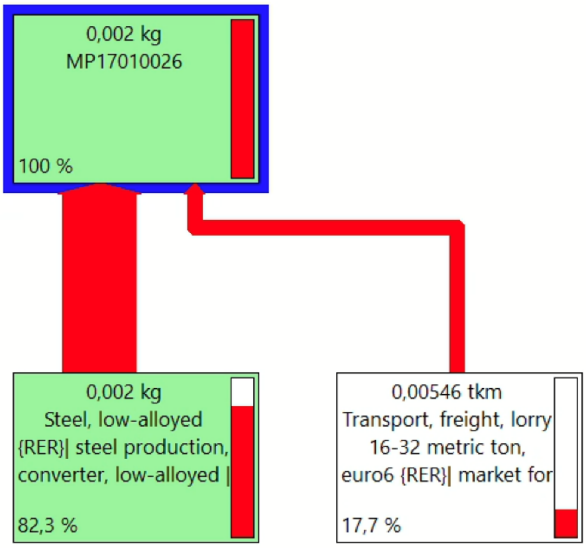

Figure 17. Network results of MP17010026

2.4 Impact Assessment

This section is focused on evaluate a wide range of impacts related from the life cycle of the housing assembly from GLN.

Impact category	Unit	Total	PBT GF30	MP1701 0022	MP1701 0023	MP1701 0025	MP1701 0026	Deep drawing, steel, 38000 kN press, automode {RER}| deep drawing, steel, 38000 kN press, automode | Cut-off, S
Abiotic depletion	kg Sb eq	4,79E-07	1,14E-07	3,5E-07	1,25E-08	5,95E-10	6,02E-10	6,46E-10
Abiotic depletion (fossil fuels)	MJ	0,21	0,20	2 $x10^{-3}$	$9x10^{-3}$	4 $x10^{-4}$	4 $x10^{-4}$	1 $x10^{-3}$
Global warming (GWP100a)	kg CO2 eq	0,01	0,01	2 $x10^{-4}$	8 $x10^{-4}$	4,17E-05	4,36E-05	1 $x10^{-4}$
Ozone layer depletion (ODP)	kg CFC-11 eq	2,14E-08	2,13E-08	1,28E-11	5,86E-11	2,76E-12	3,12E-12	9,86E-12
Human toxicity	kg 1,4-DB eq	0,02	8 $x10^{-3}$	0,01	1,2 $x10^{-3}$	5,99E-05	6,07E-05	2 $x10^{-4}$
Fresh water aquatic ecotox.	kg 1,4-DB eq	0,01	4 $x10^{-3}$	7 $x10^{-3}$	2 $x10^{-3}$	1 $x10^{-4}$	1 $x10^{-3}$	1,4 $x10^{-3}$
Marine aquatic ecotoxicity	kg 1,4-DB eq	31,32	12,21	8,41	2,54	0,12	0,12	7,91
Terrestrial ecotoxicity	kg 1,4-DB eq	2,63E-05	1,76E-05	7,26E-06	9,18E-07	4,35E-08	4,59E-08	4,31E-07
Photochemical oxidation	kg C2H4 eq	3,44E-06	2,51E-06	4,71E-07	3,91E-07	1,86E-08	1,88E-08	2,48E-08
Acidification	kg SO2 eq	6,04E-05	4,43E-05	1,24E-05	2,98E-06	1,41E-07	1,46E-07	3,83E-07
Eutrophication	kg PO4--- eq	2,12E-05	1,54E-05	3,76E-06	1,52E-06	7,24E-08	7,33E-08	3,57E-07

Table 8. Impact assessment indicators of Housing assembly. Source: SimaPro

Abiotic Depletion

This impact category its related to the reduction of the availability of natural resources which does not come from living beings. This indicator takes into account the time of regeneration of material, meaning the time the resources take to be available again, is very low, comparing to the exploitation of the same resources. (Sostenible, 2019b)

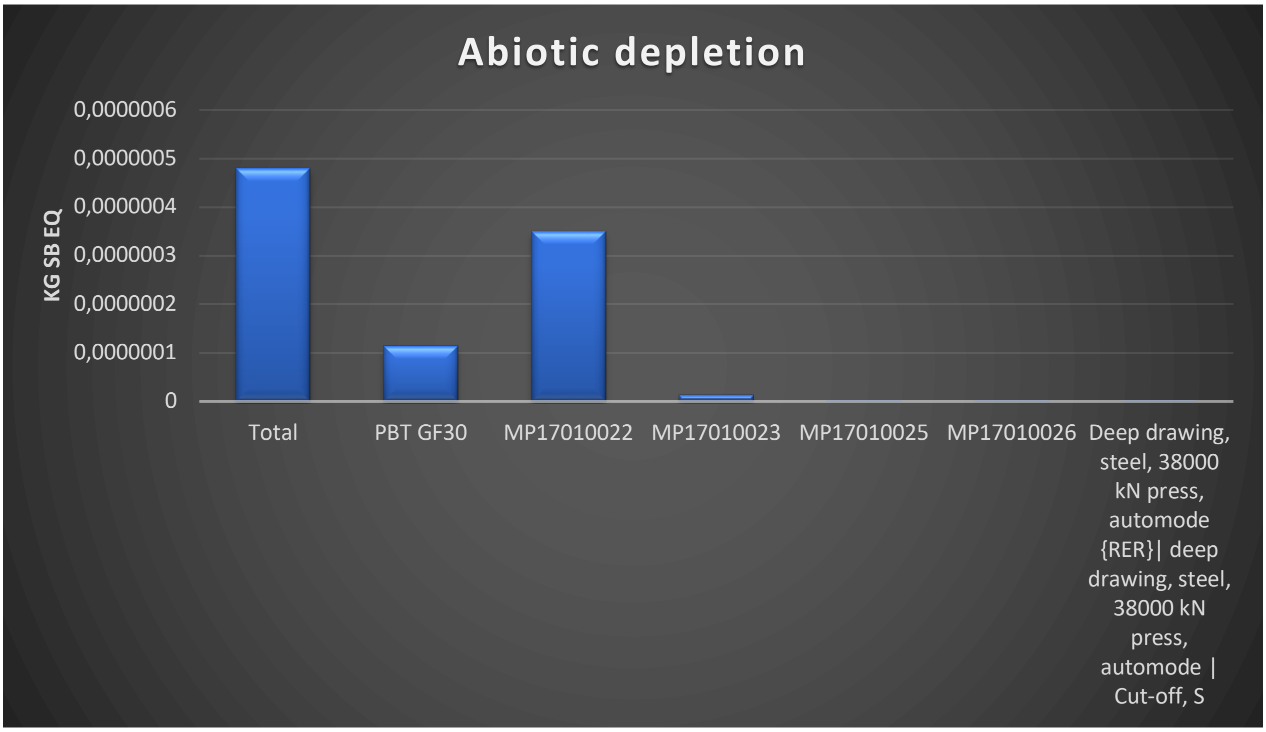

Figure 18. Graph of impact from housing assembly, abiotic depletion category

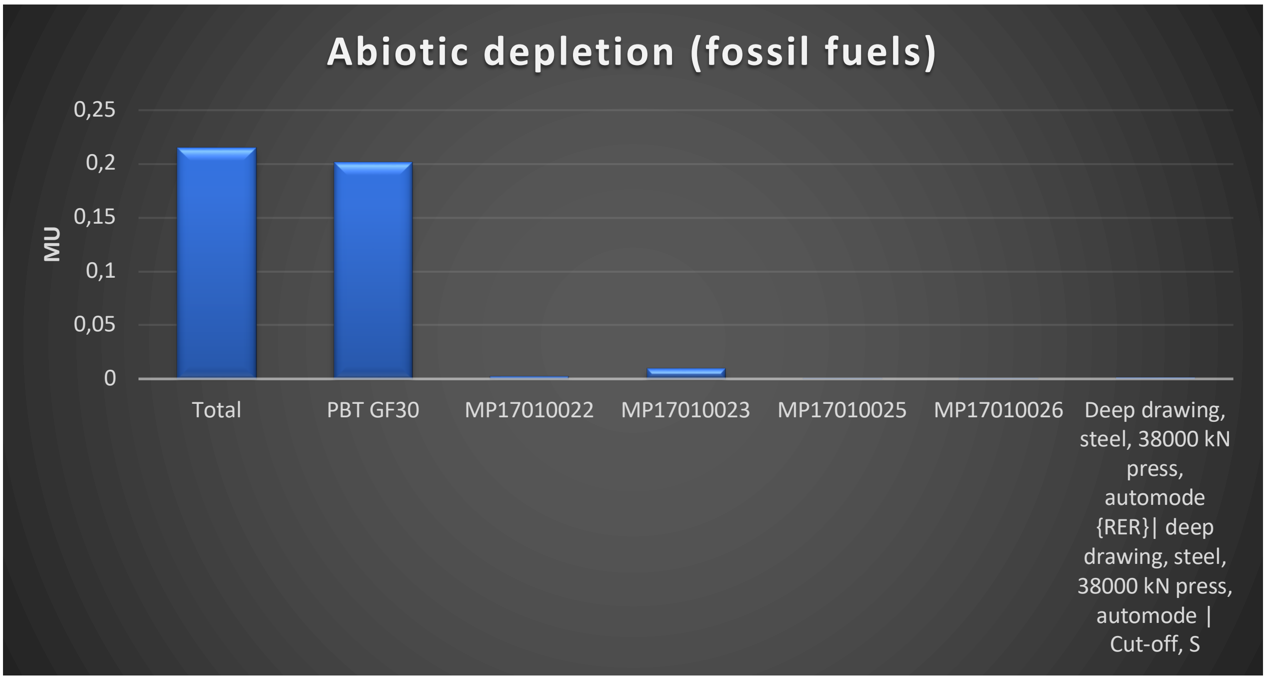

Figure 19. Graph of impact from housing assembly, abiotic depletion (fossil fuels) category

Global Warming Potential

The indicator used in LCAs is the radiative forcing expressed by CO_2-equivalent value (GWP), which is a midpoint indicator. "*The contribution to the greenhouse effect is the sum of the products of released quantities of the individual greenhouse-relevant pollutants (m_i) and their respective GWP (GWP_i) according to the following formula:*" (Klöpffer and Grahl, 2014): $GWP = \sum_i (m_i \text{ x } GWP_i)$

Greenhouse gas	$(GWP_i)_{100}$ (CO_2-equivalents)
Carbon dioxide (CO_2)	1
Methane (CH_4)[a]	25.75
Methane (CH_4), regenerative	23
Dinitrogenmonoxide (N_2O)	296
Tetrachloromethane	1 800
Tetrafluoromethane	5 700
Hexafluoroethane	11 900

Table 9 - Global Warming Potential of some substances. Source: Klöpffer and Grahl (2014)

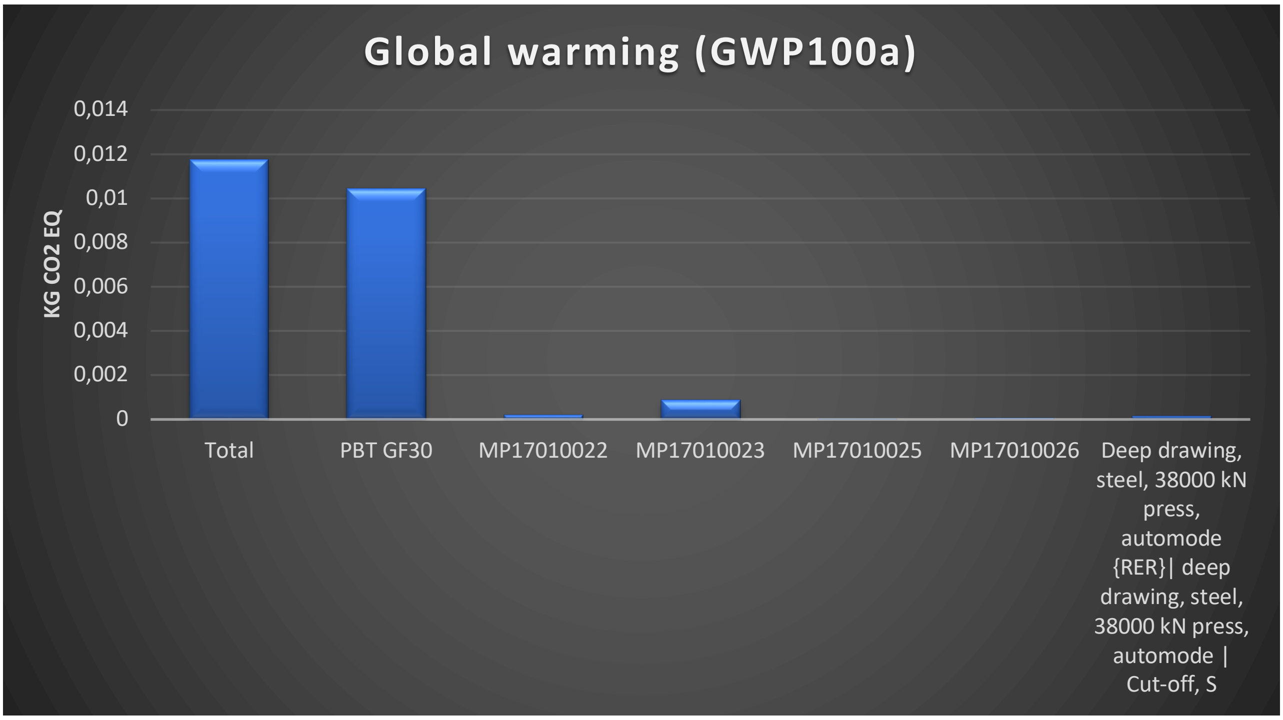

Figure 20. Graph of impact from housing assembly, global warming (GWP100a) category

Ozone Layer Depletion (ODP)

This indicator is to measure the relative amount of degradation on the ozone layer.

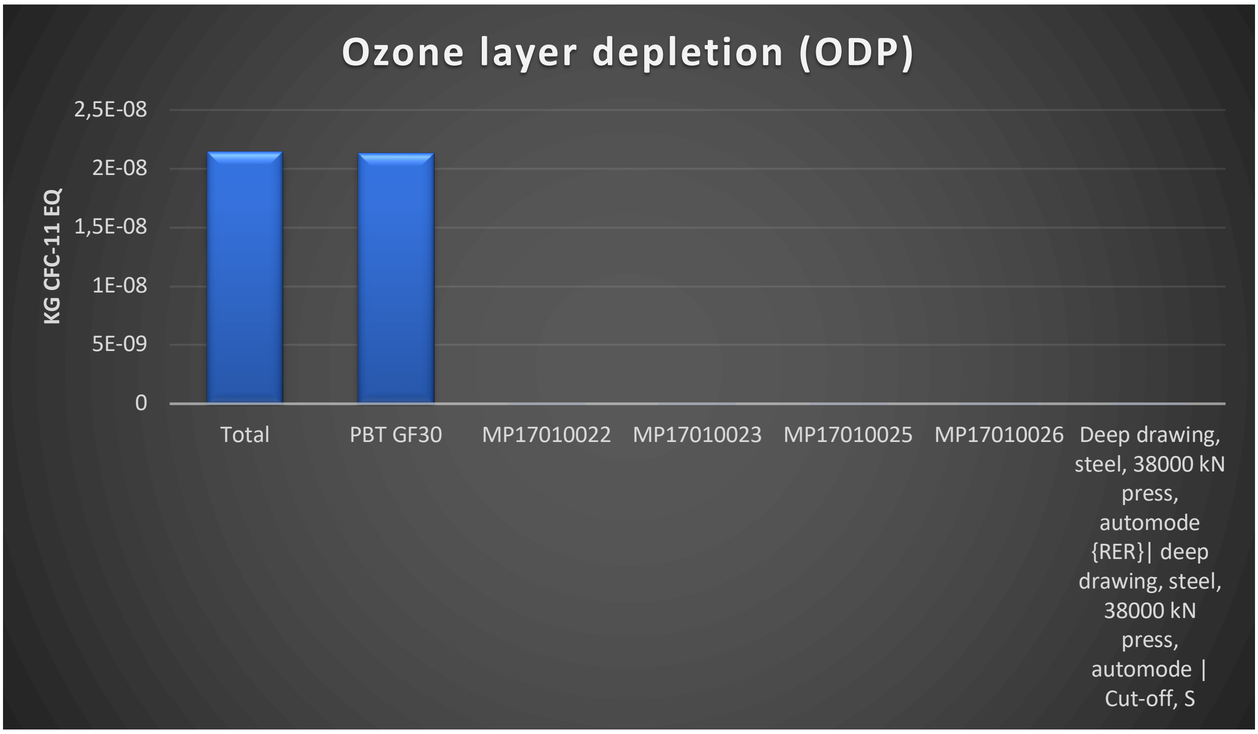

Figure 21. Graph of impact from housing assembly, ozone layer depletion (ODP) category

Human Toxicity

This indicator is about the potential to induce hazardous impacts on humans, such as cancer and non-cancer effects which can be caused by chemicals released into the environment (air, water, soil, etc.) at any point in the product, service, or system's life cycle.

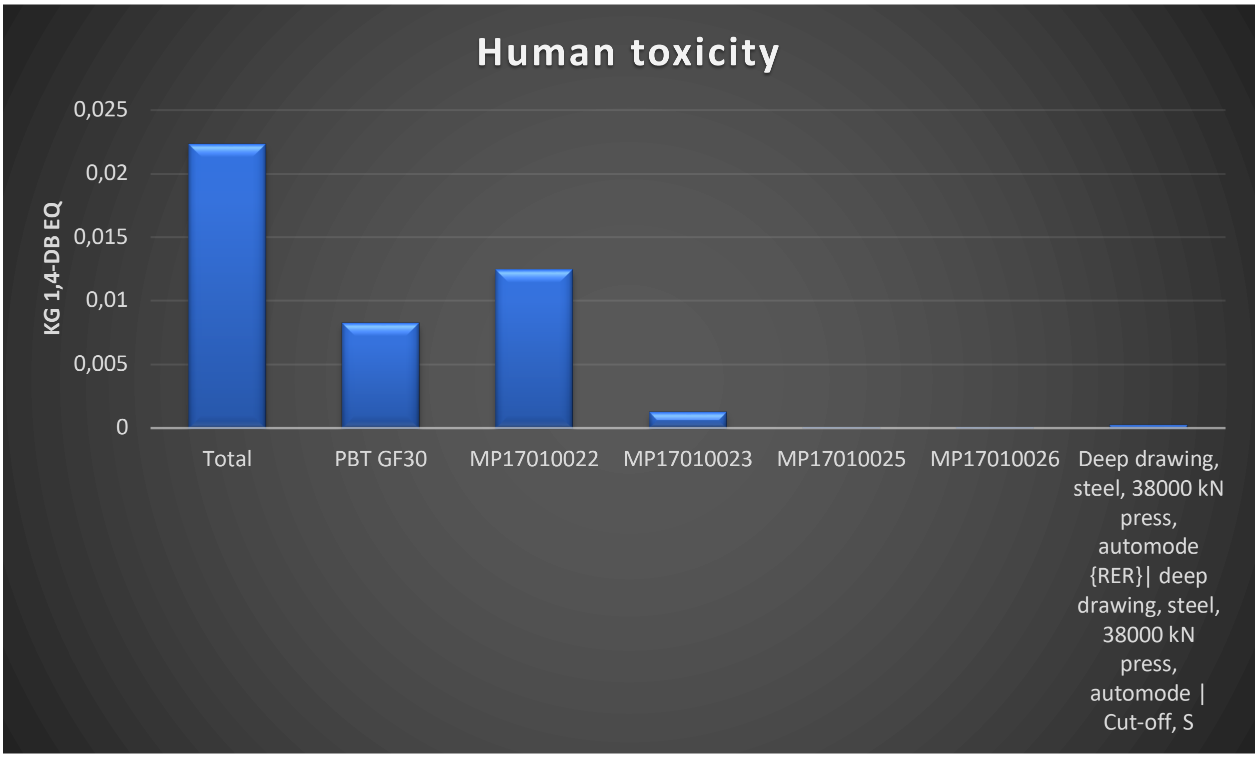

Figure 22. Graph of impact from housing assembly, human toxicity category

Ecotoxicity

Ecotoxicity is the ability of a biological, chemical, or physical stressors alter and have a negative impact on the environment and the species that live there. The impact indicators below are the same indicator (ecotoxicity) in different types of environments (fresh water, marine and terrestrial).

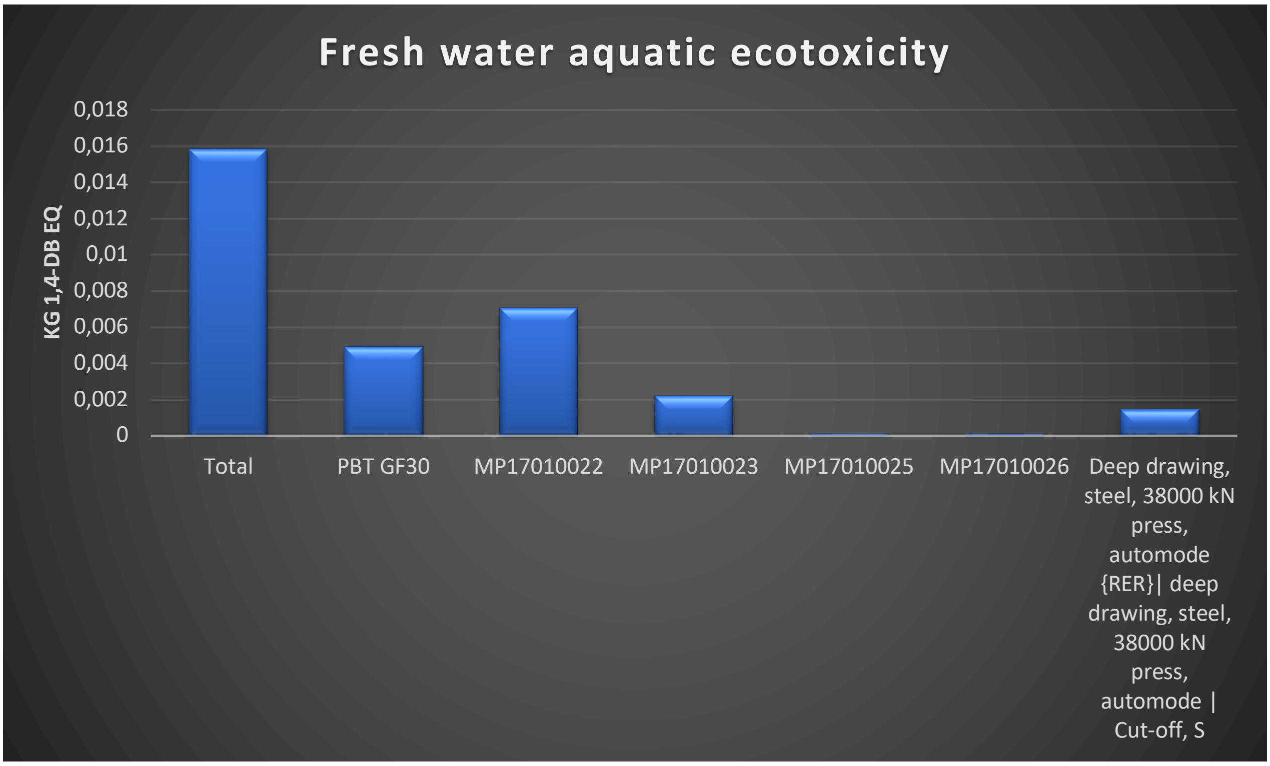

Figure 23. Graph of impact from housing assembly, fresh water aquatic ecotoxicity category

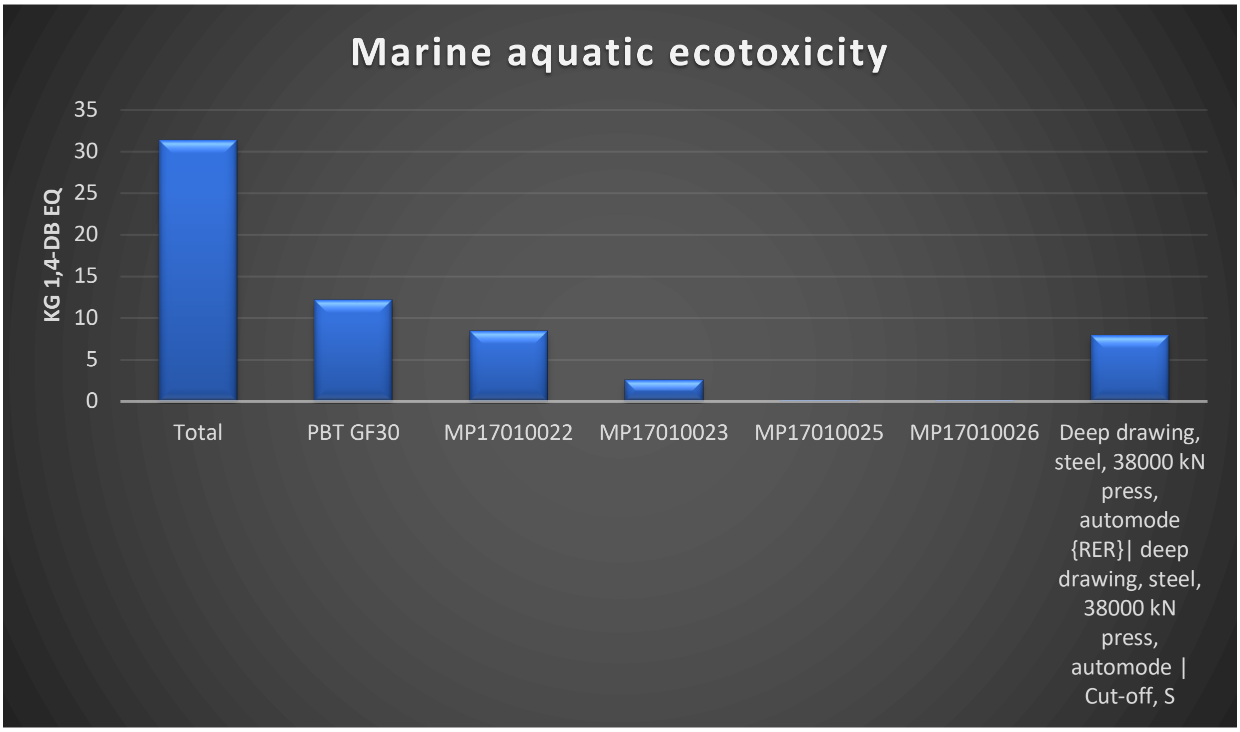

Figure 24. Graph of impact from housing assembly, marine aquatic ecotoxicity category

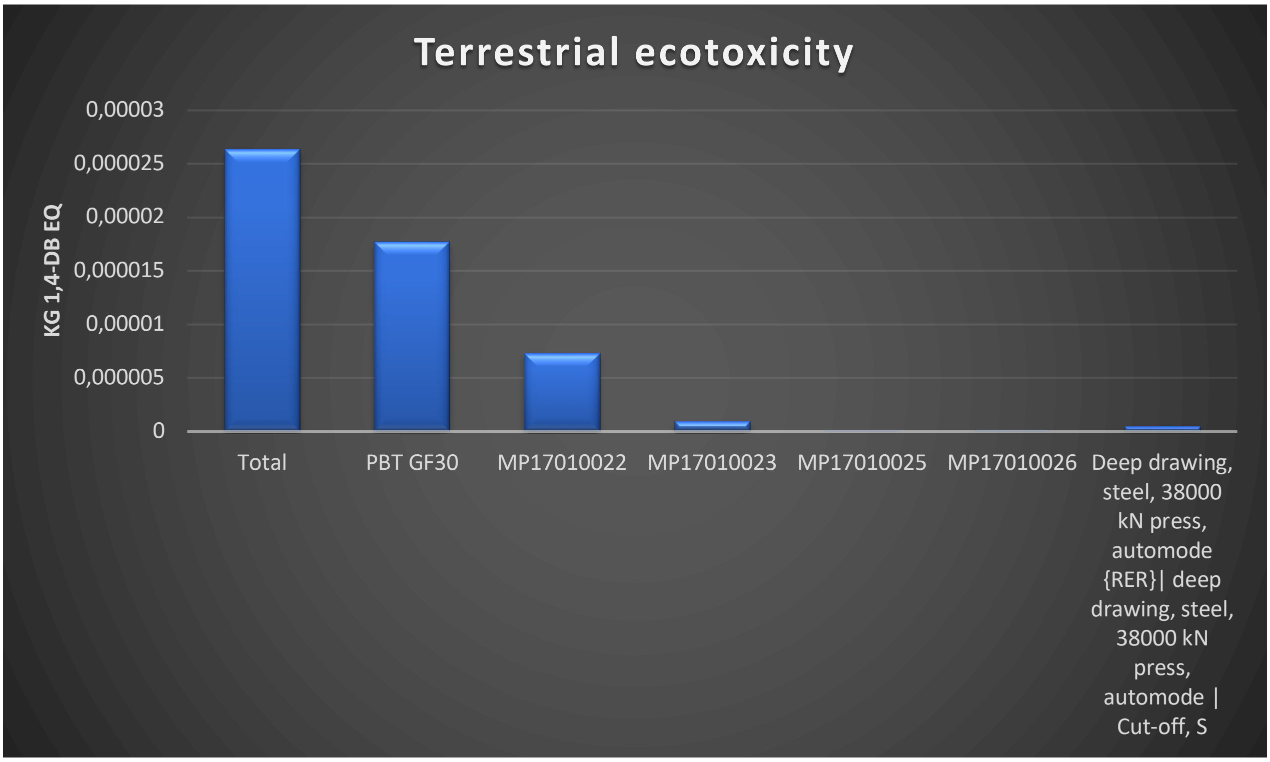

Figure 25. Graph of impact from housing assembly, terrestrial ecotoxicity category

Photochemical Oxidation

This indicator is when emissions from fossil fuel combustion reacts with sunlight creating new chemicals, this process is called photochemical oxidation. (LCANZ)

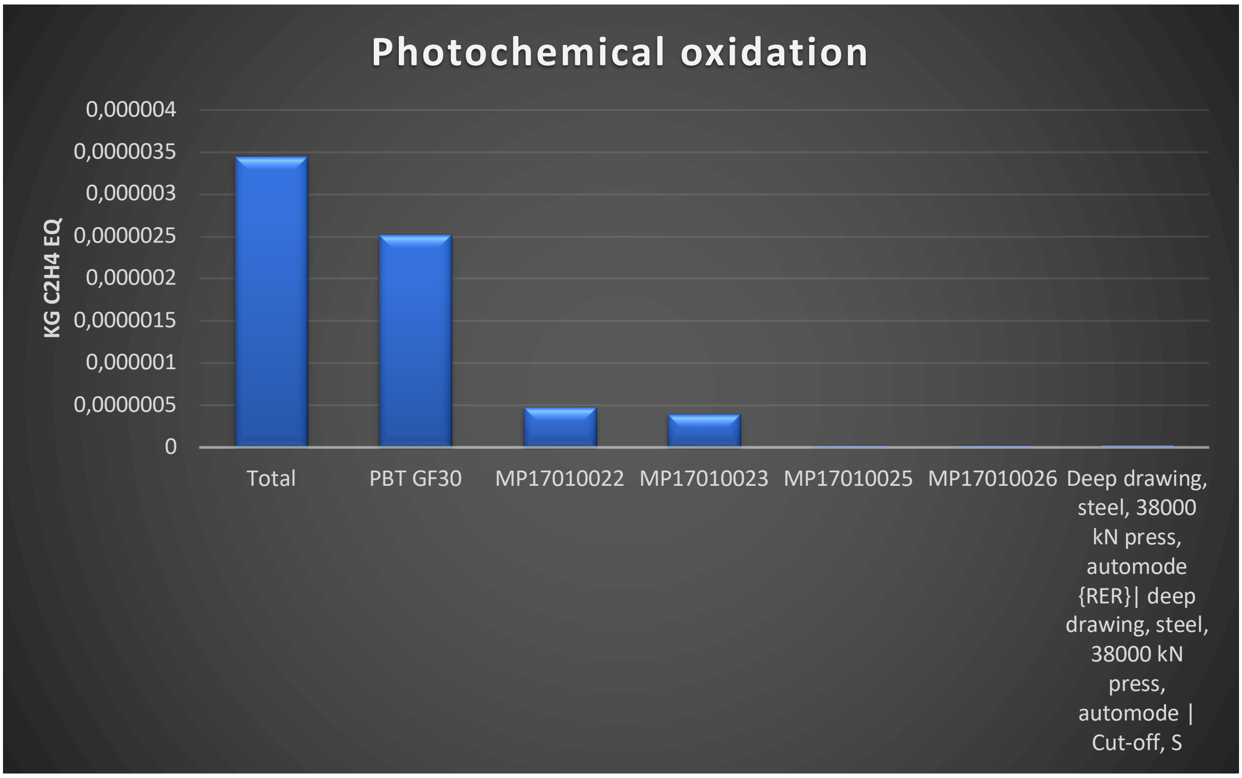

Figure 26. Graph of impact from housing assembly, photochemical oxidation category

Acidification

Acidification is the decline in the environment's pH values. It has the potential to harm both the soil and the water. On the soil, the repercussions can include soil deterioration, which affects plants and microorganisms and can lead to erosion. In the ocean, delicate species may suffer a decline, putting the marine ecosystem at risk. (Sostenible, 2019a)

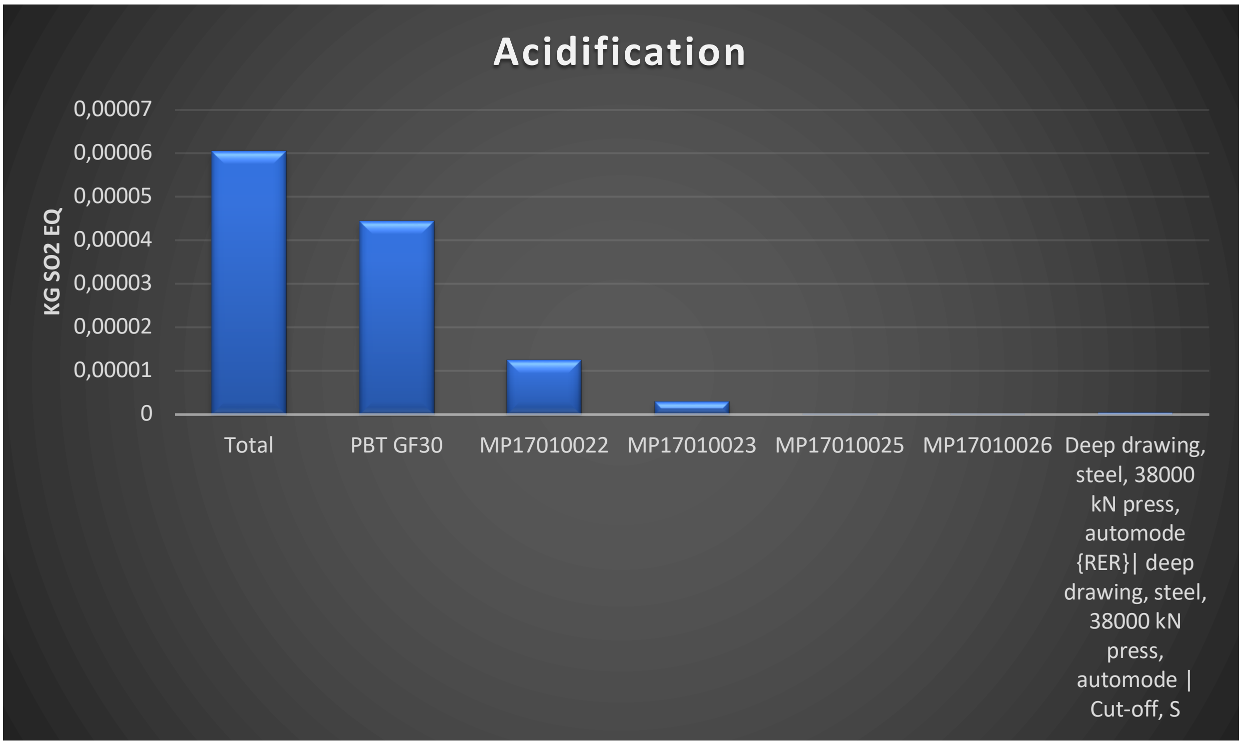

Figure 27. Graph of impact from housing assembly, acidification category

Eutrophication

It is the process by which an aquatic ecosystem's minerals and nutrients, mainly nitrogen and phosphorus, are gradually enriched. The abundance of these nutrients stimulates the growth of algae and phytoplankton, which can have negative repercussions such as the death of aerobic creatures and the death of plants due the block of sunlight which make photosynthesis difficult.(Sostenible, 2019c)

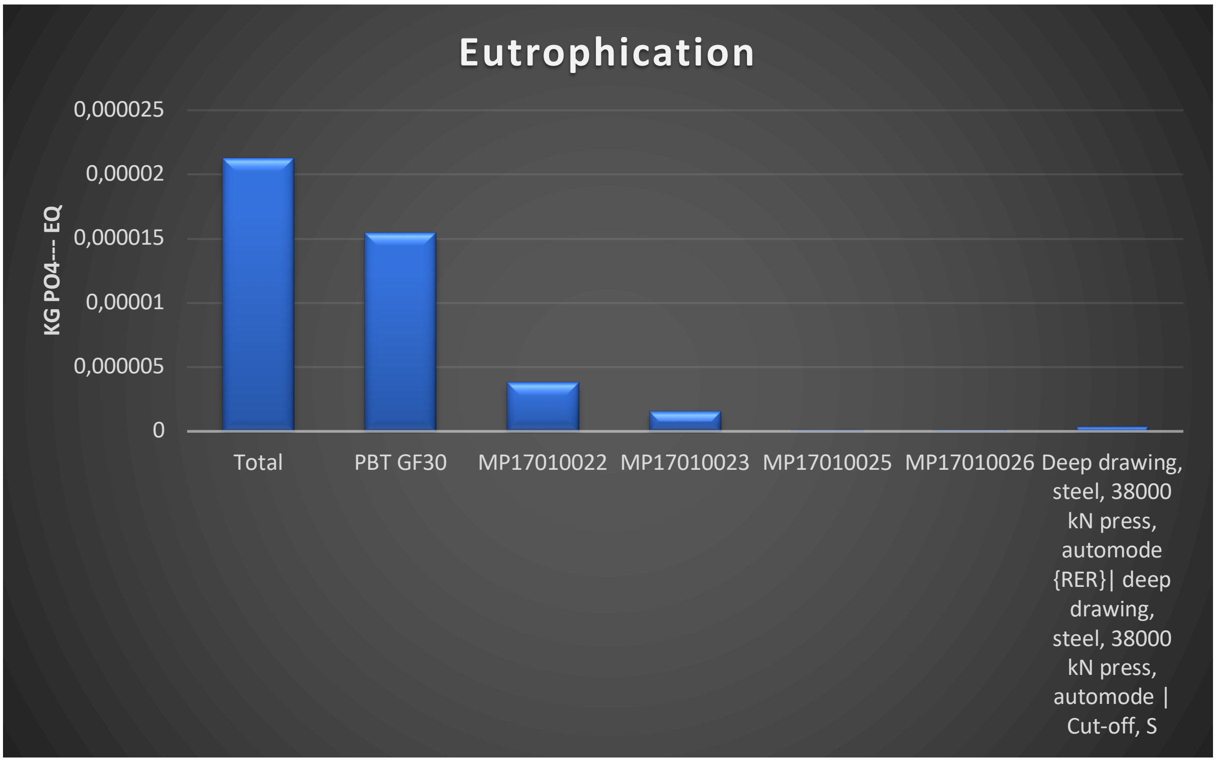

Figure 28. Graph of impact from housing assembly, eutrophication category

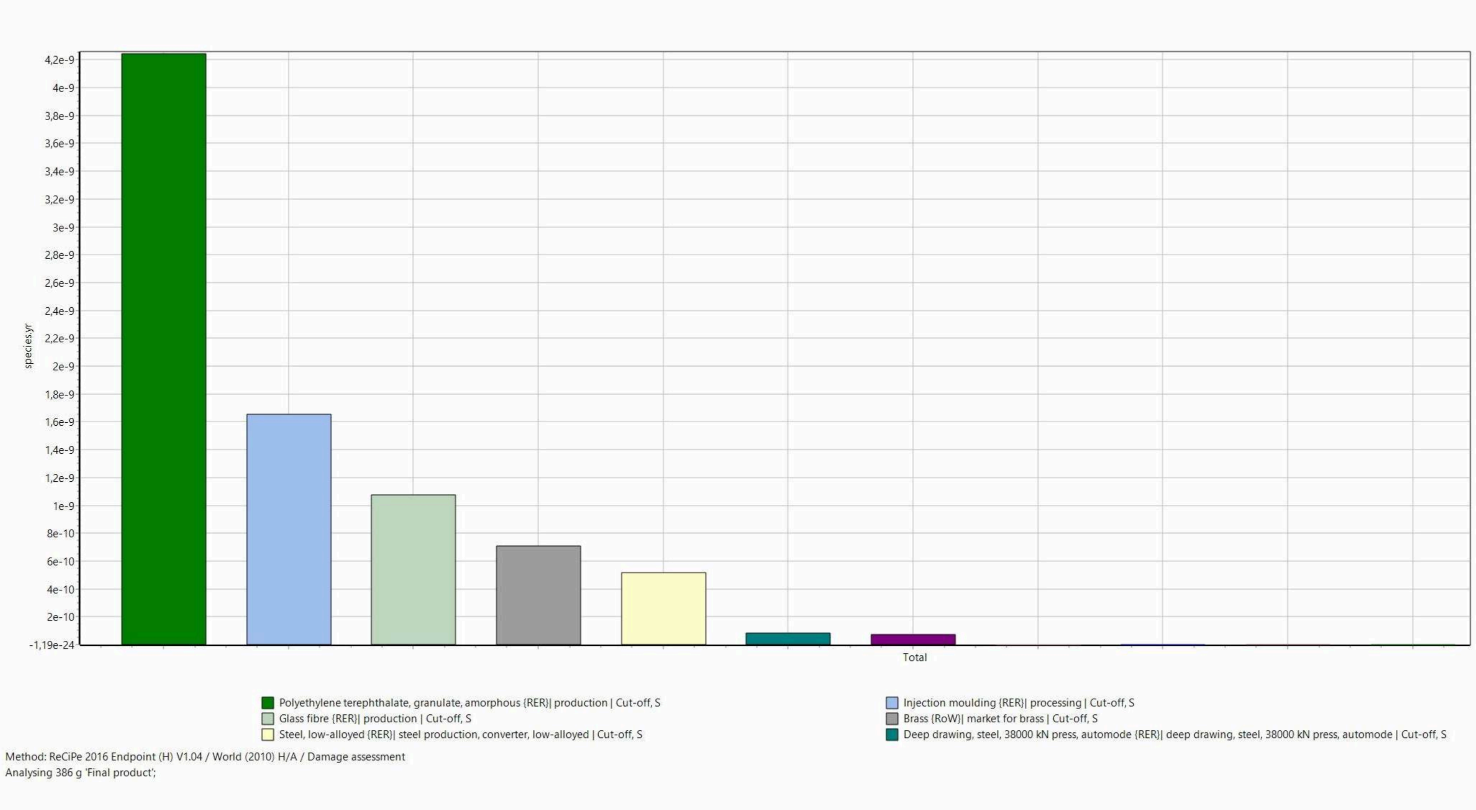

Figure 29. Ecossystem impact - Method: ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A / Damage assessment

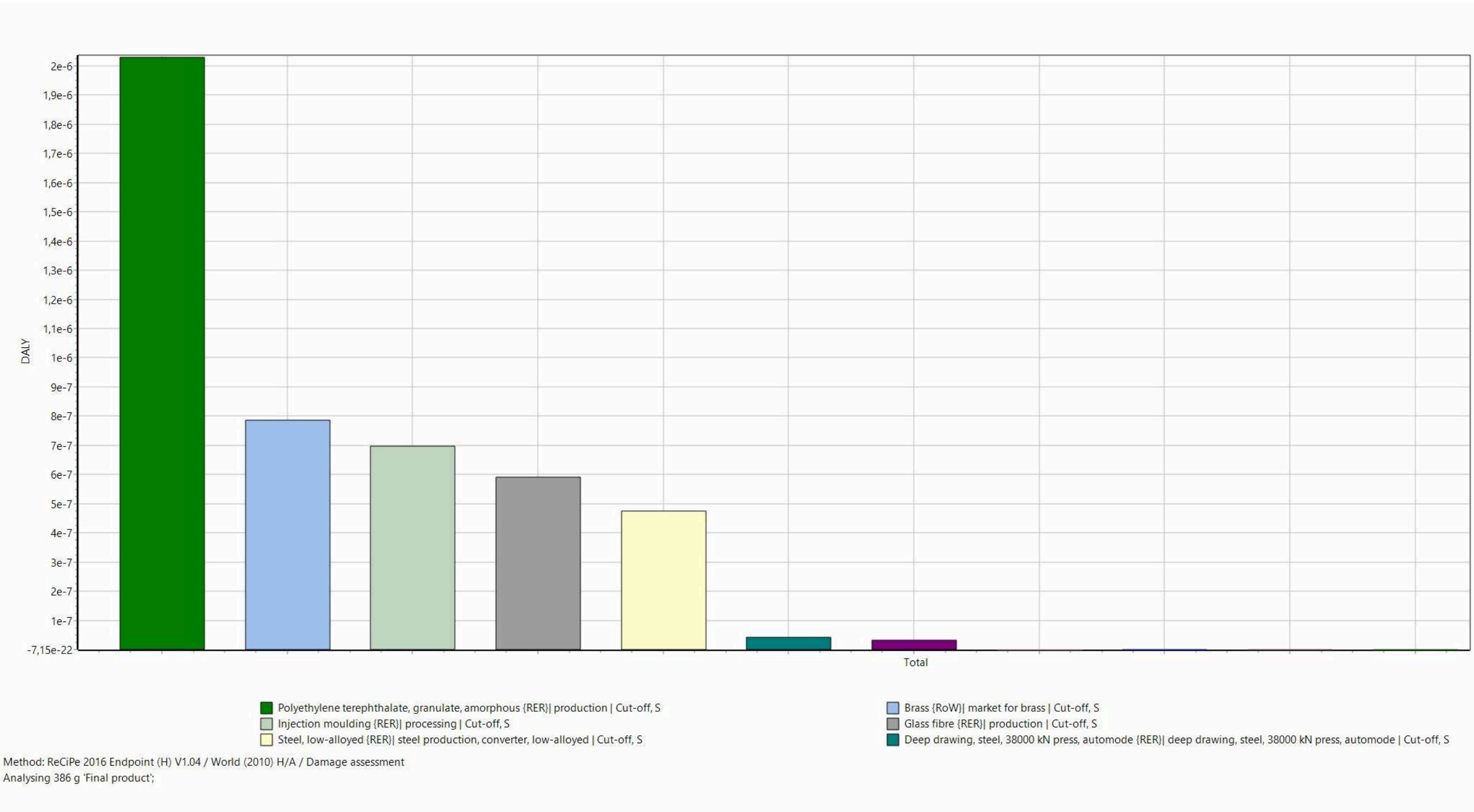

Figure 30. Human Health - Method: ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A / Damage assessment

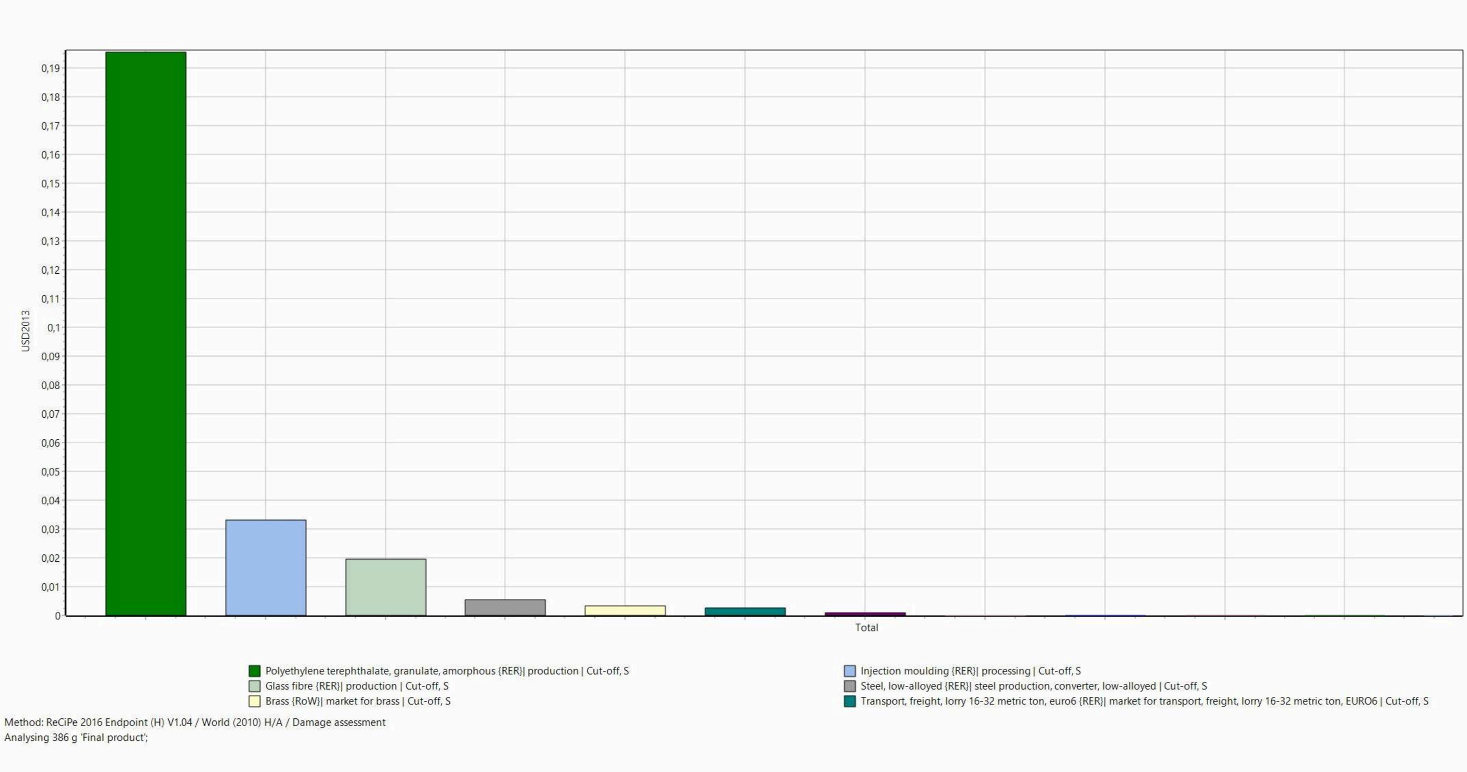

Figure 31. Resources - Method: ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A / Damage assessment

2.5 Interpretation

Although the environmental impacts generated by 1 unit of the product 474 is very low, when it comes to ecotoxicity it is possible to see that the housing assembly contribute in a big impact specially in the marine aquatic ecotoxicity. The Global Warming Potential (GWP) is also an impact to pay attention which is low when we analyze 1 product but can be big when the analysis is for 1 year of production which can be seen on the next topic "2.6 Current Situation".

2.6 Current Situation

The current situation of GLN is that in 2021 was produced 133277 units of Housing assembly and 128956 units were sold, which means that 4321 units were rejected (3,2%). The rejected units go to landfill due the impossibility of reuse the materials because of the inserted metals cannot be extracted. This is the biggest challenge that the company is facing on the housing assembly product.
It is possible to see on the Network results (figure 29) below, the Global Warming Potential impacts that the housing assembly production and rejection of 1 year can cause.

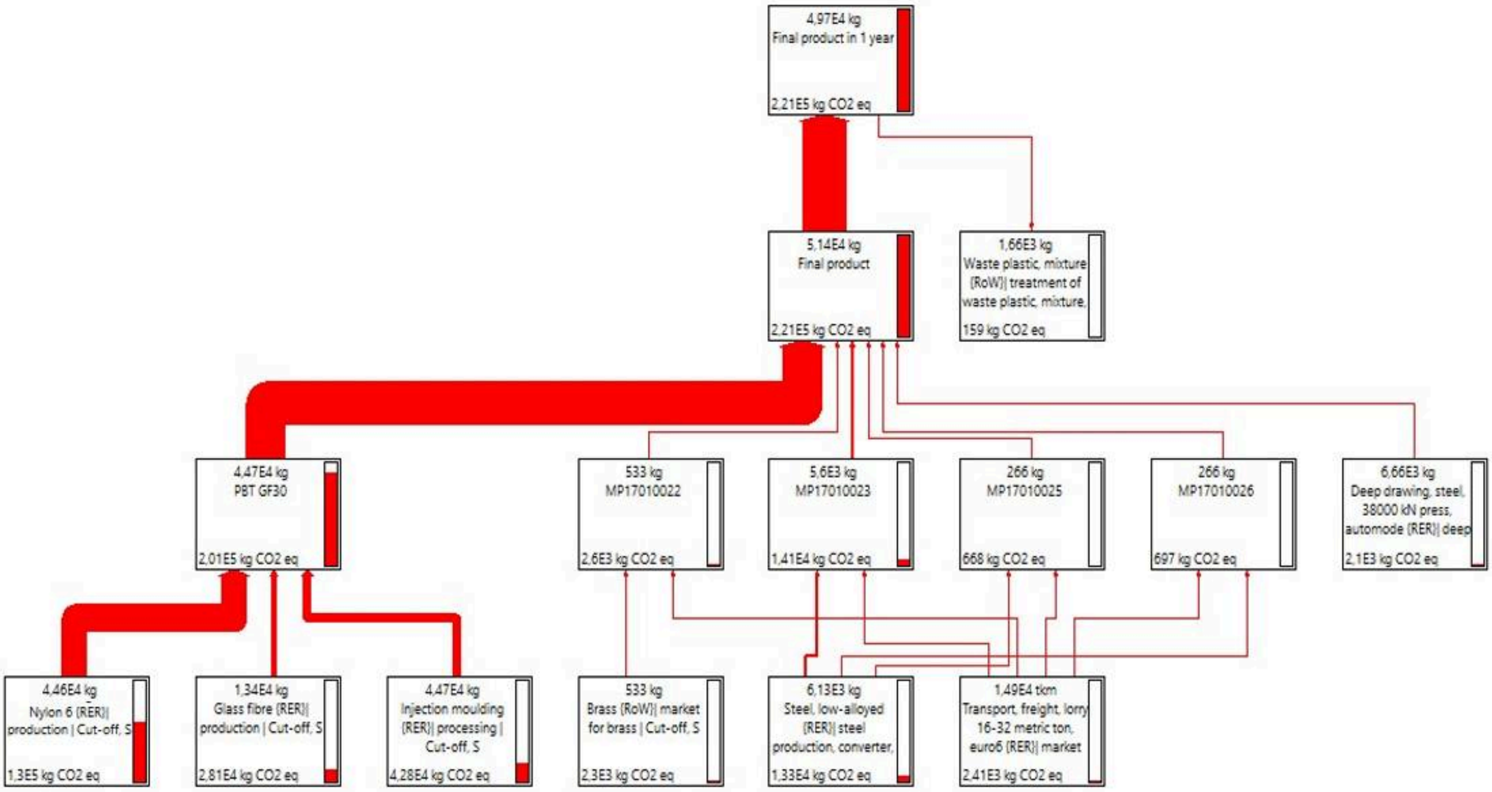

Figure 32. Network results of 1 year of Housing Assembly production

2.7 Possible Solutions

Due to the current situation, a possible solution is to use adhesives on the housing assembly. So instead of using press fit to insert the metals on the housing it could use an adhesive to bond the metals parts and the housing part (PBT30GF).
Adhesive bonds have the advantages of being lightweight, spreading stress over the bonding region, preserving aesthetics, and being reversible.
There are a lot of types of adhesives in automotive assembly, some of them can include: "epoxies, polyurethanes, methylmethacrylates, rubber-based anti-flutters, PVC, butyls, bitumens, thermoplastics, and in-component manufacturing silicones."(Moran, 2020)
According to Wahab (2015) although it requires some knowledge of the proprieties and the application, choosing the adhesive is very important due its versatility. Because there is no universal adhesive that works in every application, choosing the right adhesive can be difficult, and the range of available solutions can make it even more difficult. The kind and nature of the substrates to be bonded, the cure and adhesive application process, and the expected conditions and stresses that the joint will face in service all play a role in adhesive choosing.
Reversible adhesive is the process of destroying or weakening the bond of the adhesive. Depending on the type of adhesive used, in order to achieve the reversible adhesive heating, frequency or solvent is added to the bond.
The most frequent sort of thermoreversible action is hydrogen bonding, which is used to bond hot melt adhesives such thermoplastic polyurethanes and polyamides. At room temperature, adhesives rely on strong hydrogen bonds established between adhesive molecules or between the adhesive and the adherend. However, as the temperature rises, the hydrogen bond gradually dissolves, hastening the adhesion degradation.

Another type of reversible adhesive is based on Diels–Alder reaction, The reaction is a temperature-dependent, dynamic chemical reaction. The DA reaction is frequently utilized in self-healing system reactions, including reversible adhesives, because the reaction conditions are moderate and do not require a catalyst, and the reaction yield is high. (Liu et al., 2021)
There is a downside on the use of heat and chemicals, it could damage the components (or substrates) because they can be aggressive not only for the adhesive but for the components as well.(Ciardiello et al., 2020)
Based on the excellent work of Ciardiello et al. (2020) a good adhesive solution is an adherent made of a polypropylene copolymer with 10% by weight of talc which is a nanomodified adhesive was prepared by adding weight concentrations of iron oxide particles (5% and 10%) in his work experiments were made with 4 variants of the adhesive, manual mixing (5% and 10%) and extruder (5% and 10%)

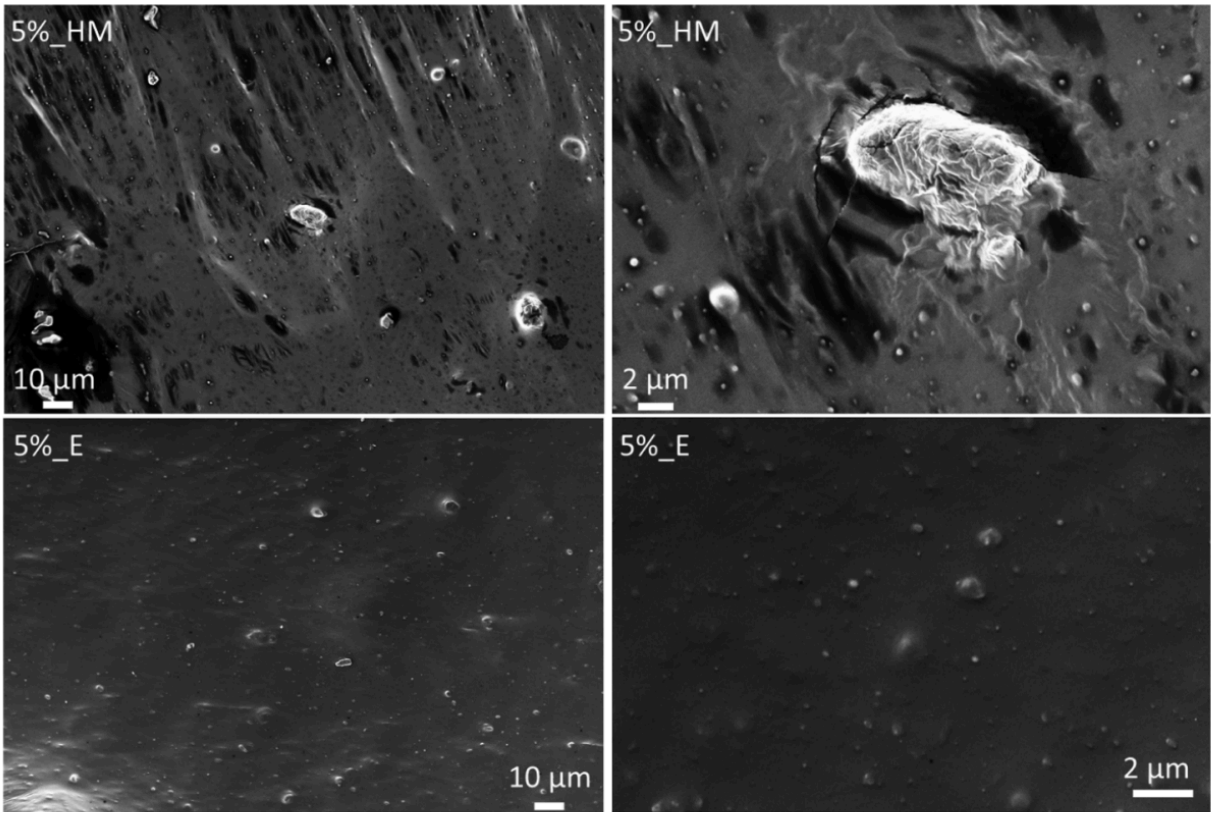

Figure 33. Scanning electron microscopy (SEM) images of 5%_HM and 5%_E, with two different magnifications.(Ciardiello et al., 2020)

They did the mechanical tests, more precisely the single lap shear test (SLJ test) which is the use of plates to the adhesion between the plates and the adhesive. On this teste Ciardiello et al. could see how much force they could apply and how much displacement the plates did. At this comparison the author used 5 variants: Pristine (0% of iron oxide particles) and the 4 modified adhesives, manual mixing (5% and 10%) and extruder (5% and 10%).

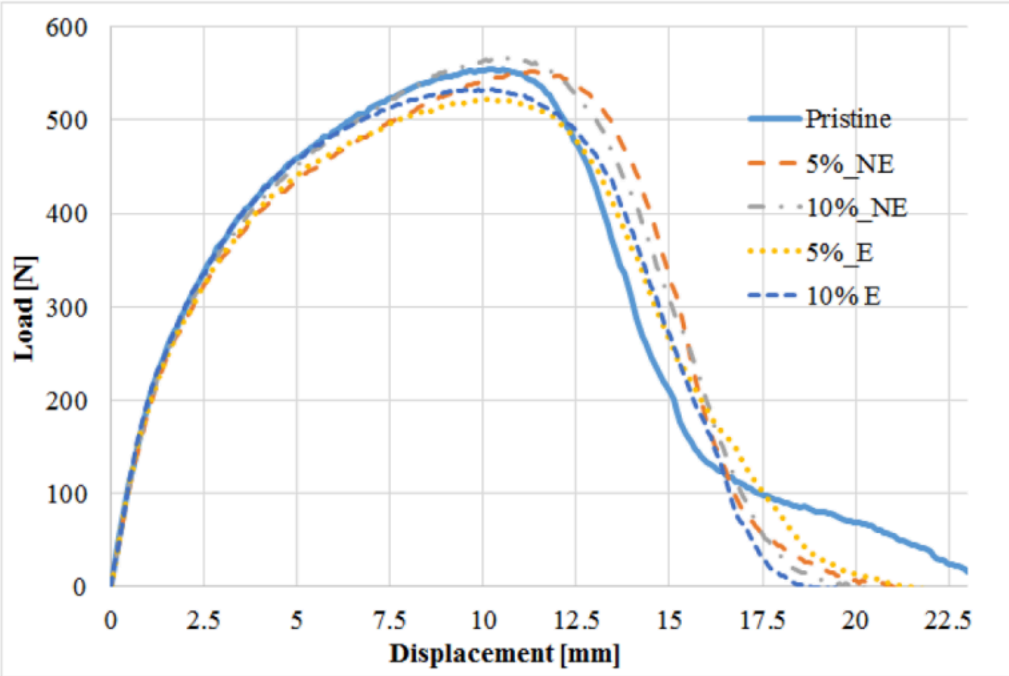

Figure 34. Mechanical test results of the neat and nanomodified adhesives modified with both the manual mixing and extrusion methods.(Ciardiello et al., 2020)

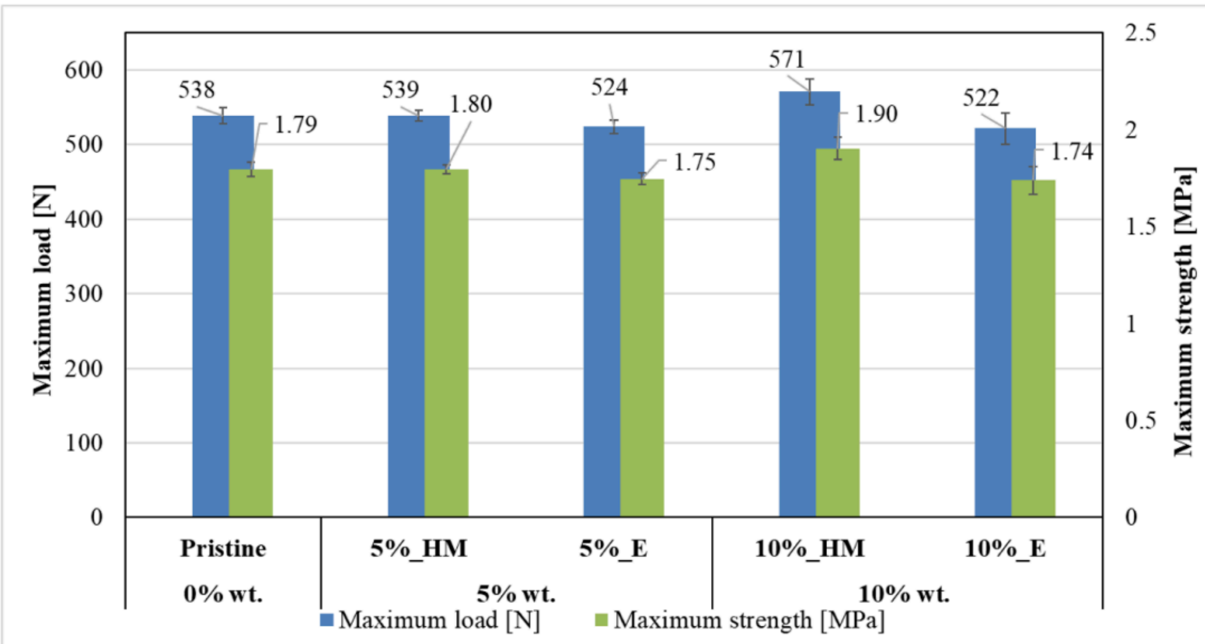

Figure 35. Maximum mean load and strength for all the five adhesive compositions.(Ciardiello et al., 2020)

It is possible to see that the nanomodified adhesive mechanicals properties does not significantly differs from the pristine adhesive, the bond force continues to be good. But the nanomodified adhesive has a disbond property, by using microwave or induction technology it is possible to disbond this adhesive without damaging the components. These technologies can heat locally therefore just heating the adhesive and not the components. According to Ciardiello et al. (2020) the disbond temperature of these adhesives is 140ºC.

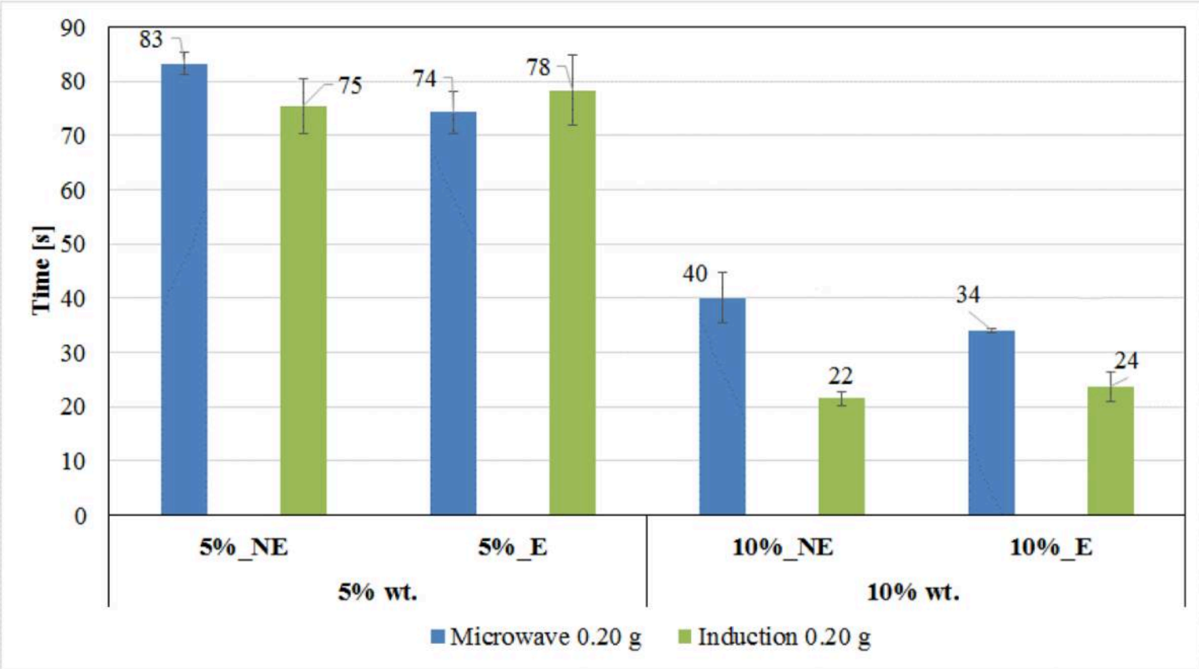

Figure 36. Microwave and induction heating tests conducted on modified adhesives(Ciardiello et al., 2020)

Ciardiello et al. (2020) ran temperature tests using a layer of 0.20 grams of adhesives. In figure 34 its possible to see how much time it takes to the adhesives reaches 140ºC, and therefore disbond, based on microwaves or induction. Its also possible to analyze that some factors:

- Adhesive with 10% of iron oxide particles reaches the disbond temperature faster than adhesive with 5% of iron oxide particles.
- Adhesive mixed by extruder reaches the disbond temperature slightly faster than non-extruder (hand mixing)
- In most cases (3 out of 4 tests) induction heats faster than microwave.

2.8 Comparisson

In this section the current situation (scraps going to landfill) vs the future situation (recycling by using the solution from section 2.7) is compared.

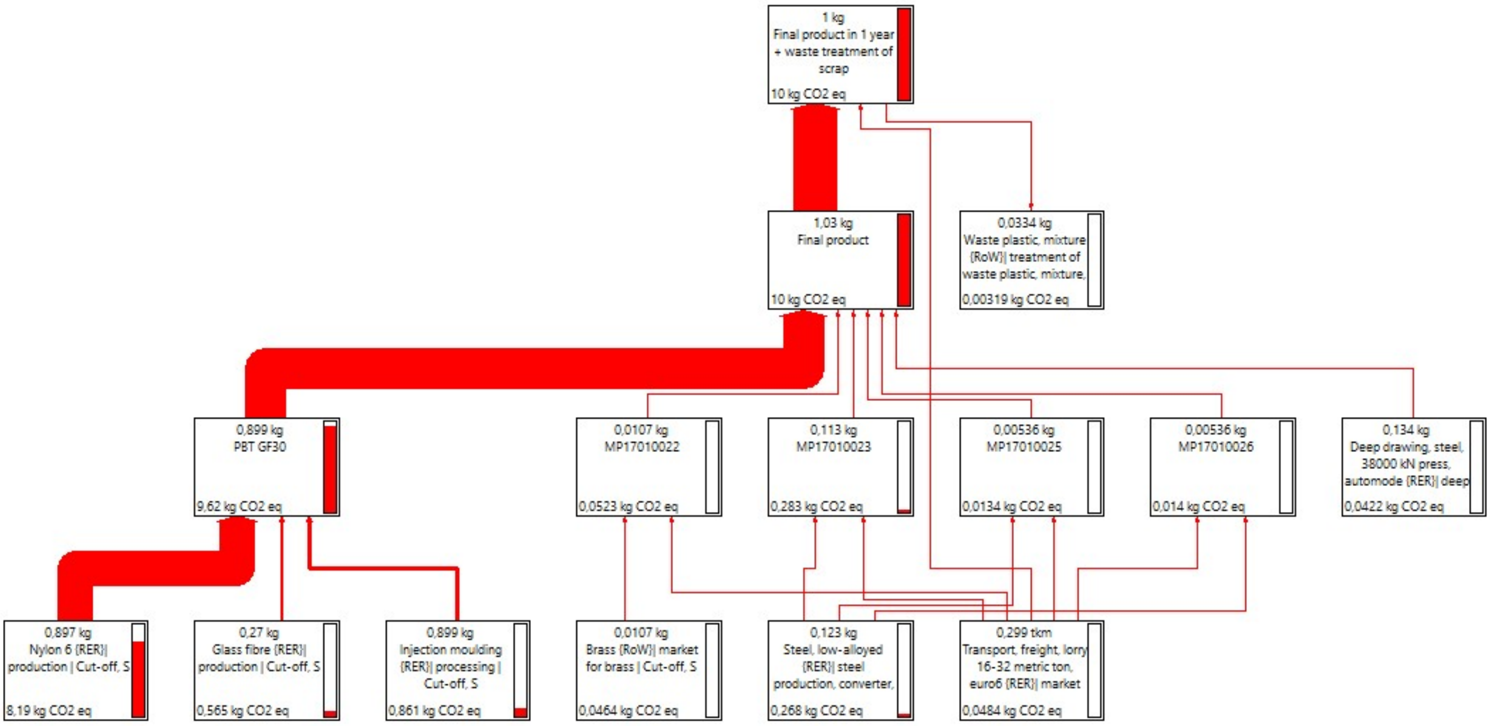

Figure 37. Network of 1 Kg of housing assembly in the current situation

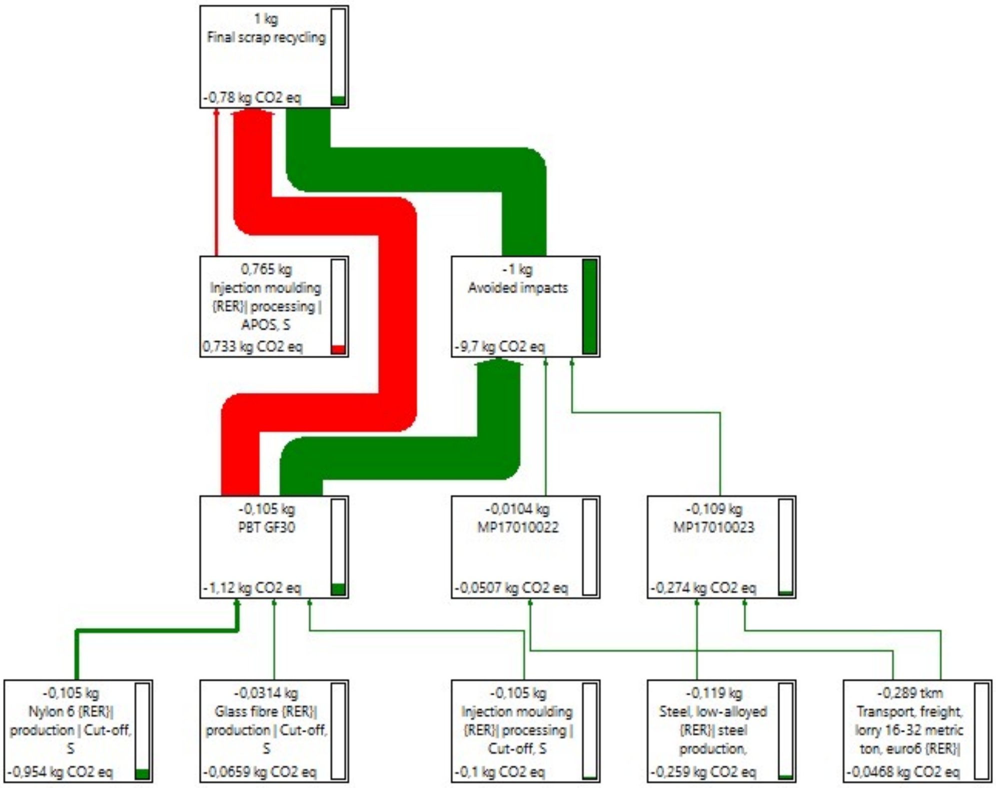

Figure 38. Network of 1 Kg of the recycled scrap

On figure 37 is possible to see the quantity of CO_2 that is produced in 1Kg of the final product in the current situation. But with the solution of reversible adhesive the scrap could be recycled and therefore avoid 9,7 Kg of CO_2.

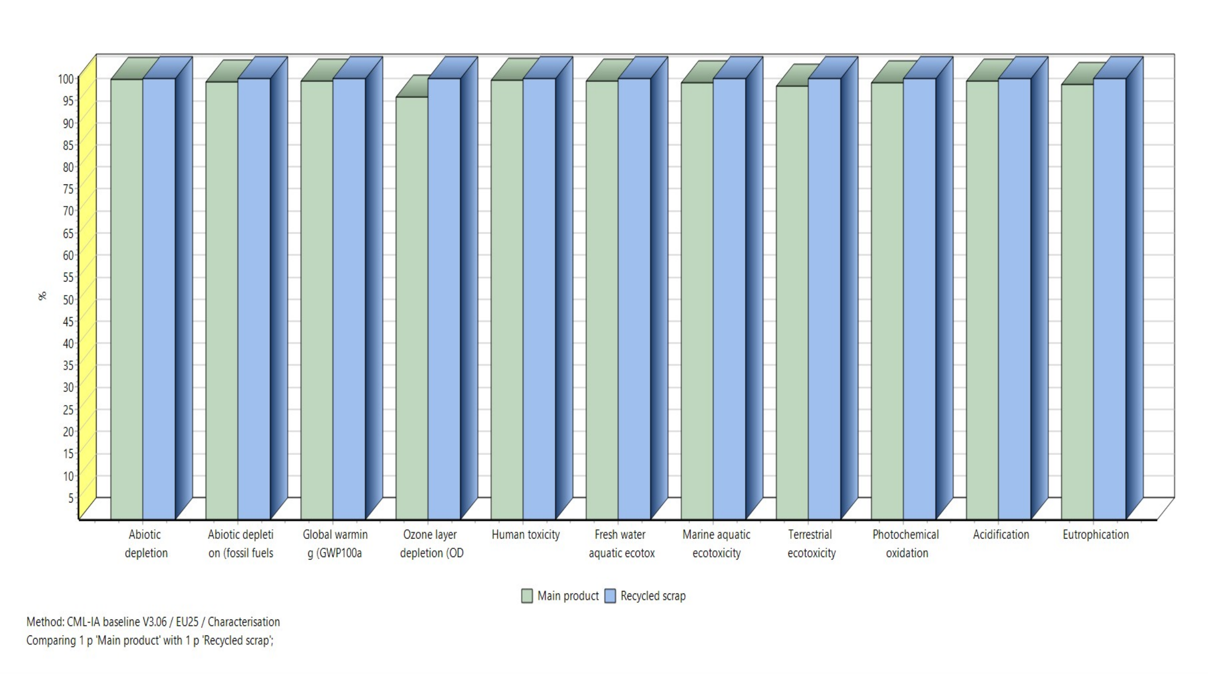

Figure 39. Comparison of Final Product vs Recycled Product

On figure 39, which is the comparison between the main product (final product) vs the recycled scrap (recycled product) it is possible to see that the impacts of both products are almost the same since all the products and transformation are the same. The recycled scrap causes slightly more impacts due the fact that is the main product (which didn't pass the quality control) + injection molding process (redo the process to make to product satisfactory).

It is important to highlight that although the recycled product causes more impact than the main product, the focus should be on the scrap, which in the currently situation goes to landfill and causes way more impact than in the future situation when the scrap is recycled.

3 Life Cycle Costing (LCC)

Life cycle costs are summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced during their life. The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives so the least long term cost of ownership is achieved.(Barringer et al., 1995)
With all the data given by GLN (table 10) it is possible to create the networks and see the differences between the current situation and the future (with the reversible adhesive) in the life cycle costing of the product 474.

Product	Cost	Unit
MP17010022	90 €	Kg
MP17010023	12,08 €	Kg
MP17010025	13,91 €	Kg
MP17010026	97,5 €	Kg
PBTGF30	4,05 €	Kg
Electricity per final product	0,25 €	unit
Electricty	0,19 €	kWh
Workers per final product	1.3	Workers
Sallary per worker	11,00 €	Hour
How long it takes to make a final product	68	seconds
Landfill	57,80 €	Ton
Scrap transport	0,82	KgKm

Table 10. Costs of product 474

The data was imputed in the software, SimaPro, using the method "LCC housing / LCC – characterization" and doing a calculation of analysis and comparison. The results are the table 11, which has 4 types of impact category in one year of production on the current situation compared with the reversible adhesive situation; and the network of the materials.

Impact category	Current situation	Avoided Impacts (Reversible adhesive)
Materials costs	746.491,28 €	-24.100 €
Transport costs	14.535.512,80 €	-469.000 €
Energy costs	42,46 €	0 €
Labour costs	27.703,70 €	0 €

Table 11. Results LCC current situation vs reversible adhesive

Materials costs

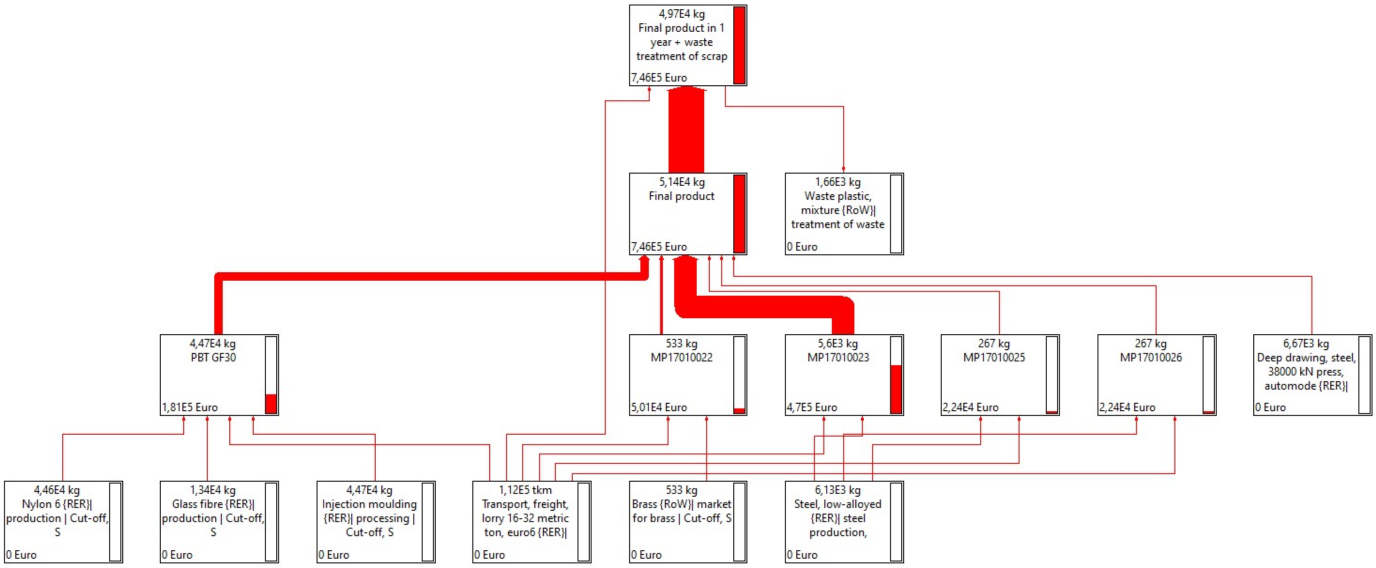

Figure 40. Network of material cost current situation

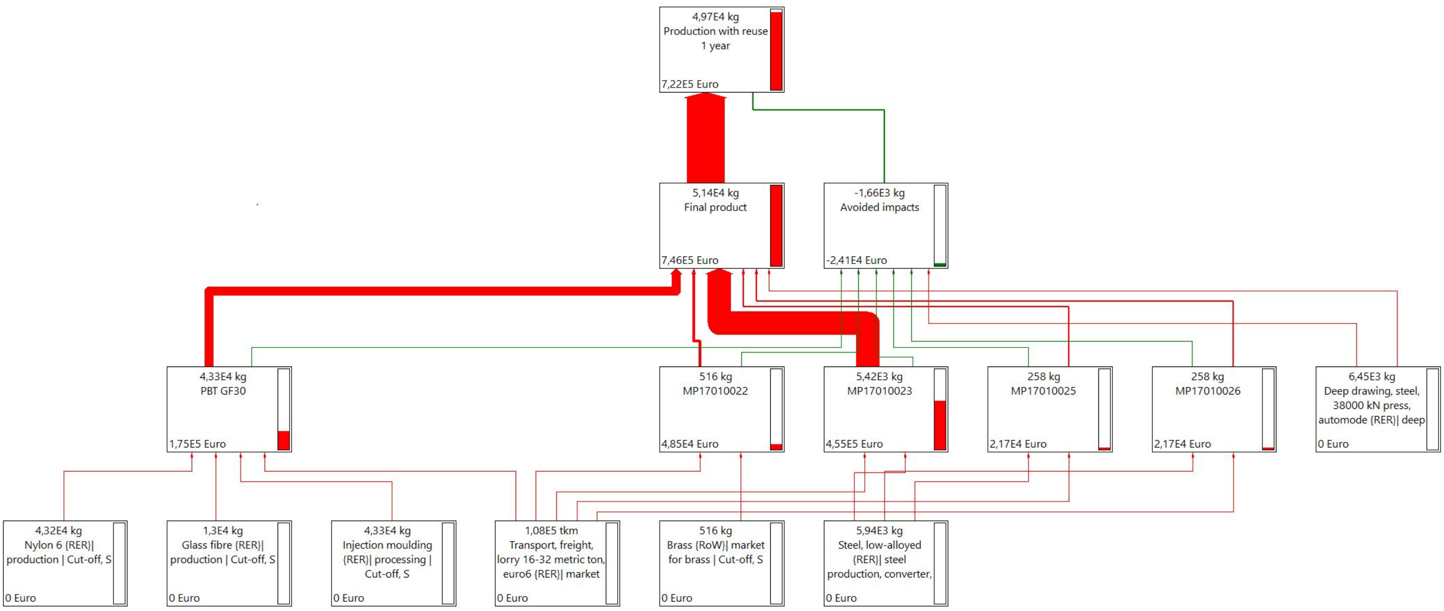

Figure 41. Network of material cost with reversible adhesive

In figure 40, the network of material cost of the current situation considering a production of 1 year of the product, plus the rejected/scrap material, which has a total of 746.000€. On the other hand, in figure 41, which is the material cost of the future situation of reversible adhesive, the total cost is 722.000€. This 24.000€ (3,2%) of avoided impacts is due the reuse of the scrap, instead of the scrap going to landfill, with reversible adhesive the rejected product can be separated into PBT GF30 and metal inserts again, ad reused to create a new, and with good quality, final product; thus saving 24.000€ over a course of one year.

Transport costs

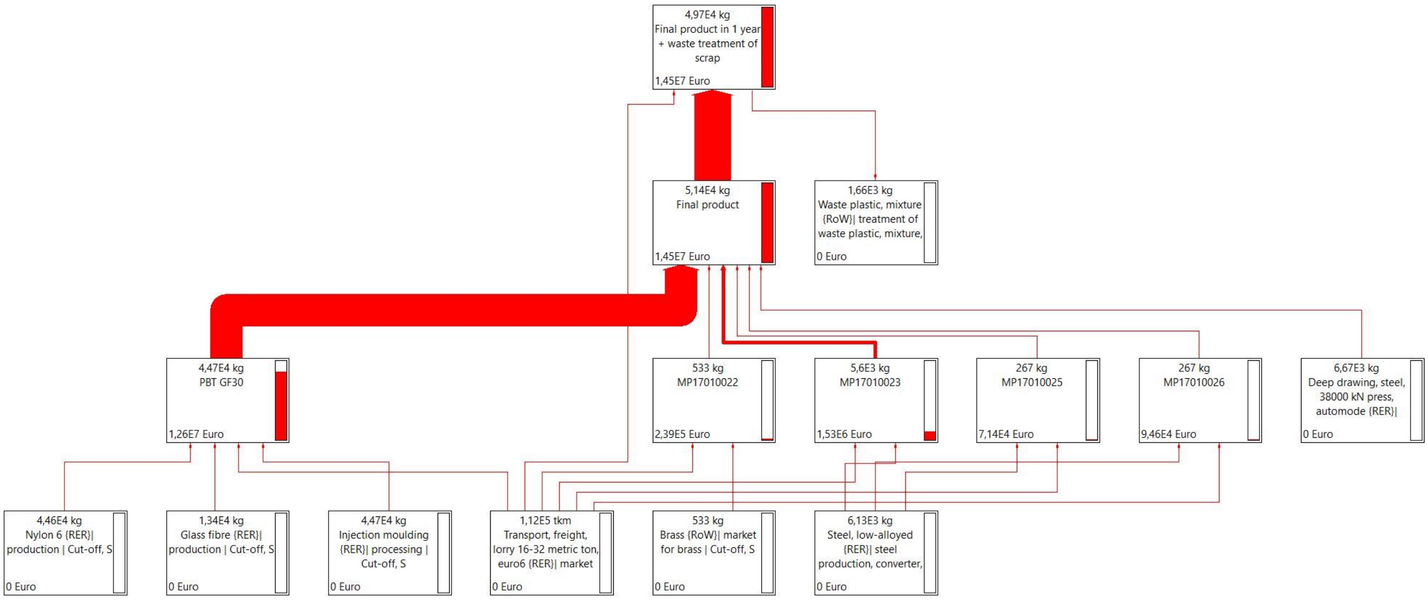

Figure 42. Network of transport cost current situation

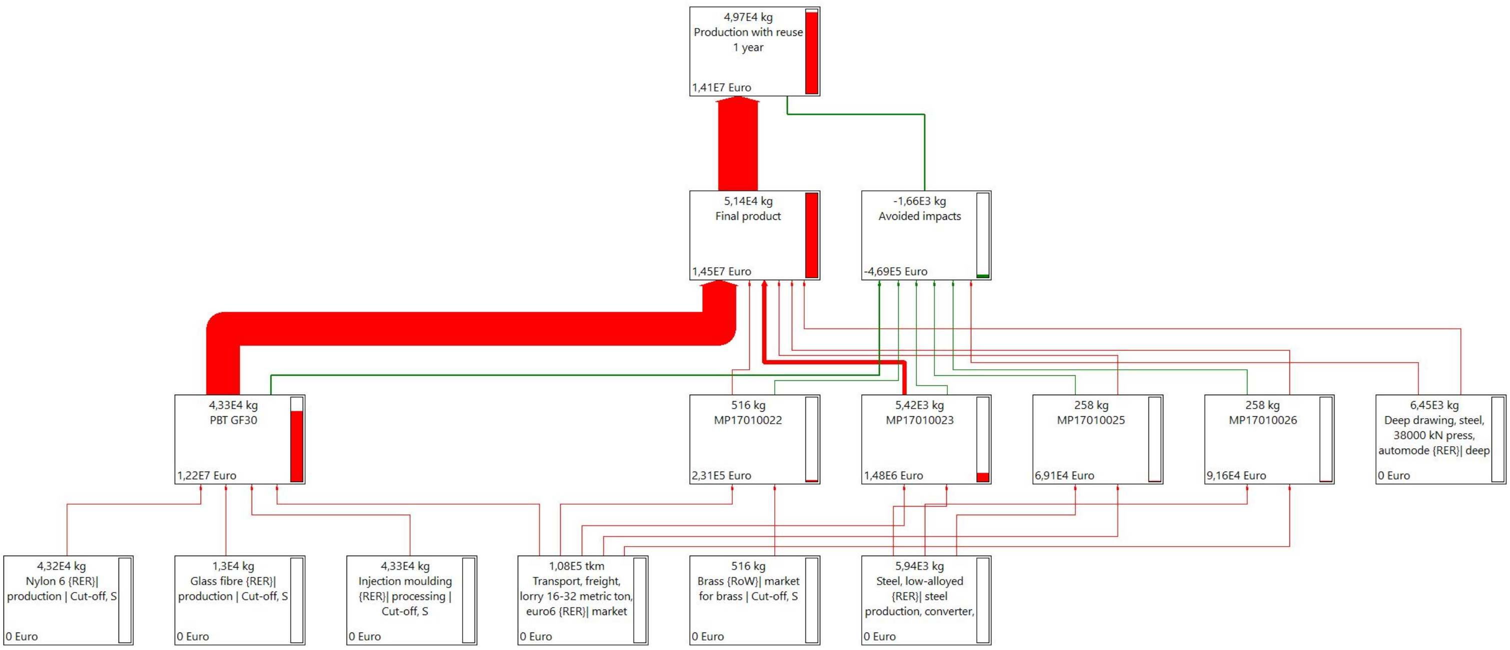

Figure 43. Network of transport cost with reversible adhesive

In figure 42, the network of transport cost of the current situation considering a production of 1 year of the product 474, plus the rejected/scrap material, which has a total of 14.500.000€. On the other hand, in figure 43, which is the transport cost of the future situation of reversible adhesive, the total cost is 14.100.000€. This 400.000€ of avoided impacts is due the reuse of the scrap, instead of the scrap going to landfill, with reversible adhesive the rejected product can be separated into PBT GF30 and metal inserts again, ad reused to create a new, and with good quality, final product, therefore, avoiding transportation of new material; plus the avoided cost of landfill and transportation to landfill, thus saving 400.000€ (3,2%) over a course of one year.

Energy costs and labor costs

These 2 categories did not have changes due the fact that the workers will be working the same amount of time, instead of loading the scrap product to the landfill truck and going to the landfill they will be reusing the material of scrap, that is separated die the reversible adhesive, to create new products 474. Although the energy of the future situation, with the reversible adhesive would be slightly bigger than the current situation, due the fact of using induction to disbond the metals inserts and redo the process again to create a new product 474, the consumption is so low that is not considered.

4 Discussion

After both the LCA and LCC analysis and comparison between the current situation and the future situation, the results were satisfactory. Both the environmental impacts and the economic impacts were reduced by roughly 3,2% which is not much, but considering that the company, GLN, on the product of study does not have big environmental impacts on the current situation any improvement is good.

The 3,2% of avoided impacts on environmental and economic aspects were not a coincidence, the percentage is the same of the scrap products (products that did not pass on the quality control tests) in one year. This, as mention before, is currently the biggest problem of product 474, because the company after a year of production produces 3,2% of scrap which cannot be reused nor recycled due the fact of having metal inserts on the polymer PBT GF30. But with the solution proposed, adding a polypropylene copolymer with 10% by weight of talc which is a nanomodified with weight concentrations of iron oxide particles (5% and 10%) as a reversible adhesive, which can be disbond using induction or microwaves without damaging the metals nor the polymer, the scraps can be reuse and therefore avoiding environmental and economic impacts caused by the scrap amount.

The research questions were answered through the thesis:

1- What are the impacts caused by product 474 on the environmental? After the Life Cycle Assessment (LCA) analysis a data of environmental impacts were generated which is possible to see on topic "2.4 Impact Assessment" with an interpretation on the topic "2.5 Interpretation".

2- What are solutions to make product 474 more sustainable? Using reversible adhesive technology is a possible solution, for more details see topic "2.7 Possible Solutions".

There are a few drawbacks on this work, due the limitations of database of the software SimaPro, some elements were not found and therefore substituted, for instance, the PBT GF30 was not on the database, and was substituted for Nylon 6 + Glass fiber, which did not change the results. Another drawback is due the fact of time to write this thesis, the proposed solution, could not been tested and therefore only the theoretical results is found on this work.

5 Conclusion

The Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis of product 474 shows that although the product does not have big impacts on the environment neither on the economical aspect of the company GLN in the current situation, it can improve. By propose a new solution using the reversible adhesive, polypropylene copolymer with 10% by weight of talc which is a nanomodified with weight concentrations of iron oxide particles (5% and 10%), it will eliminate the scrap problem of the company, by reusing the material of the scrap (PBT GF30 and the metal inserts) to make new product 474 with the right quality, therefore, the new solution lower the environmental impacts and also save around 3,2% on costs compared with the current situation.

5.1 Future work

This work can be the base for new LCA and LCC analysis on similar products or products from GLN, and also can be the initial work on the same product, 474, to test the possible solution of the proposed reversible adhesives physically.

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