Re-designing a Polestar 2 interior door panel

Aiming to reduce the environmental impact by half

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Bachelor's thesis in

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

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Cover: Polestar 2 interior with new cork door panel.

Gothenburg, Sweden 2022

ABSTRACT

This bachelor’s thesis was written in cooperation with the car manufacturer Polestar in Gothenburg focusing on sustainability by using alternative materials and design strategies to reduce the carbon dioxide emissions by 50% during the manufacturing of a Polestar 2 interior door panel. The materials used to manufacture a car’s interior account for 10% of all the emissions generated during car production. The project has included an analysis of the current problems with the existing door panel regarding materials and emissions created but has also worked with examining a door panel's lifecycle from a cradle-to-grave perspective. This was explored by performing a Life Cycle Analysis with two different softwares, openLCA and GRANTA Edupack. The collected data and the impact assessment calculations created a baseline when scouting for new and more sustainable material options. Methods used for the Life Cycle Assessment have been retrieved from literary studies as well as from the company’s own LCA report 2021. Furthermore, more creative methods for conceptualisation, idea generating and material scouting have been used. To visualise how certain materials would be perceived by customers, concepts were visualised in Photoshop. These concepts were evaluated using decision making matrices which led to the final concept. The final concept was modelled in Catia V5 and rendered in Autodesk VRED. The result was a door panel made of cork and a coffee-polymer, which reduced the carbon footprint by 68%. The project shall provide a base for further research in material development within the automotive industry.

Key words: materials, sustainability, LCA, Life Cycle Assessment, car interior, emissions

SAMMANFATTNING

Detta examensarbete utfördes i samarbete med biltillverkaren Polestar i Göteborg med fokus på hållbarhet inom material och design genom att reducera koldioxidutsläppet med 50% vid produktionen av dörrpanelen i en Polestar 2. Materialen som används för att skapa bilinteriörer bidrar med cirka 10% till allt utsläpp som genereras vid framtagningen av nya bilar. Projektets process har bestått av att undersöka problematiken med den befintliga dörrpanelen gällande material och utsläpp samt att ta hänsyn till dörrpanelens hela livscykel ur ett vaggan-till-graven perspektiv. Detta gjordes med hjälp av en livscykelanalys vilken beräknades med programmen openLCA och GRANTA Edupack. Denna datainsamling och beräkning skapade ett nuläge att utgå ifrån i det fortsatta arbetet med att hitta nya och mer hållbara material utifrån koldioxidutsläppet. Metoden och tillvägagångssättet som användes vid livscykelanalysen har hämtats ur litteraturstudier och redan genomförda LCA-rapporter av företaget. Utöver metodiken för livscykelanalysen användes det även kreativa metoder för koncept- och idégenerering samt materialforskning. För att kunna visualisera hur de olika valda materialen skulle skulle se ut på en innerpanel användes Photoshop. Alla kvarstående koncept analyserades och evaluerades med hjälp av beslutsfattningsmatriser. Det slutgiltiga konceptet modellerades i Catia V5 och renderades sedan i Autodesk VRED. Den slutgiltiga panelen bestod av kork och en kaffe-polymer och reducerade koldioxidfotavtrycket med 68%. Projektet ska ses som utgångspunkt för mer efterforskningar inom materialforskning inom fordonsbranschen.

Rapporten är skriven på engelska.
Nyckelord: material, hållbarhet, LCA, livscykelanalys, bilinteriör, utsläpp

PREFACE

This bachelor's thesis was written to explore new material options for interior car door trims. The thesis shall finalise the studies of the three-year long program *Högskoleingenjör inom Design och produktutveckling* at Chalmers University of Technology. The study has been executed during the spring term of our third year and has 15 credits out of a total of 180 credits for our program.

A project like this does not come without help from different people. We are grateful for our supervisor and examiner Olof Wranne, who also has been Head of the program for the past three years, at the department for Industrial and Materials Sciences. He has provided us with pointers regarding the execution of the project and always had advice when we had questions. We would also like to thank *Material ConneXions* in Skövde, for their support during material research and providing us with access to their material database. Lastly, we would like to thank our supervisor at Polestar, Jonas Göthlin, who has given us a better insight in how the company works with sustainability and concept creation.

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1. INTRODUCTION

For our bachelor's thesis for the program *Högskoleingenjör inom Design och produktutveckling* at Chalmers tekniska högskola, we worked together with the automobile manufacturer Polestar. From the beginning, we decided on focusing on sustainability which is why the assignment of redesigning a Polestar 2's interior door panel with the aim to reduce the environmental impact through life cycle analysis, was fitting. The project's outcome should be a complete Life Cycle Assessment of the current Polestar 2 interior door panel, an idea generation process using several creative methods to generate concepts, research on new materials using adequate research tools, reconstructing, and redesigning the door panel so it would blend in with the interior of a Polestar 2 as well as performing a Life Cycle Assessment on the new door panel and visualising the final surface concept. The above-stated actions were documented and evaluated in our final technical report as well as a rendered CAD model.

1.1 Background

Resources like unrefined oil for fossil fuel production have decreased since society has begun to excavate these resources to draw profit from it. Therefore, it has become the goal of many companies to invest in green energy from renewable sources, like solar-, water- and wind energy. This shift towards a more sustainable future has even reached a lot of companies in the automobile industry. The car manufacturer Polestar focuses on enhancing performance and comfort in electrically powered vehicles. The company has launched two different car models of which the Polestar 2 (PS2) is solely electrically driven. The Polestar 2 is their latest model and offers high performance combined with a clean design, which is both simplistic and elegant. With that said, Polestar has the goal to become a climate-neutral company by 2030 on both internal and external levels. To reach the zero-emission goal, the company presents four key drivers for sustainable development: climate neutrality, circularity, transparency, and inclusion.

1.2 Aim

The aim of this study is to redesign the present Polestar 2 interior door panel using new materials to reduce its Life Cycle Assessment outcome by 50%. The materials used inside of a Polestar 2 are approximately taking up 10% of the overall manufacturing emissions. Polestar is aiming for a zero-emission production chain by 2030. This will require searching for new and recyclable material options with an increased lifespan as well as implementing circular design strategies.

The decrease of 50% shall be achieved through numerous actions like the execution of a Life Cycle Assessment of the current door panel, scouting new possible materials for the redesigned door, redesigning the interior of the door as well as performing a final Life Cycle Assessment of the new interior door panel.

The scope of the thesis can be summarised as follows:

- The project will include an LCA of a Polestar 2 door panel
- The project will include searching for new and sustainable materials for a Polestar 2 door panel
- The project will include LCA reassessment with the new materials on the door panel
- The project will include redesigning the interior door panel with the new materials

1.3 Boundaries

The thesis' boundaries are set as follows:

- The project excludes life cycle analysis for the exterior of the Polestar 2 car door.
- The project excludes searching for new and circular material for the exterior of the Polestar 2 car door. This excludes even the glass for the door windows.
- The project excludes all the mechanical features inside the door panel, such as the functionality of the buttons and door handle.
- The project excludes the economic impact new materials found for redesigning may have on the retail and manufacturing price.
- During the project assumptions about transport distances must be made which results in approximative values on distances transported.

1.4 Precision of the research question

As stated in 1.2, the aim of this thesis is to redesign the present Polestar 2 interior door panel. To be able to redesign and reduce the emissions created by the interior door panel, the following guiding questions are used during the project.

- Where do the Polestar 2 materials derive from and how are they manufactured?
- What are important criteria when it comes to choosing materials?
- Which new sustainable and possibly unconventional materials fulfil Polestar's design requirements?
- To what extent can new materials increase the lifespan of car interiors and improve the LCA outcome in comparison to existing materials in car interiors?
- How can the door interior be (re)designed to replace faulty or broken components in the easiest way possible?
- Is it possible to reach a final shortage by 50% on the LCA result? If not, how much can the environmental impact be reduced?

2. THEORETICAL BACKGROUND

Protocols for sustainability in theory
To improve their cars Polestar has come up with four key drivers for sustainability (Polestar, 2022).

1. *Climate neutrality* - Net-zero greenhouse gas emissions
2. *Circularity* - Design that eliminates waste and pollution
3. *Transparency* - The whole truth about electric car sustainability
4. *Inclusion* - A sustainable future for all

These key factors are based on numerous studies and protocols for sustainable development. Some of these protocols are the United Nations 2030 Agenda aiming towards a more sustainable and resilient planet. The agenda includes a 17 sustainable development goal plan promoting global prosperity by reducing inequality within humans, improving health and education while still supporting economic growth and tackling problems related to climate change. Life cycle assessments are evaluated and improved constantly to create more accurate results on the environmental impact of a product. In Polestar's latest life cycle assessment report from 2021, they followed the GHG - protocol, short for Greenhouse Gas Protocol, when performing their life cycle assessment for their entire product range. The GHG - protocol accounts for a variety of greenhouse gases from a cradle-to-gate perspective including methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) emissions (GHG, 2011). Even if the GHG-protocol takes all these greenhouse emissions into account, Polestar's latest LCA results were presented in *carbon dioxide equivalents - CO_2-e.* CO_2-e's are an accumulation of the main greenhouse gases generated during a product's life cycle.

Studies on materials
Developing new concepts for car door panels is not as common as creating new concepts for an entire car, but nevertheless as important. In 2016 a paper called *Design of the Interior Door Panels in a 1969 Chevrolet Camaro* was written by a student from The University of Queensland (Majoo, 2016). In his paper, Majoo examined the design of an interior door panel by reengineering different components as well as other automotive manufacturers' design and material choices. Majoo's study had similar requirements compared to this thesis project and followed a design engineering methodology process.

In 2006 Holbery and Houston wrote the article *Natural-fiber-reinforced polymer composites in automotive application* comparing different materials regarding weight, durability, processing methods and area of application regarding the interior of a vehicle. The comparison of different natural fibres in combination with how they are being processed were particularly valuable for a better understanding during the material research phase.

3. METHODOLOGY

The outcome of the thesis work is to reduce the LCA outcome expressed in CO_2-equivalent by using new and innovative materials which fulfil the technical and mechanical requirements as well as the prerequisite to be fitting into an already existing Polestar 2. The methods used for achieving these goals during the thesis work are stated below.

Literary research and trend analysis
Literary research was carried out to gain broader knowledge needed to understand the complex process of how a life cycle assessment is done. Information was searched in several literary databases like Chalmer's own as well as books on material science. Further, the research included becoming familiar with the terms within the automotive industry to be able to use those correctly.

Life cycle assessment
The Life Cycle Assessment (LCA) was performed to calculate the current door panel's environmental impact expressed in CO_2-equivalents per kilogram (CO_2-e/kg). The method includes following steps: disassembling the current product, in this case the PS2 interior door panel, weighing all the components of the panel, creating a Life Cycle Inventory (LCI) and a Life Cycle Inventory Analysis (LCIA), performing the LCA considering the boundaries set in the cut off criteria and interpreting the outcome of the data supported by an LCA calculating tool, openLCA. This created an essential base for searching for new materials.

Material analysis
Analysis of materials in GRANTA EduPack and openLCA were performed to obtain a better insight into which materials would or would not work in cars. Less extensive LCAs were done in GRANTA and used as a guideline while searching through new materials.

The lateral approach - De Bono's six ways of thinking
This creative idea generating method was used to discuss and express thoughts on the materials found as well as to state advantages and disadvantages of them. Using this method helped to map out possibilities the new materials might have.

Pugh-Matrix
The Pugh-Matrices were used to evaluate the materials found during literary research and compared to the original materials to screen out the less proper materials to be used in a car's interior. This method was performed twice to be able to be left with the better options to conceptualise further.

PNI - Positive Negative Interesting
This method was used in the conceptualisation phase of the design process. The PNI stated the positive and negative aspects of each material. This supported the decision-making process for the final concept.

Elimination matrix

At the end of the conceptualisation phase a decision had to be made which is why an elimination matrix was used to screen through the materials' properties and whether they would meet certain requirements or not. This matrix resulted in deciding the final material used for the final door panel concept.

4. LCA OF THE CURRENT POLESTAR 2 DOOR PANEL

The following chapter will introduce how a Life Cycle Assessment is carried out, present the scope and the boundaries in case of this project. In this Life Cycle Assessment, the environmental impact of the current door panel will be calculated.

4.1. Introduction to LCA

Life Cycle Assessment (LCA) is a methodology developed for a better understanding of the impact products and services have on the environment. A Life Cycle Assessment considers the environmental impact of a product during its whole life cycle, cradle to grave, and can assist in identifying opportunities to improve the environmental performance of that product at various points in this life cycle. This enables the possibility to decrease the environmental impact in one area of the life cycle, without, unknowingly, increasing the impact in another area.

There are four different phases in an LCA. The first phase is the goal and scope definition phase, where the intended use of the study is described as well as the system boundary and level of detail. The next phase is an inventory and collection of the input/output data needed for the study, the Life Cycle Inventory analysis phase (LCI). In the third phase, the Life Cycle Impact Assessment phase (LCIA) the data is further processed and sorted in different emissions categories and the environmental impact of the studied system is quantified. The final phase is life cycle interpretation where the results of the LCIA and LCI are summarised and discussed (Cays, 2021).

4.2. Goal and Scope Definition

Goal definition

The main goal of this part of the thesis is to evaluate and quantify the environmental impact of the existing materials on the Polestar 2 door panel and will be used to compare with the LCA of the re-designed door panel. This provides a basis to reach the goal for the whole thesis; reduce the environmental impact, calculated in kg CO_2-equivalent, of the door panel by half.

Scope definition and datasets

The Greenhouse Gas Protocol is a Life Cycle Assessment method which examines the lifecycle of a product regarding greenhouse gases emitted from material acquisition to End-of-Life. Its purpose is to create guidelines for companies who want to investigate their possibilities to improve the amount of greenhouse gases emitted throughout the entire value chain. The method assesses all the emissions at every possible *scope.* The GHG method is divided into three different scopes.

- Scope 1 accounts for every emission that is created by the organisation or company themselves and can be therefore controlled by them. This includes company vehicles fuel combustion and emissions directly linked to company buildings.

- Scope 2 covers electricity for both heating and cooling systems and their emissions.
- Scope 3 includes emissions upstream from purchased materials and goods, transportation to the production sites, fuel and energy related to the production of the product, company assets and waste generation during production. Downstream emissions imply transportation and distribution to customers, the processing of every sold product, the use of the sold product, its End-of-Life waste treatment, and investments a company has to make to stay competitive within the industry.

While scope 1 is directly influenced by the company the other scopes are influenced indirectly through actions on the production sites and the decision made at material acquisition as well as how a product should be transported. The GHG method aims to discover toxic emissions created throughout both upstream and downstream activities (Greenhouse Gas Protocol, 2011). In this case the PS2 door panel meant having to examine it mostly through scope 2 and 3. However, mostly excluding the use phase as the door panel does not have a direct connection to fuel from either electricity or fossil fuels.

The Life Cycle Inventory was then transferred to the Life Cycle Assessment calculating program openLCA which provides access to a variety of databases for assessments through a product's life cycle. For the LCA of the Polestar 2 interior door panel the European reference Life Cycle Database is used (European Commission, 2015). The database's aim is to quantitatively assess the environmental impact products have during a product's whole life cycle. The database works considering the Product Environmental Footprints (PEF) categories and rules towards more sustainable products and product use. Together with the openLCA methods extension which includes different protocols like eco indicator 99, ecoinvent but also the Greenhouse Gas Protocol method which is used both in Polestar's LCA report from 2021 and in this project (GreenDelta, 2022).

4.2.1. System description - door panel

The components of a car door panel are called *door trims* (Figure 1). During the project all calculations were based on a rear door interior panel. These trims can be categorised into ten main trims which can look differently depending on the design and expression of the whole car interior.

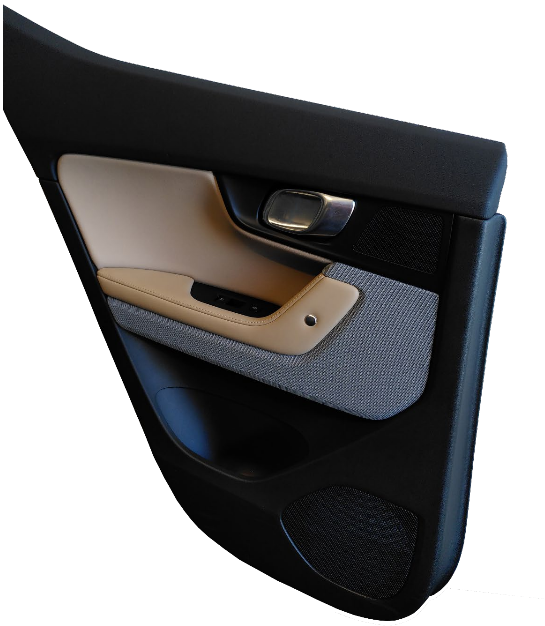

Figure 1: The PS2 interior panel of a left side rear door including all door trims

Waistrail

The waistrails' function is to protect the passenger from being impacted if a crash occurs. The waistrail is a longitudinal structural part of a car door's interior. The waistrail is the second area to be impacted after an initial deformation when a crash occurs. The first area to be impacted is the outer door shell. The waistrail of the Polestar 2 door panel covers the structural metal waistrail and consists of two parts, an upper part, and a lower part (Figure 2).

Figure 2: Waistrail in two parts after disassembly

The lower part supports the structure of the upper part of the waistrail. In the case of this door panel, the waistrail is made of a compound of polycarbonate (PC) and acrylonitrile butadiene styrene (ABS). PC is used in many automotive applications due to its high impact strength and high elasticity modulus, which means it can be easily processed and moulded into complexer shapes. When exposed to UV-rays it does not thermally expand, which is another key component of why it is being used frequently in car interior design. Because cars are exposed to sunlight and heat during summer, PC-plastic is often used due to its optimal strength retention at higher temperatures. (International Polymer Solutions Inc., n.d.) ABS has been a part of the automotive component production since the early 90's due to Injection moulding has proven itself to be the most cost-competitive in the automotive industry. When selected in the correct way PC/ABS fulfils both the expectations of manufacturers and customers, when it comes to safety, quality, and comfort in a cars' interior (SAE Technical Paper Series, 2007).

Armrest

The armrest is a part on a door panel, where a passenger can place their arm comfortably. The whole armrest consists of two components, the actual armrest, and the grab handle, shown in figure 3 and 4 below.

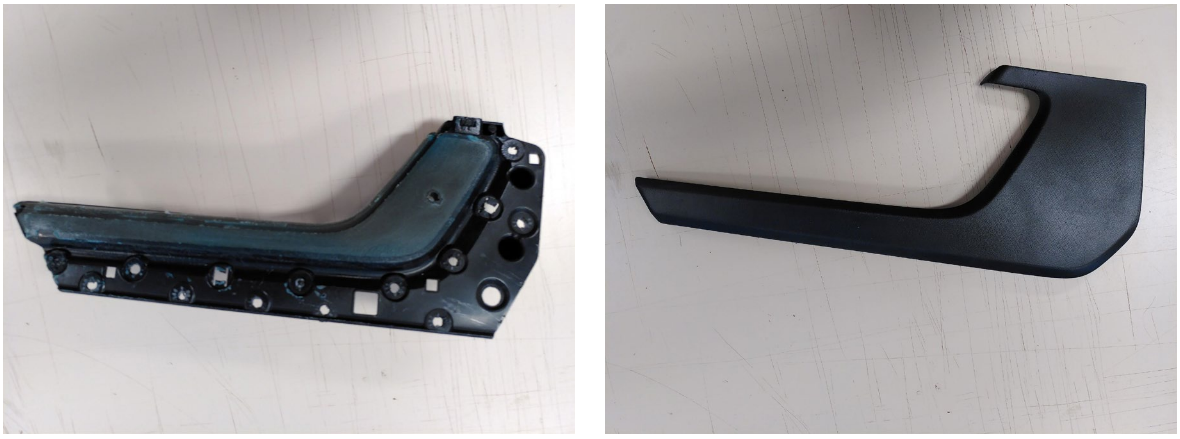

Figure 3: Armrest after disassembly

Figure 4: Grab handle after disassembly

The armrests are installed onto all front and rear doors. They serve as both armrests and door handles for passengers and drivers to close the door. In the Polestar 2 door panel the grab handle and the armrest are integrated into each other. Armrests are tested regarding how much load can be applied without causing constant deformation as well as they must meet requirements regarding comfort. The armrest is manufactured from a PC/ABS blend. PC/ABS blends have a high tolerance to different temperature exposures, can be injection and compression moulded and have a higher strength property than just PC. The foam used for covering the armrest to make it more comfortable are either polyethylene (PE) or polyvinyl chloride (PVC) foams which are both mainly used for upholstery in the automotive sector. The grab handle is made from ABS solely due to ABS being the most common and still most cost-competitive material used in car manufacturing (SAE Transactions, 2007).

Door handle

The door handle's purpose, shown in figure 5, is to open the door from inside the car. It should be reachable for all the passengers sitting next to the door without requiring the passenger to over-rotate their torso.

Figure 5: Door handle

The door handle is made from polyamide, commonly known as nylon, and reinforced with 40% of unspecified minerals (PA6-MD40). This material is often used in automotive applications. PA6-MD40 though is sensitive when exposed to moisture and humidity from saltwater and does tolerate UV-light fairly well (Granta EduPack Design Limited, 2021).

Handle fastening

The handle fastening (Figure 6) keeps the door handle in place and is another part that is inserted into the interior door panel.

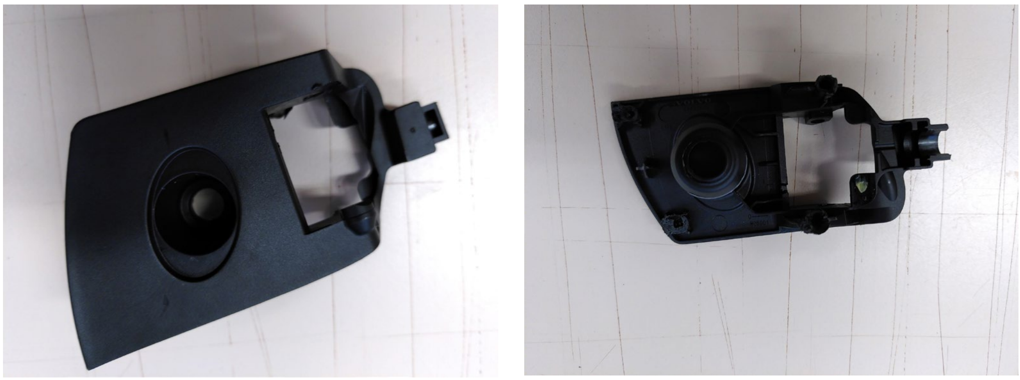

Figure 6: Door handle fastening

The fastening is made from another PA-blend called PA6-GF15, meaning that this plastic application is glassfibre reinforced by 15%. This makes the material more enduring to loads and stresses applied while being lightweight and having a lower density. It can be dyed to any colour, surface- and heat-treated, but also be processed in many different cost-effective ways like injection moulding or thermoforming. However, PA6-GF15 is not recyclable (Granta EduPack Design Limited, 2021).

Door shell

The door shell, shown in figure 7, is the biggest component of the entire interior door panel. Every other loose component is then either screwed or welded onto the door shell. Small plastic pins that stick out from the door shell are used to fasten the other components onto the door. These pins are then exposed to heat to weld the different components onto the shell.

Figure 7: Door shell of a Polestar 2 door insert

The door is made from medium density polyethylene filled with 15% minerals (PE-MD15). A common mineral for filling is the clay mineral talc which originates from hydrated magnesium silicate and is excavated all around the world (Minerals Education Coalition, 2022). PE or MDPE is a lightweight plastic option that can be injection moulded into complex shapes at a low cost.

Pocket

The pocket is placed on the lower part of the door panel and is used for storing smaller objects in a car. The pocket's material is the same as the door shell's namely PE-MD15. This is likely due to the same strains the door shell and the pocket must endure as well as the fact that the pocket is fastened by inserting small plastic pins sticking out from the door into the pocket's holes and afterwards exposing these pins to heat. An image of the door pocket is shown below in figure 8.

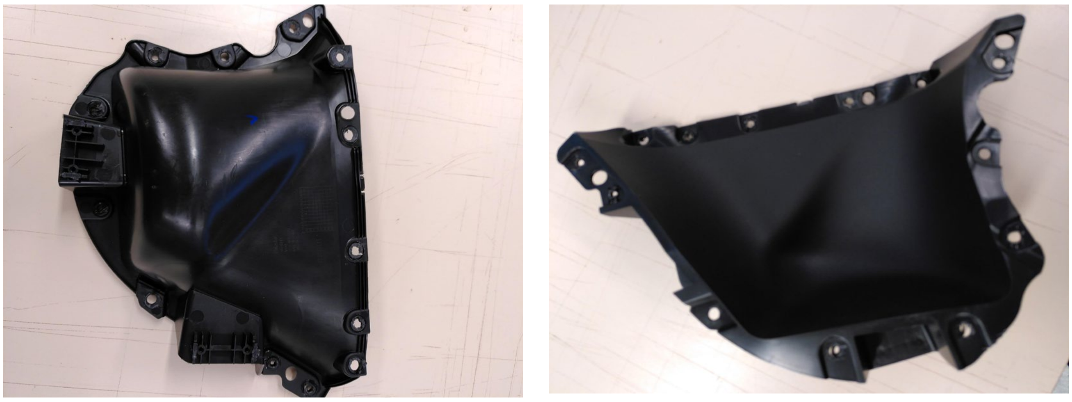

Figure 8: The door´s pocket with fixation holes

Metal parts

To fasten every single component there are 15 screws involved in the assembly process. The material of the screws was not specified or written on them, but commercial screws, washers and nuts are manufactured from martensitic stainless steel. Apart from these fixing elements the door includes a metal spring which enables the door handle to close and open (Figure 9).

Figure 9: Nuts, screws, and the door handle spring

Currently metals are the only parts which can be fully recycled with already existing techniques. This means that metal is a material which is 100% reusable and can therefore contribute to a fully circular material flow.

Other

Besides from the above-mentioned parts the door panel contained several other components (Figure 10).

Figure 10 (from left to right): Window buttons, the decor button, and the door fasteners

The two window buttons are made from PC/ABS, which has good resistance to cut and crack growth as well as good fatigue resistance. A drawback with the use of PC/ABS blends is that its durability when exposed to UV light decreases significantly if solely PC or ABS are being used. The polymeric blend is also more flammable than its compound materials. The surface finish can be both smooth or textured which can be a factor when it comes to the perceived feel and experience of the interior for the customer (Granta EduPack Design Limited, 2021).

The decor button did not serve any particular purpose other than elevating the interior design of the door panel. It is made from PA6-MD40 which is excellent for injection moulding processes for complex shapes. As aforementioned the material has issues with exposure to saltwater and UV-rays but has a low-flammability rate.

The objective of the door fasteners is to keep the interior door panel in position on the exterior shell. These clips are manufactured from PA6-GF15, the same material as the handle fastening. The major downside of glass fibre filled polymers is that they are not recyclable and can only be combusted for energy with current techniques.

The whole system as such consists of 22 different components of which four are textile materials for upholstery. The function of a door panel will be further described in the section of this chapter.

4.2.2. Function, functional unit, and reference flow

The function of the door panel is to serve as an interface between the car's interior and the door's internal functions, and between passengers in the vehicle and the door (Pradeep S. A. et al, 2017).

The functional unit of this part of the thesis is a left back door panel of the Polestar 2. The result will be presented in CO_2-equivalents (CO_2-e) per functional unit.

As a reference flow a basic LCA in GRANTA Edupack, called EcoAudit, was used. GRANTA takes an estimation of the travelled distance between the primary processing production of the raw materials and the production of the parts into account, as well as the transport of the door panel from China to Sweden is included in the calculation. In chapter 4.3.4. *Life Cycle Impact Assessment (LCIA)* results are shown of the CO_2 footprint in kilograms for the Polestar 2 interior door panel, both in GRANTA and openLCA.

4.2.3. System boundaries

The system boundaries determine which unit processes will be included in the LCA and must be consistent with the goal of the study. The goal of this LCA is to be able to compare the outcome with the LCA outcome of the re-designed door panel. The LCA outcome will be a carbon footprint, this means that the greenhouse gas emissions are combined in a CO_2-equivalent. The LCA will study emission from cradle-to-grave and include the extracting and refining of raw materials, transports, manufacturing, and End-of-Life (Figure 11). The use phase will not be included in the LCA, however can be used as a comparative tool. The impact in this phase will differ much depending on how the car is charged, for example with wind electricity mix in Sweden or with global electricity mix, and this would have an impact on the outcome of the LCA without saying much about the materials selected. If the use phase is used to compare different materials during an LCA, the electricity mix of Europe will be used. The impacts associated with the manufacturing of the vehicles used in transport, the building of the factory and the manufacturing of the production machinery are also outside the system boundary.

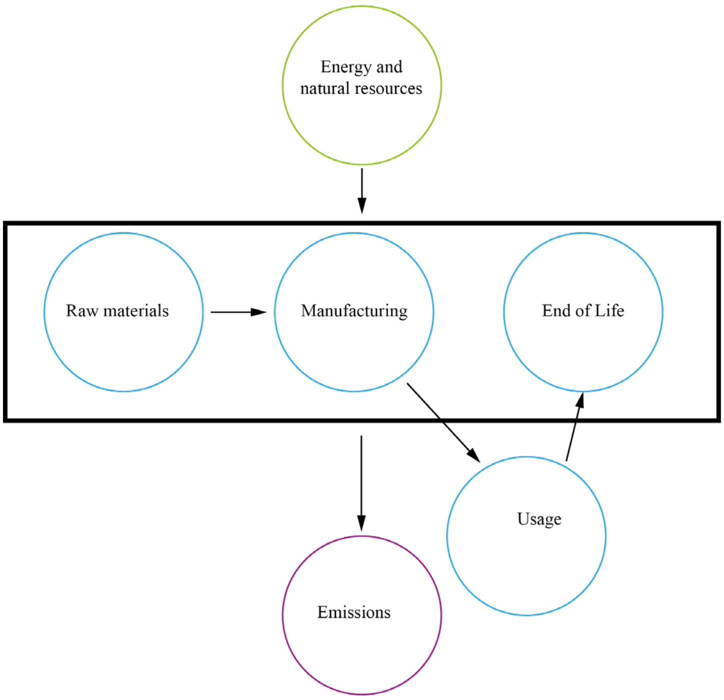

Figure 11. System boundary for the current Polestar 2 door panel

4.2.4. Cut-off criteria

The problem of conducting an LCA of a product system is modelling 100% of this system. Cut-off rules enable the omission of, for example, non-relevant cycle stages or processes and products from the system model, with the condition that the omitted processes and materials do not exceed 5% of the total energy use and mass (Cays, 2021). In other words, the cut-off criteria are the quantitative definition of the system boundaries.

4.3. The door panel's life cycle assessment

To calculate the environmental impact, the PS2 door panel has several methodological steps that need to be executed as stated in chapter 4.1.

The goal and scope of the LCA is:

> *To evaluate and quantify the environmental impact of the existing materials on the Polestar 2 door panel and will be used to compare with the LCA of the re-designed door panel.*

After having defined the scope and the system boundaries the inventory and collection phase begins. To create an inventory, the *Bill of Materials* (BOM), the PS2 door panel was disassembled. All the components of the door panel were logged in a table and classed by name, material, and weight. In the final column an image was attached to be able to easily identify each component (Appendix 1). The BOM provides the information used as an input in openLCA. In openLCA the European reference Life Cycle Database (ELCD) database is used to calculate the emissions caused to produce the raw material, transport and manufacturing of parts and the door panel.

4.3.1. Assumptions

In Polestar's own LCA from 2021 the total carbon dioxide equivalent emitted for one car during its entire life phase is about 25 tonnes CO_2-equivalents (t-CO_2-e). These 25 t-CO_2-e for a standard range motored Polestar 2 are compiled from 16 t-CO_2-e from materials production, 5,7 t-CO_2-e from the lithium-ion battery modules, 2,1 t-CO_2-e for the actual manufacturing phase of the car, and 0,5 t-CO_2-e for the car's End-of-Life phase. According to Polestar the interior automotive parts with all materials used account for about 10% of the total CO_2-e emitted. This means that the entire interior exudes 2500 kg CO_2-e. Those 2500 kg are used as a reference number to verify whether the LCA result of how much CO_2-e, one door panel emits is realistic or not.

Polestar currently produces the majority of their automotive parts in China and their cars are assembled in China as well. In case the place of production or manufacturing was unknown, an assumption was made. For the first transport route, the transportation of the polymer granules, 500 km with a 22 ton lorry was assumed. This was probably a very conservative assumption; 500 km is a short distance in China. When the place of the manufacturing plant was unknown, which was the case for parts produced by a company called AELXQ, 800 km with a 22 ton lorry was assumed.

Assumptions about door panel components, that were not marked with a manufacturer or a part number or had no material information imprints, were made as well. This was the case for the upper and lower part of the armrest as well as the grab handle assuming that these components were made from PC/ABS and ABS respectively.

For all metal compounds used for screws, washers and the spring in the door handle mechanism can be made from various types of steel. Steel used in the production of one car are sintered, galvanised steel, cold-rolled coil martensitic stainless steel, ferritic cold rolled coil stainless steel as well as unalloyed steel (Røyne & Bolin, 2021). Therefore, another assumption about these metal parts was made. For the execution of the following LCA all metals used were assumed to be cold-rolled coil martensitic stainless steel.

4.3.2. Limitations

Limitations of LCA methodology

LCA is a study of the real world in a simplified model and depends on assumptions and scenarios. Another limitation is the large amount of data needed to conduct an LCA and this, together with lack of available data, can lead to uncertain conclusions.

An LCA results in information on several environmental impacts. When comparing two products it can be difficult to choose which impact, for example greenhouse gas emissions or biodiversity is most important in this product's case.

Limitations of the study

The CO_2 emissions from energy needed to manufacture the parts and produce the materials are taken from the LCA database, European reference Life Cycle Database (European Commission, 2015). No data was collected about actual emissions from manufacturing plants. Another limitation of the study is the choice not to include leather, upholstery, and fabrics, because the materials of the fabrics and upholstery were unknown. Transports between manufacturing and production sites in China were estimated in those cases the location of a manufacturer was not found.

4.3.3. Life Cycle Inventory results

Using the common methodological approach for performing an LCA as described above the outcome was an inventory list consisting of every single different component of which some are used to clothe the bare interior plastic parts to elevate both life expectancy of the component as well as the aesthetics of the door panel. The objective of creating this inventory is to gain knowledge about which materials are used in common automotive part production. In figure 12 all the materials used, their processes, as well as their End-of-Life treatment is shown.

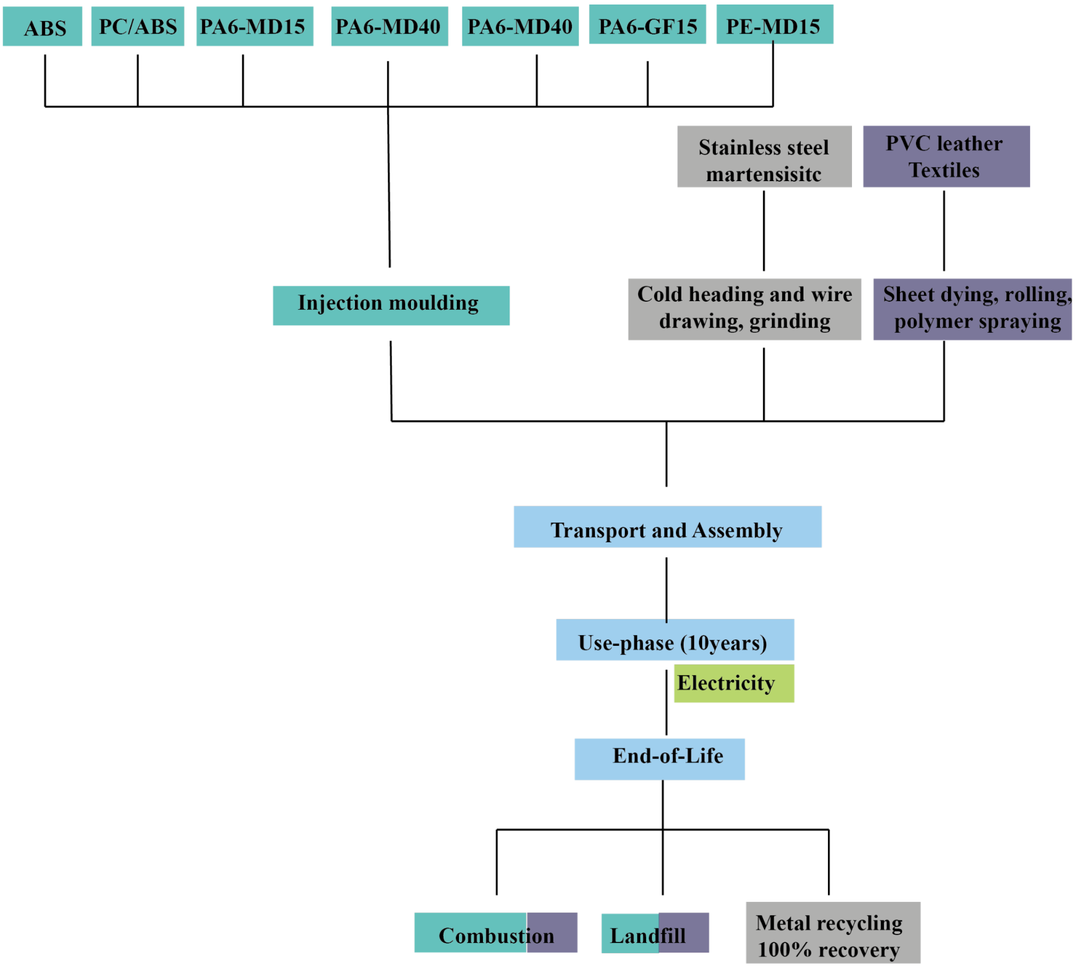

Figure 12: Materials used in the door panel and their production processes

As aforementioned the door panel consists of several parts which combined create the whole interior door panel. Every single part was logged, received a name, synonym, or its product name, and was weighed. Besides these criteria the material of each part was written down and a picture for easier identification was attached as well (Table 1). The whole door panel weighed 2,8 kg and has in total 22 different components of which four are cloth-like textiles and upholstery.

Table 1: Part name, material, and weight of each part

Part name	Material of the part	Weight in kg
Armrest lower part	PC/ABS	0,1122
Armrest upper part	PC/ABS	0,194
Pocket	P/E-MD15	0,1595
Upper speaker grill	ABS	0,1278
Door shell	P/E-MD15	1,266
Waistrail	PC/ABS	0,2988
Waistrail (under)	PC/ABS	0,1251
Grab handle	ABS	0,1118
Handle (left)	PA 6-MD40	0,0736
Handle fastening	PA 6-GF15	0,0262
9 door fasteners	PA6-GF15	0,0372 (4 grams/ fastener)
Decor button	PA 6-MD40	0,0011
Window buttons	PC/ABS	0,0055
Vegan leather WeaveTech	PVC	0,0724
Woven textile	PE	0,0154
Waistrailcoating		0,0577
Leather Coating	Leather	0,0350
Foam for comfort	PE	0,0031
4 metal washers	Stainless steel martensitic	0,0079
15 screws	Stainless steel martensitic	0,0479
Self-locking screw	Stainless steel martensitic	0,0084
Handle spring	Stainless steel martensitic	0,0071

As aforementioned, the data used to calculate the LCA outcome stems from the European reference Life Cycle Database. The database provides compiled datasets from different life cycle databases which are tools that are included in proprietary software such as GaBi which was the software Polestar used for their LCA. Therefore, the reliability of the datasets applied for calculating the outcome of the existing door panel was evaluated to be highly credible. However, the European reference Life Cycle Database contains a significant amount of *dummy data*, which is collocated data, meaning that the datasets are still valid and applicable to the object examined but an approximation of all its inputs for the specific dataset is provided. These collocations are applied to make up for missing data and treat uncertainty when calculating the emissions during the Life Cycle Assessment. Examples for uncertainties are the approximation of the distance goods and materials are being transported from a known provider to an unknown provider or manufacturer, usage of different crafts to distribute the final product to the end users as well as the final products EoL-treatment.

The procedure of the door panel's LCA contains several *flows* and *processes* which together create a *product system.* The product system in this study is the current door panel (OpenLCA, 2022).

Flows

A flow is a material, product or energy input and output within the product system. Each flow has a unique name and a flow type describing what kind of attribute the flow has. These attributes can be weight, number of items or volume. A flow could either be an elementary flow, a product flow, or a waste flow. An elementary flow could be i.e., material or energy to and from the product system into the environment. A product flow looks over material and energy that is exerted between the processes in the product system and the final product. Lastly, a waste flow is a material or energy that leaves the product system meaning the product has reached its final life expectancy. During the LCA of the PS2 door panel 49 flows were created. Some of them are shown in figure 13.

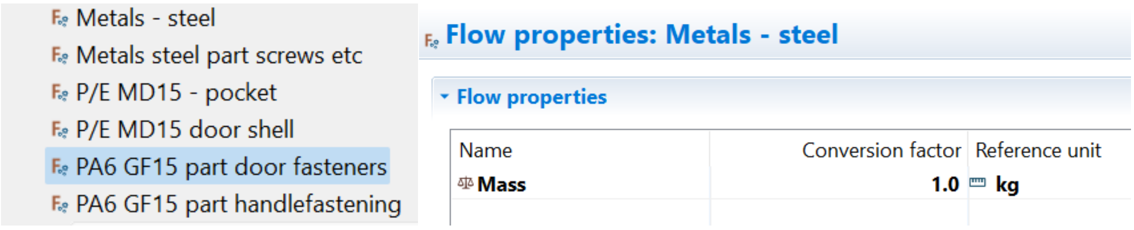

Figure 13: Examples of flows for the LCA

Processes

A process is an activity that transforms data inputs into data outputs. Each process has an output flow as a quantitative reference and shows the result of a process. Processes can be either unit-bound or system-bound. Unit processes are the smallest unit throughout the whole LCA for which input and output data are quantified, while system processes combine the inputs and outputs. An example of a process is shown below in figure 14.

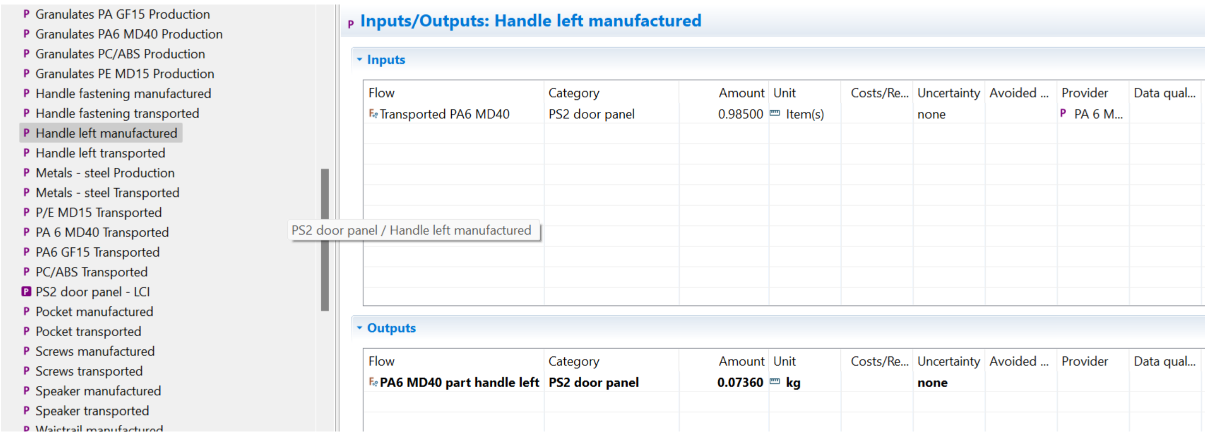

Figure 14: Process of manufacturing the door handle

Product system

The product system is the system in which the entire LCA is performed. Product systems include at least one or multiple processes and is defined by a reference process which in this case is the emissions created from the production of the door panel and its EoL potential. The product system manages the input and output flows from which the environmental impact is calculated. The calculations then give an insight on how many impacts are tied to a specific process or flow in all connected upstream processes.

The PS2 door panel

To be able to calculate the door panel's impacts the flows and processes created are included into the calculations of the LCA. To give an example of how the impact of a part is being calculated, the process for the part "pocket" is described below.

- First a flow for the material ABS is created then an attribute is assigned to the flow. In this case mass in kilograms.
- The ABS is then used to produce granules for injection moulding operations at another manufacturer or industry site. So therefore, the flow ABS granules must be created.
- Then the process *Granulates ABS Production* is created. The processes are the steps where the conversion from raw materials or partly finished goods to a better processable material or a final good happens. In figure 15 the process for the production of ABS granules from the raw polymer material is shown.

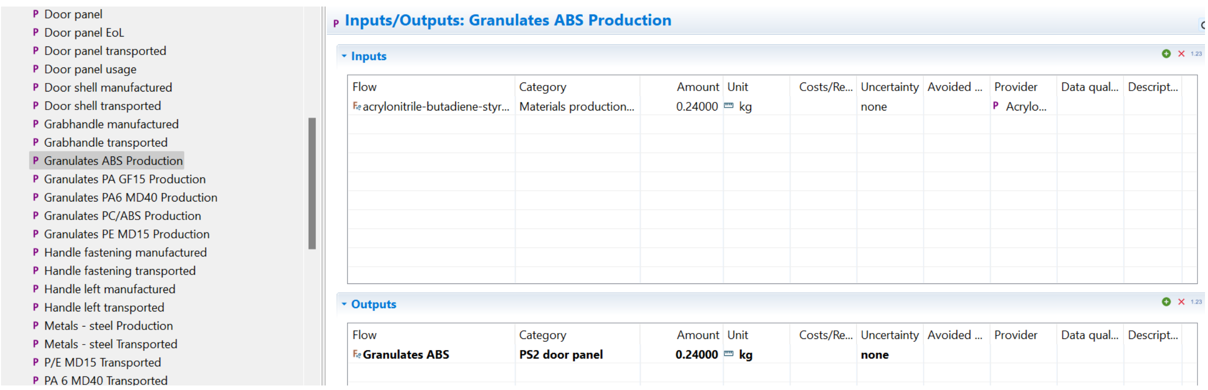

Figure 15: Production process input for ABS granules

- The ABS granules are then being transported to another manufacturer to produce parts from them. The *pocket* is the result of the transported ABS granules.
- After the *pocket* has been made, it is then transported further to be placed into the right position on the *door shell*. Once all door trims are mounted, the entire door panel is shipped to Sweden and enters the use phase, which is mostly omitted in this study.
- The expected lifespan of a car and therefore its door panel is 15 years. At the end the transported door panel is disposed of regarding the current End-of-Life treatments available.

This process is then repeated for every single flow of materials and transport. The result of this procedure is a product system shown in figure 16. It includes the raw materials, part production as well as the door panel being freighted to Gothenburg, Sweden. Further distribution to the customer was not taken into account.

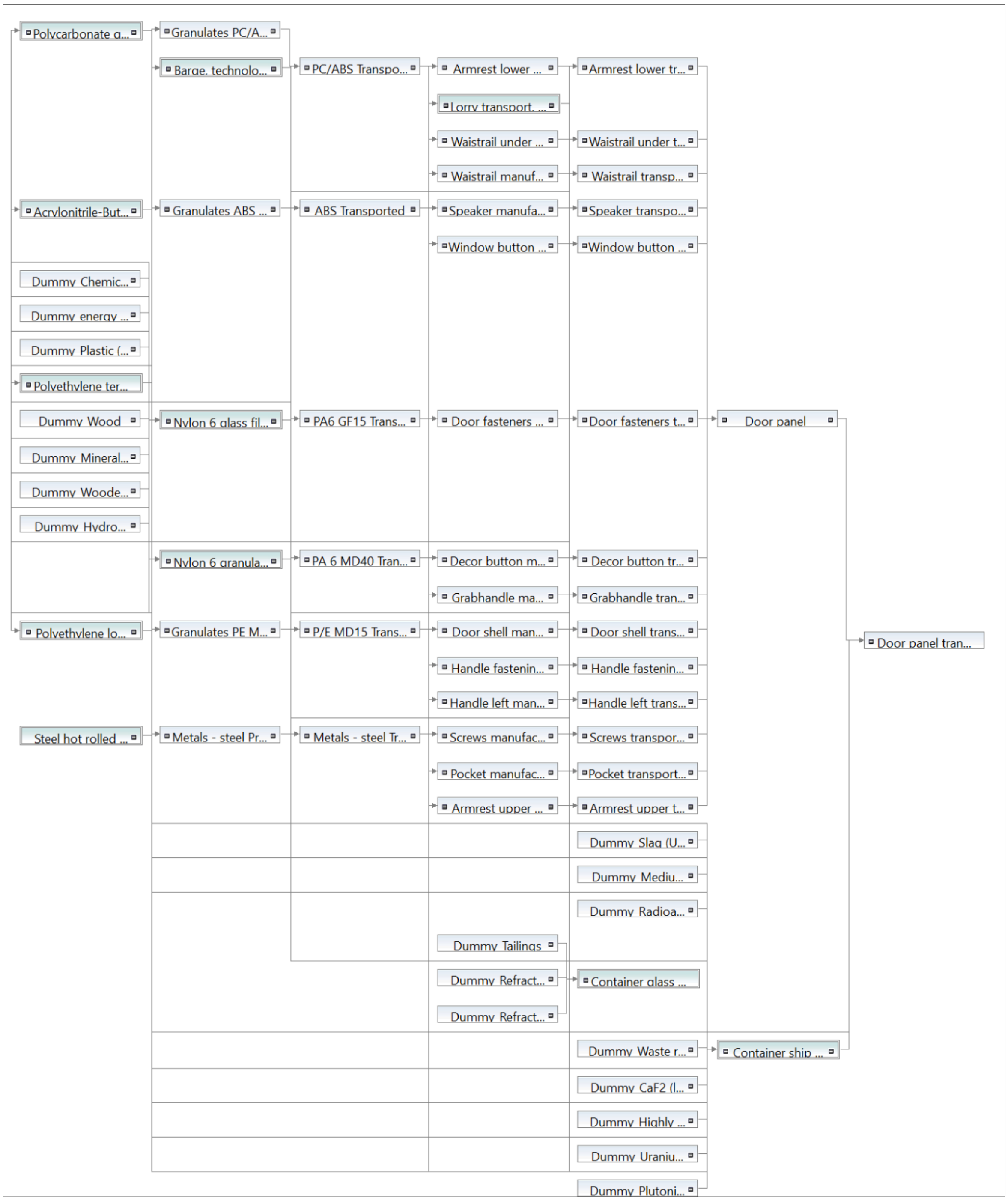

Figure 16: Process tree of the existing PS2 door panel from manufacturing to shipping to Sweden

4.3.4. Life Cycle Impact Assessment (LCIA) results

As a reference flow an LCA of the door panel in Granta Edupack was used. The total CO_2 footprint in GRANTA is 19,9 kg (Figure 17). The total footprint in openLCA of the door panel is 22,05 kg (Figure 18). The difference in outcome between the two LCA calculations is the fact that in GRANTA, in contrast to openLCA, no account is taken to transports between material production and manufacturing of the parts, nor the transports between the factory where the parts are produced and where the door panel is assembled are calculated. The transport calculated in GRANTA is the transport by ocean freighter between China and Sweden. In OpenLCA it is indicated that the transports by lorry are a big part (10,1 kg) of the total environmental impact of the door panel (Figure 19).

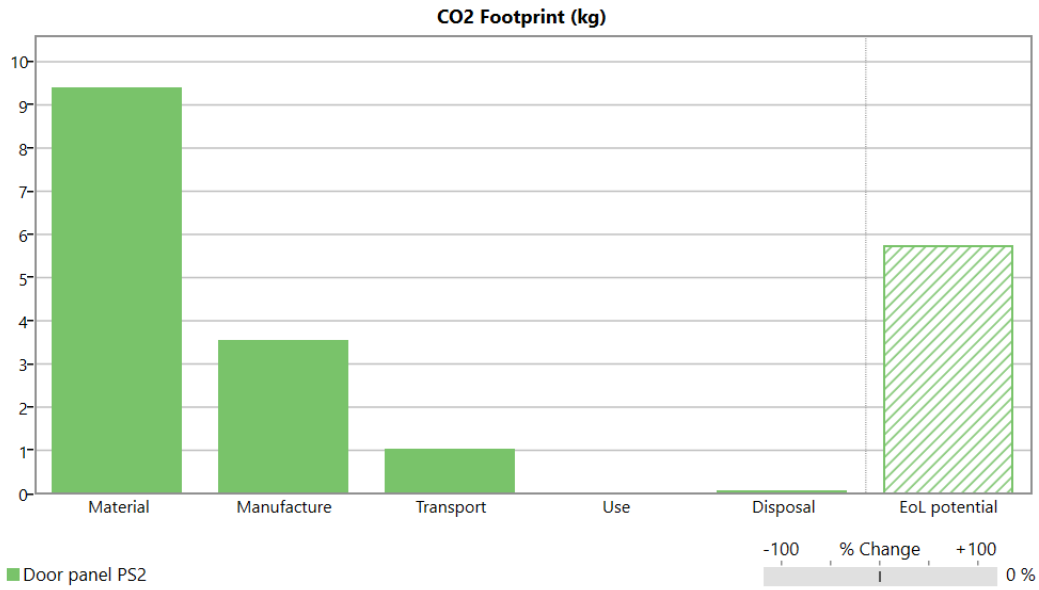

Figure 17: Polestar 2 door panel CO_2 analysis with GRANTA Edupack, 19,9 kg in CO_2-equivalent

In GRANTA the outcome in CO_2 footprint is subdivided in different impact categories such as transportation, material (including material production), use phase (outside the boundaries in this thesis), End-of-Life potential and manufacture (Figure 18). This enables an insight in where the impact is highest or where changes in the production process can make a positive difference.

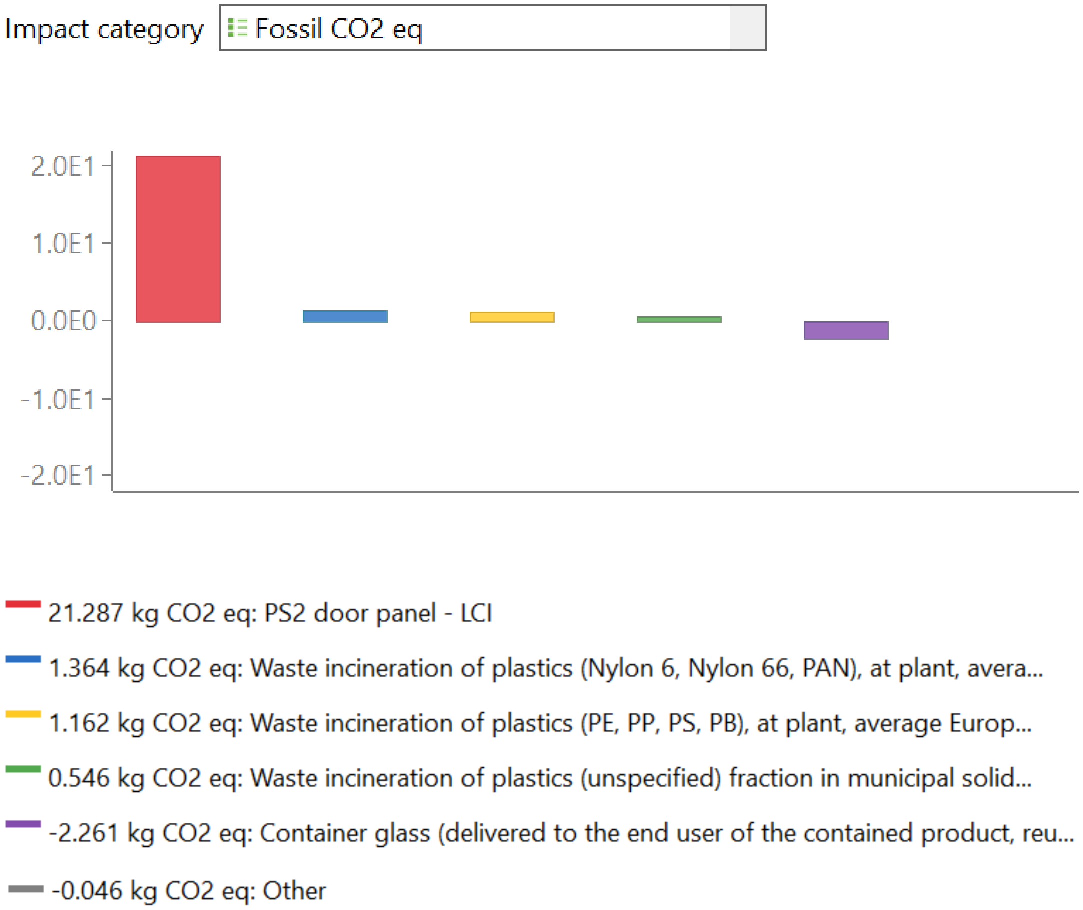

Figure 18: CO_2-equivalent for Polestar 2 door panel in openLCA, 22,05 kg in CO_2-equivalent

In openLCA the impact can be divided over the whole door together with End-of-Life impact or over the categories with the largest deviation. Figure 19 shows that transport by lorry and the production of Polycarbonate granules have a big impact on the total footprint.

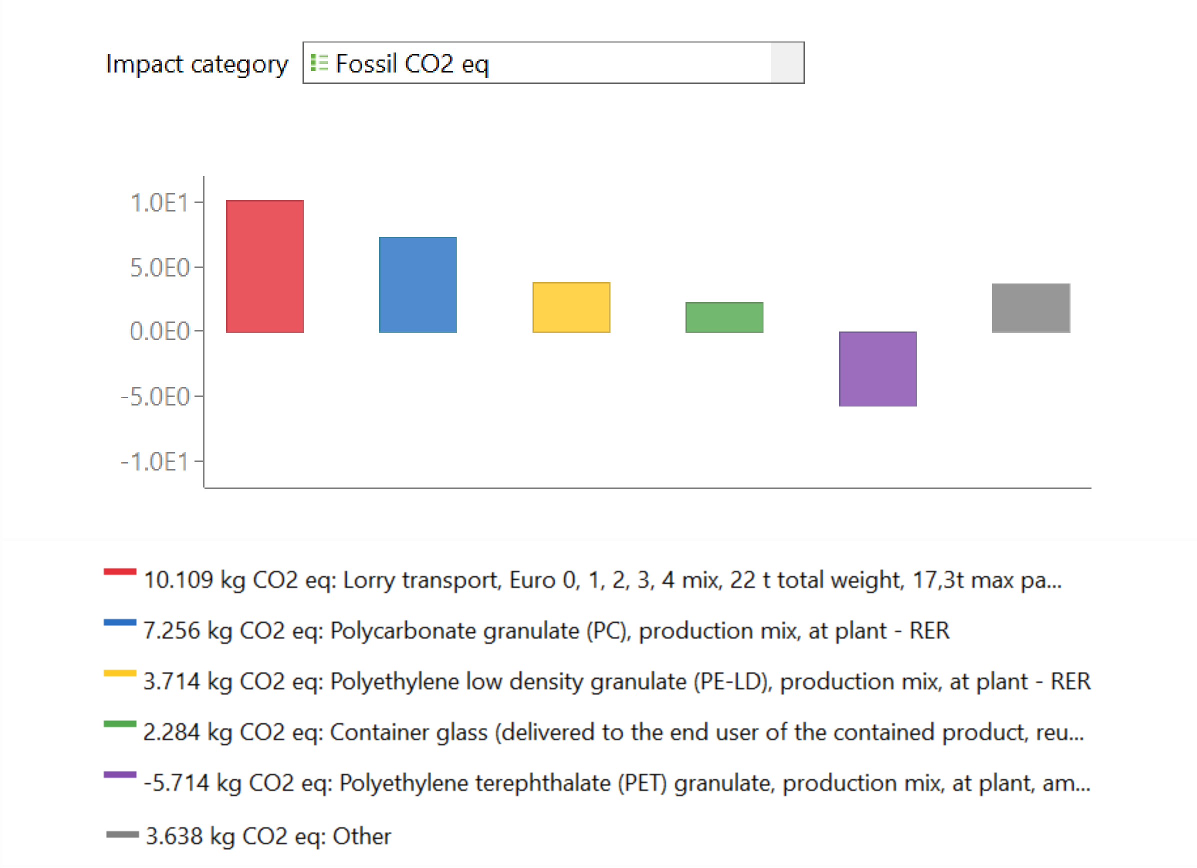

Figure 19: CO_2 footprint in openLCA distributed over different impact contributors

The impact of transport in openLCA, as shown in figure 19, is something that is not that easy to influence by choosing new materials for the door panel, as is what this thesis is meant to do. Where the material will be bought and produced will have a big impact on the outcome of the CO_2 emissions, and therefore there will be even a bigger uncertainty in the LCA calculation for the new door panel as it was for the existing one.

5. RE-DESIGNING THE DOOR PANEL

To start the process of redesigning the door panel information was gathered. Research for new materials as well as technical material requirements, how cars are recycled, and a criteria list was made.

5.1 Research new materials

Searching for new materials was the main driver in this project. It required deeper knowledge about new and unconventional materials, their processing as well as an understanding of the materials being used in the current door panel. The current panel is mainly made of Medium Density Polyethylene filled with 15% talc (P/E-MD15) and Polycarbonate/acrylonitrile butadiene styrene (PC/ABS). The primary processing method is injection moulding which is a process where a special machine liquifies the polymer granules, then injects the liquid polymer into a specific mould under a set pressure. This process enables a manufacturer to succeed in creating very complex shapes with as little flash as possible. Flash occurs when the moulding pressure exceeds the machine's ability to regulate pressure which results in a melt flow across the mould parting line (Osswald & Menges, 2012).

Fossil-based yet biodegradable plastics were excluded as an option for the new door panel solely because they are not bio-based (Figure 20). This was because it is cheaper for manufacturers to produce new plastic instead of investing in a new recycling system. The advantage of bio-based and non-biodegradable plastic is that it is not fossil-based and therefore does not deplete the already low fossil oil levels many manufacturers will encounter in the next couple of years. Since Polestar is working towards its *zero-emissions by 2030* goal, non-biodegradable plastic will not be a driver for an emission-free approach throughout the entire value chain.

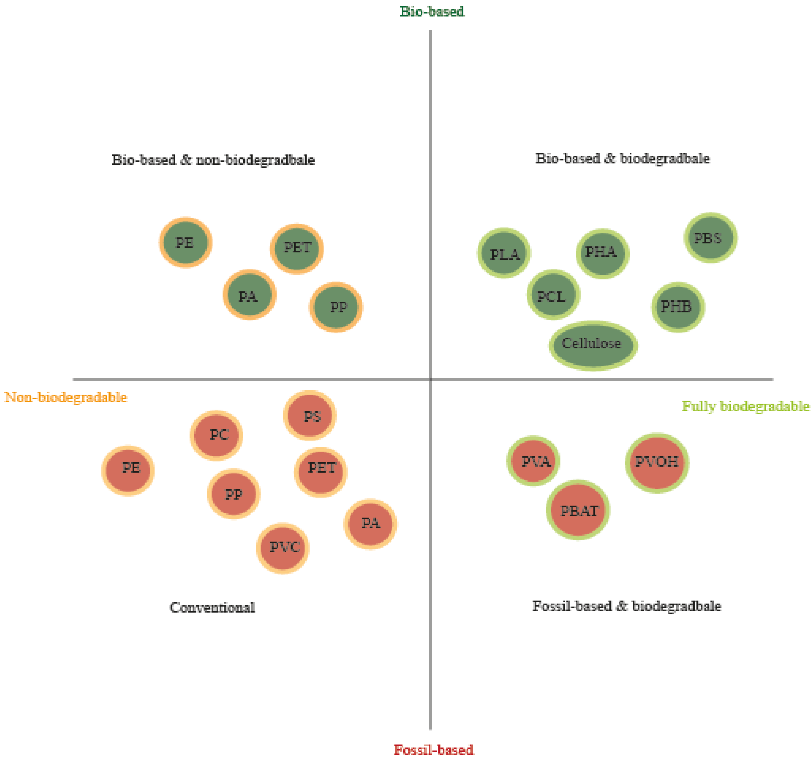

Figure 20: Overview on fossil- and bio-based plastics

After some research the decision was made to search for new materials in three different directions. One direction is looking for materials that have well-established recycling methods today, like metals. Another one would be the use of a natural fibres composite to reduce the number of fossil-based materials or to find a bio-based, biodegradable polymer.

Materials with well-established recycling methods

Aluminium is an example of a metal that can be recycled and reused an infinite number of times and has the advantage that the amount of energy used to melt aluminium after the first time is reduced by 93%. The energy requirement to produce one metric ton (mt)of primary aluminium is 186,262 MJ/mt, compared to the 11,690 MJ/mt to produce secondary (recycled) aluminium, and that is only one of the advantages of recycling aluminium (Schlesinger, 2014).

The US-based company Technowood produces aluminium panels coated with non-flammable natural wood coating. These wooden veneers are weather-resistant and durable. The aluminium in combination with 100% natural wood veneers offers the appearance of solid wood, while reducing the actual consumption of wood by approximately 98%. The material is resistant to deformation after having been bent into its desired shape, has a high endurance as well as it outlives normal solid wood. The aluminium can be coated with any type of wood such as oak, teak, ash, beech or even mahogany. The material is fireproof making it usable for both interior and exterior spaces. The wooden veneer can be further coated with a polymer varnishing making it mechanically strong, UV resistant, heavy metal free and made weatherproof as well as free from volatile organic compounds (VOC) emissions, see chapter 5.2 *Technical material* *requirements* for more information about the requirements a material must meet. The panels are easy to clean and are used for applications like facades, screens but even urban furniture.

Wood is produced through natural biological processes in growing trees and contains about 50% carbon and the energy needed to manufacture and process wood is relatively low. The post-use options of wood are to reuse without reprocessing of the product, recycle with reprocessing into another product and energy recovery, avoiding fossil emission (Worrell & Reuter, 2014).

Natural Fibres Composites

Natural Fibres Composites are used in the automotive industry to manufacture inner door panels. Polymers reinforced with Natural fibres have excellent stiffness to weight ratio, are more sustainable compared with carbon or glass fibres due to the biodegradable fibres and low-cost (Fuentes Molina et al, 2021). The downside of Natural Fibres Composites is that the material is more flammable because of the natural fibres used, more with cellulose and less with wool, and flame retardant PP is used to counteract (Bajpai & Singh, 2019). The material can be recycled approximately 4-6 times before the thermomechanical properties change, and after being recycled 7 times, the tensile strength is decreased by 17% and the tensile modulus by 28% (Zhao et al. 2022). Recycling methods used are mechanical, chemical, and thermal recycling. With mechanical recycling, crushing and grinding the polymer waste to reduce the size, the outcome is raw material that can be used to produce the same applications. Limitations are that the material must be reinforced after mechanical recycling. Chemical recycling provides raw material for alternative fuels and thermal recycling energy and material for cement production (Fuentes Molina, 2021). Door panel parts made of Natural Fibres Composites are pressed out of non-woven mats (Figure 21). The advantage of the material is the possibility of creating complex shapes, but the downside is the amount of spillage, approximately 20%, as it is not possible to use the whole mat when pressing (Peças, Carvalho, Salman & Leite, 2018).

Figure 21: NFPP composed door panel

Other problems of recycling plastics are the high recycling costs compared to the costs of producing virgin plastics and the difficulty to separate all the different kinds of plastics (Degnan & Shinde, 2019).

NFPP is used in the interior manufacturing of the latest Polestar 2 model and is a plastic material reinforced with a natural fibre matrix reducing the use of plastic by 70%. Using NFPP gives the door panel structure and strength while maintaining a low weight which is beneficial during a vehicle's entire use phase.

Biodegradable and biobased materials

For inspiration in the search for new materials a visit to Material Connexion in Skövde was made. Material Connexion is a material database and material library, where one is able to see and touch different kinds of possibly implementable materials.

One of the materials found is Cork Recycled Leather. This material contains 35% cork bark and 65% recycled leather. To harvest cork the cork tree is not cut down, but only the bark is stripped. The use of recycled leather reduces the environmental impact further (Material Connexion).

To replace fossil-based polymers for example Polyhydroxybutyrate (PHB) was found. PHB is a bio-based and biodegradable plastic and to produce PHB the cyanobacteria *Nodularia spumigena* can be used. *Nodularia spumigena* is the phytoplankton that causes algal blooms in the Baltic Sea (Wong, 2019). Another material made from algaes is Marine Cotton, a textile for which Melanie Glöckler (2017) used freshwater algaes (Peters & Drewes, 2019).

Dutch OVDesigns is a company producing polymers that can be injection moulded, based on coffee. The polymer is 100% biobased from natural resources (sugar cane) and 30% coffee. The German company Nat-2 is producing vegan leather based on coffee grounds for their shoes.

The Austrian company Dyntex produces a fabric that is entirely made of the castor oil plant. It is lightweight and extremely durable and because of the mono material composition the material is easy to recycle (Material Connexion).

Moulded Bamboo® is a patented material which does not contain plastic, chemicals, or any other toxic substances. The material is environmentally friendly and plant based which makes it 100% biodegradable. The bamboo plastic is made from rice starch, which is used as a natural binder, bamboo sawdust and fibres to reinforce the material. Any colour can be added into the mixture, creating pastel colours. When compression or injection-moulded the material obtains good mechanical strength, high dimension precision and a good surface finish (Li & Yang, 2015).

5.2 Technical material requirements

To be able to redesign a door panel, a list of requirements both technical and mechanical were used as a reference frame during the screening process of new materials. These requirements examine prerequisites for materials used in the interior of cars. To be able to meet a material's requirement it must be approved by several different testing methods as well as live up to numerous standards regarding both physical and mechanical properties. Examples of tests that can be executed are tests for flammability, abrasion and scratches, wear and impact, endurance, crack resistance, as well as flexing and strength tests.

Flammability is tested by the ISO 3975 standard/FMVSS302, which examines the polymeric interior materials in trucks, machinery, and passenger cars. This standard is not a necessity in some countries by law and therefore implemented differently throughout the automobile industry. The procedure for the testing is the same for all standards ISO, FMVSS etc. The material testing uses a specimen of 102mm by 356 mm which is mounted in a horizontal position and exposed to an open flame for 15 seconds. The specimen is not supposed to burn faster than by a rate of 100mm/minute. This standardised test does not consider any possible toxic fumes emitted from the burning materials (ISO, 1989).

The injection-moulded panel must meet numerous requirements for it to be approved in a vehicle. A car's interior is a complex environment which is why materials used must be tested thoroughly. A chemical screening is performed to ensure that the materials are non-toxic for humans and the environment (Recticel, 2017). For this the VIAQ standard (vehicle indoor air quality) is used. The main contributors to the VIAQ are so called volatile organic compounds, short VOC. These VOCs are particles made from carbon, derived from all the interior parts, and can vaporise into the air. Some examples for VOCs are benzene, formaldehyde, and styrene, which all have shown to evoke possible health implications (UL, 2022). Currently an international standard for how many $\mu g/m^3$ of VOCs are acceptable in a car's cabin does not exist. It is up to manufacturers to create their own standards and tolerances.

A, for Polestar specific, requirement sheet served as a guide for all material research and its guidelines must be met even after redesigning the door to ensure passenger safety when sitting next to the door. As doors can be part of collisions, they must withstand certain impacts in order to protect the passengers in the car from severe injuries.

The reconstructing and design process is influenced by Polestar 2's current interior design and the overall design language and aesthetics. The new door panel may therefore be matched to the existing interior of a Polestar 2.

5.3 Idea generation process

The idea generating process for designing a new door panel consists of several stages. The problem description, a requirements specification and multiple design generation phases result in several different design concepts. These concepts are evaluated and lead to the final design concept (El Mogahzy, 2009).

5.3.1. Design problem requirements

To find an optimal solution for the Polestar 2 door panel the problematic areas are described in a requirement specification. A door panel's main function is serving as an interface between the car's interior and the internal functions of the door, and between passengers in the vehicle and the door.

The main functional requirement is that the materials the door panel consist of have to be recyclable, reusable or biodegradable. This requirement is more easily met when the door panel consists of few parts and fewer different materials that can be separated from one another effortlessly. This also makes it possible to replace broken or damaged parts. Various desirable requirements are mentioned in the requirement specification, such as for example the placement of parts. In table 2 all necessary and desirable criteria are shown.

Table 2: Criteria specification for the new interior door panel; Criteria are weighed by Necessary=N and Desirable=D

NR.	Criteria	N	D
1.	**Material acquisition**		
1.1	Materials used should be recyclable, reusable or biodegradable	X	
1.2	Lightweight materials		X
1.3	Materials used should not emit hazardous gases	X	
1.4	Use of non-toxic chemicals during material production	X	
1.5	Ability to produce complex-shaped parts		X
1.6	Materials used most meet requirements described i requirements sheet: *Technical regulations Door Trims*	X	
2.	**Manufacturing**		
2.1	Injection moldable		X
2.2	Can be manufactured with already existing techniques		X
2.3	Production technique must be energy efficient		X
2.4	Production technique must be non-labor intensive	X	
2.5	Use of green energy supplies only during manufacturing		X
2.6	Ability to produce complex-shaped parts		X
2.7	Reduce the number of manufacturers throughout the production line		X
3.	**Design/Form**		
3.1	Fewer components in a door panel		X

3.2	Ability to disassemble components of the door panel	X	
3.3	Reduce complexity of the parts		X
3.4	Lightweight components	X	
3.5	Does not impact the users in any negative ways regarding safety	X	
3.6	Smart placement of interior components like door handle, window opening buttons etc.	X	
3.7	Aesthetically pleasing	X	
3.8	Components are appealing to a wide variety of customers		X
3.9	The new design shall be tying into the current Polestar 2's design and shape language	X	
3.10	Design for safety, placement of door opener to force passenger looking over shoulder before opening door.		X
3.11	The new door panel components meet necessary requirements in *"material acquisition"*	X	
4.	**End-Of-Life**		
4.1	Design for Assembly and Disassembly	X	
4.2	Design for Repair		X
4.3	Design for Remanufacture		X
4.4	Recyclability of all components	X	
4.5	Design for Longevity		X
4.6	Circular material and product flow throughout the whole life cycle		X

5.3.2. Gather relevant information- Sustainable Design Strategies

Gathering useful and credible information relevant to the design problem is important (El Mogahzy, 2009). In other parts of the thesis, information relevant for the design is already mentioned, for example technical material requirements in 5.1.1 and the description of some possible material groups to use in the design in chapter 5.1. Other information that might be useful in the design process is described in this chapter.

How cars are recycled

Stena Nordic has developed a new way to recycle cars, and other products like computers, mobile phones, and bicycles, at the Stena Nordic Recycling Center in Halmstad, Sweden. Before the cars arrive at the facility in Halmstad the batteries and oil are removed. The first step is to grind the whole car into parts large as a fist. This will only take a few seconds, thereafter the iron is removed with magnets. Afterwards all the other parts are separated from one another with the use of big sieves, fans, magnets, optical sensors, and water basins. A difficult part of separating all the car materials is the fact that a lot gets stuck in the textiles and the upholstery after the first grinding. Instead of ending up in a landfill as was the practice before, the upholstery will be ground into even smaller parts and the processes with fans, sieves, magnets etc. starts again (Stena recycling, n.d.). Stena Nordic now meets the European Union's requirement that 95% of a car must be recycled (European Commission, n.d.).

Design for Sustainability

To make a car more sustainable a holistic view is required. In figure 21 the different design approaches which have an impact on the sustainability of a product are shown (Mayyasa et al., 2012). When *Designing for Sustainability* the impact of a product's whole life cycle should be considered. This means, the material of choice has an impact on everything from where and how the raw materials are mined, the amount of energy needed to manufacture, all the way down to how a product is used by the consumers. With the choice of material for the new door panel an optimization of the major elements of Design for Sustainability is aimed, there Design for Environmental Impact and Design for Recyclability were most important.

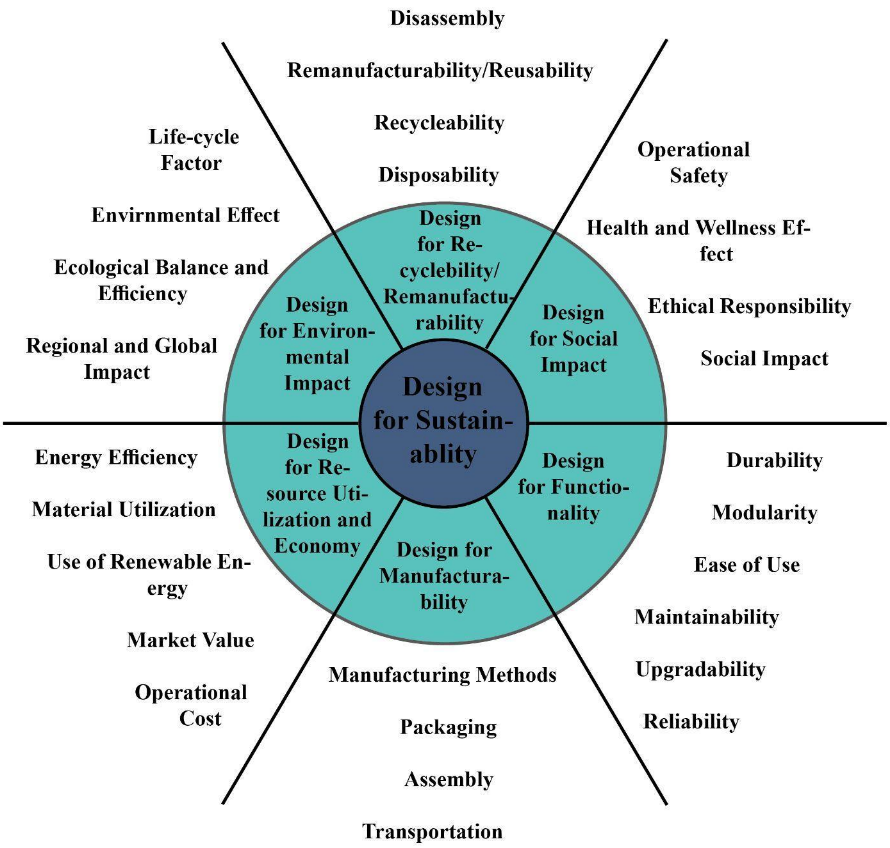

Figure 22: Design for Sustainability (Mayyasa et al., 2012)

Injection moulding
Injection moulding is the most used manufacturing process for the production of plastic parts. The process cycle for injection moulding consists of four stages and can have a duration of a few seconds to a few minutes depending on the shape complexity of the part. The process starts with a polymer blend as granules. The first cycle in the process is clamping, where the two halves of the mould are pressed together. The second cycle is the injection of the plastic granules, which are melted and set under a specific pressure on its way into the injection unit. Cooling is the third stage in the cycle, inside the mould the plastic must cool down until the part is solidified in the desired shape. After the required cooling time the part can be ejected from the mould and is pushed out by the ejection mechanism and thereafter the mould can be clamped shut for the next cycle. Some post processes after injection moulding are removing excess material, such as runners, these are channels through which the plastic passes on its way into the mould, and flashes (Basilicus Inc, n.d.). Another factor why injection moulding has gained significant importance in car manufacturing over the last decades is that there is no spillage of materials. This means that this manufacturing process does not create any waste trims or other unwanted by-products.

5.3.3. Design concept formulation - the new materials

After searching through databases and having performed a full LCA on the current door panel, the materials, which were thought to fulfil the requirements for materials used in cars from both a design and construction perspective, were listed. To get an idea about the performance of these materials in a Life Cycle Assessment, GRANTA Edupack was used to compare them, both with each other, and the existing PS2 door panel. A comparison which took the use phase into account was also included to see if this would change the LCA outcome. The use phase was set as *45 km a day, 300 days per year for 15 years in an electric family car in Europe*. In this comparison no consideration was taken to the transport of the different materials during the manufacturing stage. In the final LCA of the new door panel in openLCA transports will be taken into account as these were also included in the LCA calculation of the original door panel. To calculate the amount and weight of material used in GRANTA, a surface of 6400 cm^2 was used, the surface of the PS2 door panel flattened out, together with the specific material's density and intended thickness.

Aluminium
For interior body panels Al-Mg 5182 GM145 is used, which gives good formability and stress corrosion cracking performance (UACJ Corporation, 2022). Processes are rolling to get sheets, thereafter the sheets are pressed into the desired form. Al-Mg 5182 is a recyclable material and can be recycled multiple times without losing its strength properties (Figure 23). Since aluminium is manufactured in sheets, material spill of 20% is taken into account.

The total estimated weight of a door panel in aluminium was *($6400\ cm^2 * 0,08\ cm = 512\ cm^3$): $512\ cm^3 * 2,65\ gr/cm^3 = 1,357\ kg$.*

Figure 23: Aluminium sheets (Sapa, 2021).

Coffeeground-based plastic

A 100% bio-based polymer, the Cappuccino Polymer |124S, is made solely from natural resources (Figure 24). Already used coffee grounds are used in the manufacturing process of the coffee plastic. Other than 30% coffee, the material consists of PLA - a bio-based and biodegradable plastic - made from sugar cane. The coffee plastic can be processed in conventional injection moulding equipment (OVDesigns, 2022). For calculating the coffee plastic's impact in GRANTA, PLA from sugar cane with 30% natural fibre (coffee) was used. The door panel's weight was the same as the original's namely 2,8 kg. For End-of-Life treatment, downcycling was chosen.

Figure 24: A tray made from coffee polymer (OVDesigns, 2022)

PHB algae plastic

PHB is a short chain biopolymer PHA (is found in GRANTA) and can be used as a substitute for Polypropylene (PP) and Polyethylene (PE). To produce PHB (Polyhydroxybutyrate) cyanobacteria can be used. PHBs are not yet suited for the use in automotive parts, but will be in the foreseeable future, and can be interesting for reducing the amount of plastic waste as shown in figure 25 (Cambridge Consultants, 2018). For the calculation in GRANTA the same weight as the original PS2 door panel was used, 2,8 kg. End-of-Life treatment in GRANTA is landfill, it is possible to use PHB as food for animals or as a fertiliser, but these options are not possible to choose in GRANTA.

Figure 25: Compounded and granular PHB, © Fraunhofer IPK

Natural Fibre PP
Natural fibre reinforced polypropylene, NFPP, is a lightweight and strong material. As aforementioned NFPP comes in sheets and is made from PP granules from injection moulding and flax textile fabrication (Figure 26). The sheets are then being pressed and the excess material is cut off which creates 20% spillage which cannot be processed further. However, a door panel manufactured from NFPP does cut its original weight by half from 2,8 kg to 1,4 kg (BComp, 2022). The material uses 70% less plastic than the original material which results in 30% PP used for the whole NFPP door panel, which is approximately 0,84 kg.

This means: *1,4 kg (total weight) - 0,84 kg (PP) = 0,56 kg (flax fibre)*. According to the NFPP manufacturer a silicon layer is applied as well. Silicon has a density of 2,33 gram/cm³ which adds another 0,149 kg to the entire door panel. This results in: *6400 cm² (area entire door panel) * 0,01 cm (thickness of the silicon layer) = 0,149 kg.* For the End-of-life treatment combustion was chosen.

Figure 26: Example of a NFPP interior door panel
(https://koreanmachinery.files.wordpress.com/2021/09/30_1.jpg)

Cork

Cork granules can be pressed into form without adding extra adhesive, due to their natural resin being released during heating. 155 kg/m^3 is the density when cork is used in furniture and decorative items. Cork is fire retardant, but if cork does happen to catch fire, it does not produce flames, nor does it release toxic smoke when burning. The material is a sound isolator, durable and water resistant (Figure 27). It is processed by grinding the cork bark to get granules, thereafter the granules are heated and pressed into a form. Because of the use of granules there will be no spill material.

The weight of a door panel in cork is $(6400\ cm^2 * 1\ cm = 6400\ cm^3): 0{,}0064\ m^3 * 155\ kg/m^3 = 0{,}992\ kg$. The End-of-Life treatment is downcycling.

Figure 27: Cork, a natural material, by Clematc (2017)

Wood

Another interesting material was wood. For the calculation of wood, birch plywood was chosen. The advantages of plywood are the formability, lower density and strength of the material compared to normal wood, because of the cross-graining layers (Figure 28). A downside of plywood is the need of glue to put the layers together, a bio-based and non-toxic glue, like starch-based glues (Antov, Savov & Neykov, 2020) must be used. For the comparison in GRANTA a material thickness of 0,4 cm (4 layers) was chosen, which results in a weight for the door panel of 1,855 kg. End-of-Life treatment for birch plywood is downcycle.

Figure 28: Plywood - the different wooden sheets and the glueing is visible

In figure 29 the outcome of the CO_2 footprint in CO_2-equivalent/kg is shown. The original Polestar 2 door panel is used as reference. In this chart the production of the materials, manufacturing, disposal, and End-of-Life potential is taken into account. These are the factors that can be influenced with the choice of material and are within the boundaries set for this thesis. In GRANTA, disposal includes the impact of the collection of the material before the End-of-Life stage and the separation and sorting of the collected material. In the End-of-Life calculations GRANTA associates the future environmental savings with the End-of-Life route selected for the specific material chosen.

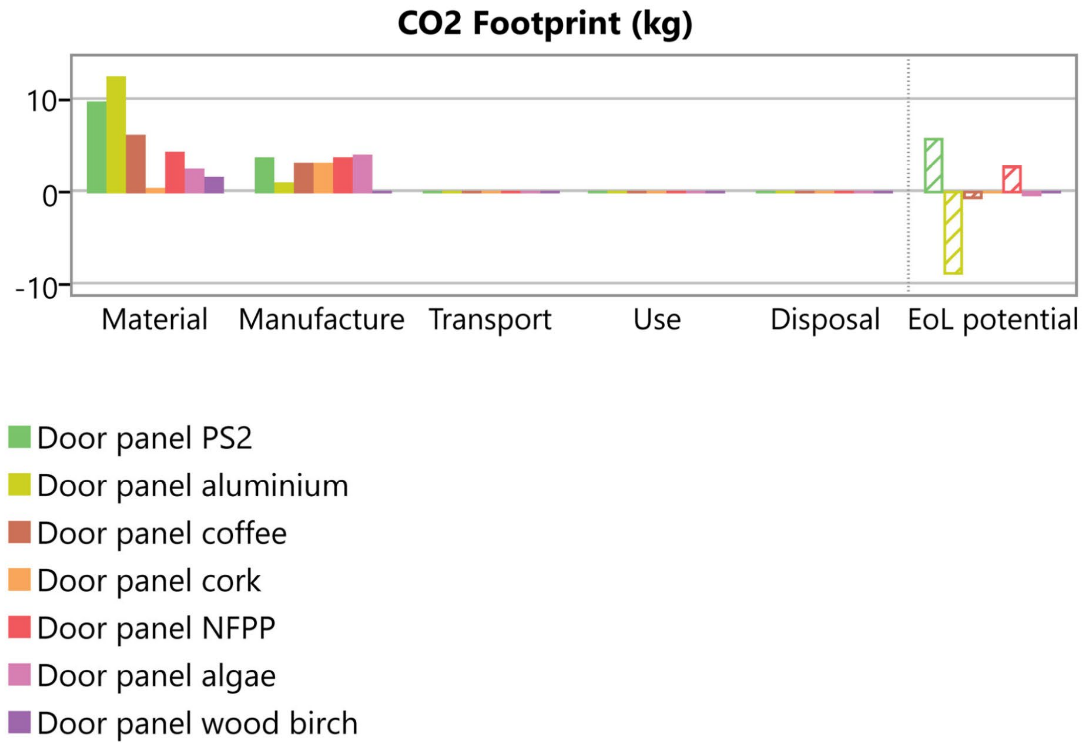

Figure 29: CO_2 footprint of door panel made from different materials

In table 3 the change is expressed as a percentage compared to the original door panel. All the chosen materials offer an improved CO_2 footprint, from NFPP with a reduction of carbon dioxide emissions of 45%, up to a door panel of plywood that shows a reduction of 92%.

Table 3: CO_2 footprint of door panel in different materials and change compared to the PS2 door panel

CO_2 Footprint (kg)	Material	Manufacture	Disposal	EoL	Total	**Change**
Door panel PS2	9,62 kg	3,63 kg	0,0887 kg	5,77 kg	19,1 kg	**0 %**
Door panel aluminium	12,3 kg	1,02 kg	0,0665 kg	-8,59 kg	4,796 kg	**-74 %**
Door panel coffee	5,97 kg	3,15 kg	0,098 kg	-0,71 kg	8,42 kg	**-55 %**
Door panel cork	0,2 kg	3,01 kg	0,0347 kg	-0,00694 kg	3,23 kg	**-83 %**
Door panel NFPP	4,17 kg	3,53 kg	0,0535 kg	2,74 kg	10,49 kg	**-45 %**
Door panel algae	2,53 kg	3,81 kg	0,098	-0,332 kg	6,098 kg	**-68 %**
Door panel wood	1,4 kg	0,0449 kg	0,0649 kg	-0,013 kg	1,497 kg	**-92 %**

The bar chart below (Figure 30) shows the CO_2 footprint when the use phase for the door panel is included. The use phase is a lifespan of 15 years as a part in an electric family car, driving 300 days a year and 45 km a day. The electricity used to charge the car is European Mix. The difference in CO_2 emitted for the different materials used in the door panel in this phase stems from the weight differences between the door panels. In this case the algae and the coffee door emitted as much or more CO_2 than the original PS2 interior panel during the use phase, while cork, aluminium and NFPP still show a lower carbon footprint in this phase.

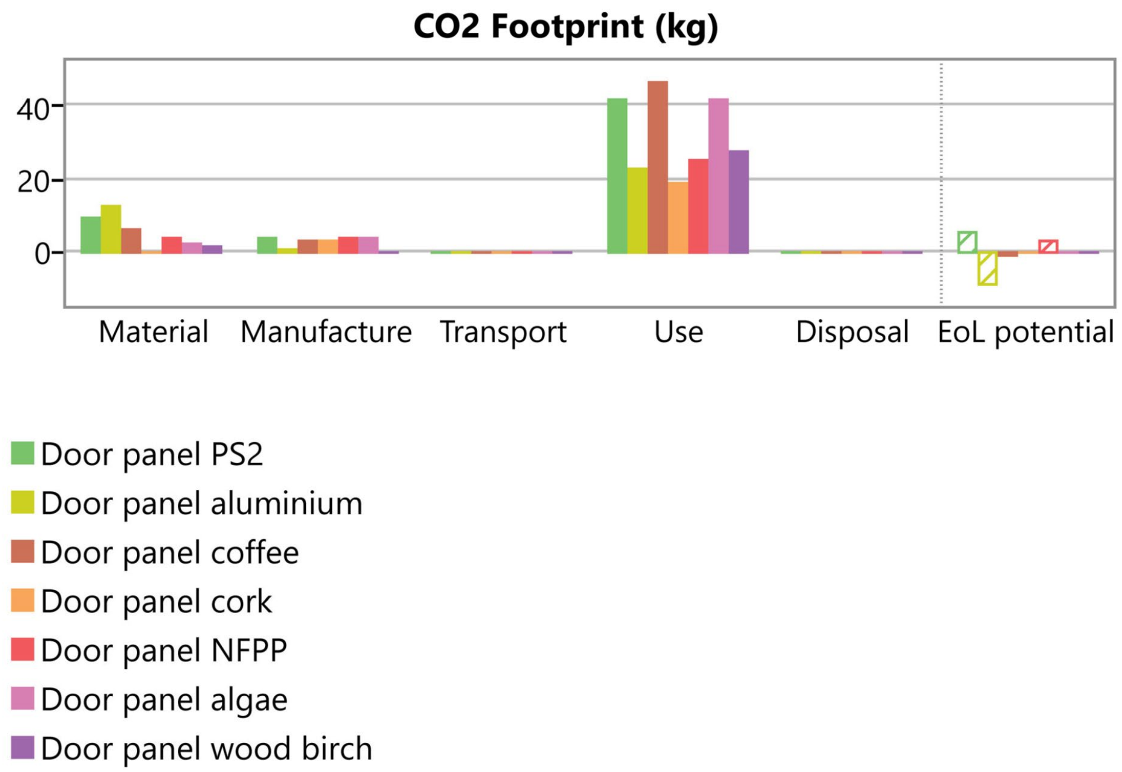

Figure 30: CO_2 footprint of door panel in different materials, with use-phase (45 km a day, 300 days per year for 15 years in an electric family car in Europe)

The table below shows the emission of all the materials in kilogram CO_2. The CO_2 emission for the production of the materials, selected manufacturing methods, use phase and End-of-Life phase were added together and this total of CO_2 emissions were compared to the total emission of the PS2 in the change column and expressed as a percentage of change (Table 4). The negative value of the bar indicates a higher End-of-Life potential which means that there is a positive impact on the environment when using the correct waste treatment.

Table 4: CO_2 footprint of door panel in different materials, with use-phase and change compared to PS2 door panel
(45 km a day, 300 days per year for 15 years in an electric family car in Europe)

CO_2 Footprint (kg)	Material	Manufacture	Use	Disposal	EoL	Total	**Change**
Door panel PS2	9,62 kg	3,63 kg	37,7 kg	0,0887 kg	5,77 kg	56,8 kg	**0 %**
Door panel aluminium	12,3 kg	1,02 kg	20,2 kg	0,0665 kg	-8,59 kg	24,99 kg	**-56 %**
Door panel coffee	5,97 kg	3,15 kg	41,7 kg	0,098 kg	-0,71 kg	50,12 kg	**-12 %**
Door panel cork	0,2 kg	3,01 kg	17,2 kg	0,0347 kg	-0,00694	20,43 kg	**-64 %**
Door panel NFPP	4,17 kg	3,53 kg	22,8 kg	0,0535 kg	2,74 kg	33,29 kg	**-41 %**
Door panel algae	2,53 kg	3,81 kg	41,7 kg	0,098 kg	-0,332 kg	47,8 kg	**-15 %**
Door panel wood	1,4 kg	0,0449 kg	27,6 kg	0,0649 kg	-0,013 kg	29,1 kg	**-48 %**

All the materials chosen had a smaller CO_2 footprint compared to the materials used in the PS2 door panel. Without the use phase taken into account all the materials, with the exception of Natural Fibre Polypropylene, reduced the CO_2 footprint by at least 50%, which was the final goal of this thesis work. When the use phase was also included in the calculation, only aluminium and cork reduce the CO_2 emissions by at least 50%.

Use phase is important when choosing new material

The use phase was outside the boundaries of the LCA calculations for this thesis, but the door panel's weight has an impact on the LCA calculations during use phase, weight reduction means a reduction of the panel's footprint. Because of this possibility to save the amount of energy needed during the use phase the need was felt to consider the use phase anyway, when choosing a new material for the interior door panel.

5.4 Conceptualisation

In the conceptualisation phase materials were applied and evaluated to conclude and decide on the final material. This stage involved various creative and systematic methods in several iteration cycles, but also practical and hands-on methods. All the tasks executed are described in the following chapters.

5.4.1. Creative design strategies

The lateral thinking approach: De Bono six thinking hats

To evaluate the materials found during material screening a more creative tool was used to obtain another perspective on how these materials may or may not be used in the new and final concept. *The lateral thinking approach - De Bono's six thinking hats* was used to examine the advantages and disadvantages of each material found. Lateral thinking means to branch out into different directions which are not yet explored to find new and innovative solutions for a current problem (Österlin, 2016).

This approach uses six different hats where each hat represents different thought processes and angles to look at when seeking for the solution of a problem or finding. The white hat includes facts like physical data, objective, and neutral thoughts as well as general information. The green hat is the creativity hat representing possibilities, ideas, and alternatives as well as lateral thinking. The blue hat is used to think about the process of thinking which means that this hat examines the possibilities there may be during the working process. The black hat shall be used when thinking critically about the problem or new finding as well as indicating caution. Benefits and optimism can be expressed by using the yellow hat. There must be reasoning behind why solutions may be beneficial as well. Lastly, the red hat is used to express a feeling or intuition of a thought and does not require any reasoning behind it (Österlin, 2016). Thoughts on the chosen materials are presented below.

Table 5: Six ways of thinking - aluminium

Material	Hat	Thoughts
Aluminium		Recyclable with current techniques Low density Better LCA outcome
		Can be painted, given a layer/veneering Can be used for bigger structural parts Hole profile in an aluminium panel can make it easier to fasten other components Known to be strong as it is used in aircrafts, give a safer feeling to customers
		Can be used as a base for other materials Does already exist in other vehicles - no need to manufacture virgin aluminium Has good physical and mechanical properties comparable to commercially used plastics
		Possibility of dents Can give "cheap" impression (when it looks like its only the inside of the door) May be perceived as cold and uncomfortable by users May be seen as old-fashioned Lots of CO_2 produced during the first material acquisition
		Lightweight Easy to form into shapes Easy to recycle - Multiple life cycles Less material required to achieve same strength properties High EoL potential
		I like the material! Alu panels with facades of wood or coating of other kinds look luxurious

The use of aluminium in a door panel would result in a significant weight reduction and the material performs well in an LCA when its End-of-Life is considered. The possibility of dents in the material, for example the seat belt buckle can cause dents in the door panel, and the fact that the material can be perceived as cold is a downside (Table 5).

Table 6: Six ways of thinking - PHA/PHB

PHA/PHB		LCA outcome is not so good Same properties as PE and PP
		Has a "story", using algae that causes algal blooms to make something good → biodegradable plastic
		New material with various possibilities, but still in its conceptualisation phase Requires a lot of energy during manufacturing
		Not yet possible to use in automotive Material is very much in its development phase Needs to be further explored to not decay when exposed to water/UV light
		Would be good alternative, no plastic waste It is 100% biodegradable New and unconventional - exciting for customers
		Door panel would still have a plastic look Cool with a material that originates from weeds

The story of PHB; a plastic that can be made of the cyanobacteria causing algal blooms in the Baltic Sea and the fact that it is fully biodegradable is interesting. The fact that the material is not yet applicable in automotive and that it will not result in a reduction of weight are negative aspects (Table 6).

Table 7: Six ways of thinking – cork

Cork		Has a very good LCA outcome Natural material Lightweight and low density
		Can be painted to change the natural cork look Can be shaped into whatever shape Can be coated for better water exposure Use the material 'invisible' (armrest/door shell)
		Must be pressed and the bark for cork making has to be collected manually Difficulties for logistics; cork production in Portugal manufacturing in Asia
		Unconventional material in automotive Does not scream "premium car" Customers must shift their mind from luxurious and uniform to more unique and sustainable
		Lightweight, fire resistant, non-toxic UV resistant Unique patterns - no cork board is the same
		I like the material! Make a statement, whole door panel of cork Unconventional, shift in design philosophy

Cork is not a conventional material in automotive but has a lot of properties that are sought for, like low density, fire resistance and non-toxicity. When the use phase is considered, cork has the best LCA outcome of the materials found (Table 7).

Table 8: Six ways of thinking - coffee-plastic

Coffee-plastic		No weight reduction Little actual fact-based data found 100% biodegradable
		Has a story New and exciting, unique Can be dyed, coated, processed like plastic Together with coffee leather for a whole coffee door panel
		More actual testing is needed Coffee grounds must be treated like a resource not waste
		Must be made fire resistant Even if dyed, coffee grain structure stays visible
		Can be used in automotive Can be injection moulded with current tools Closes the material loop

		Like the material when it is visible/obvious that it is not ordinary plastic It looks nice because it is uneven and not like usual plastic

Coffee plastic is an innovative material which is just like plastic but made from waste material which makes it more sustainable. Due to its similarities with plastic, coffee-PLA has the same weight as its original counterpart but is 100% biodegradable. The material can be coated and dyed to fit into a car's interior, and it is injection moldable which causes little to no spillage of the material. Drawbacks of coffee-PLA are that it must be made anti-flammable by coating as well as that the structure of the material, the coffee grounds, will always be present even when dyed (Table 8).

Table 9: Six ways of thinking - plywood

Plywood		Strong due to its gluing Natural glue is used like cellulose or lignin Has a lower carbon footprint than most materials
		Together with another material like aluminium or leather In more structural parts not decorations or the other way around Wooden waistrail? Would not get too warm
		How is it bent? Manufacturing possibilities? How do components need to be fastened? Which other materials should be used?
		Old-fashioned material A different way of attaching the door panel is necessary Might be not as durable and needs chemical coating to make it water resistant Flammable Cannot be reused
		Circular material Sustainable and can be sourced locally Can look very luxurious depending on which wood is used
		I like the material Fear of people not wanting to accept the material in cars - too "old timey"

Plywood is an interesting option for the interior of a car. Wood has a luxurious feel to it and can be coated with different polishes to enhance the uniqueness of each wooden panel. It gains strength through the gluing process and is relatively lightweight and 100% natural. In combination with other materials plywood can be used for the bigger structural parts while other smaller components can be made of other more sustainable materials. However, wooden panels are flammable and can only be downcycled as well as they may be perceived as old-fashioned or outdated. Chemical coatings will be needed to make the material resistant to water and ensure that it ages gracefully (Table 9).

Table 10: Six ways of thinking - natural fibre polypropylene

Natural Fibre PP		Is already used in automotive LCA outcome okay
		Even less PP use possible or bio-based PP from non-food items Can be dyed, coated painted
		Hard to recycle and creating machines for recycling is not yet explored
		The material consists of several materials 'glued' together, hard to recycle 'Cheap' material, must be painted or covered with other materials Creates a lot of spillages that cannot be reused
		Weight reduction Reduces amount of plastic used in a door panel
		Not yet optimal but not bad either - neutral

NFPP is a composite material reducing the use of plastic in a product by 70%. This makes it lightweight and reliable when used in the automotive industry. NFPP can be coated and dyed and has the same feel and look as plastic but is more sustainable than PP. One major disadvantage though is that the material's spillage cannot be reused or recycled (Table 10).

Producing plastic

Out of curiosity different kinds of bioplastics were made. None of the materials made can be used in automotive as they will dissolve in water.

The first one was a plastic of Coffee Husk/Chaff Biomaterial which can be moulded or casted. The ingredients of this material are agar agar (a gelatinous substance derived from red algae used in cooking as a substitute for gelatine), water, glycerol, and coffee grounds (Materiom, 2018). The result was a hard bio-based plastic as shown in figure 31.

Figure 31: Bio-based plastic made from coffee ground and agar agar

The second material was an Agar bioplastic that resulted in a thin transparent, strong, and flexible film (figure 32). The ingredients are agar agar, glycerol, and water (Materiom, 2018).

Figure 32: Bio-based plastic made of agar agar and glycerol

To test a material that can be used as a substitute to leather a recipe that contains sodium alginate, coffee grains, olive oil, glycerine, water, and calcium chloride for calcification was used (Fabtex, n.d.). The result was a coffee bio-leather not strong enough to use as a substitute to real leather, but when glued to a fabric it became somewhat stronger (Figure 33).

Figure 33: Coffee bio-leather

The properties of the bio-based plastics made are not yet comparable to the fossil-based plastics used in the PS2 door panel, so it is not possible to use these bioplastics as a replacement.

Ideas how to reduce the amount of material used and other ideas

By removing all buttons used to open and close the windows, and the ones used to adjust the side view mirrors from the interior door panel to the dashboards touch screen the amount of material needed is reduced.

The side view mirrors on cars will soon probably be replaced by cameras to make cars more aerodynamic and thus fuel/electricity efficient. Without a mirror to see if someone is coming from behind when opening the door, for example a cyclist or another car, the passenger must look over their shoulder. To force the person getting out of the car to look over their shoulder before opening the door, the door handle should be placed further back. In that way one cannot open the door with the hand closest to the door. By forcing the passenger to use the opposite hand, the body is twisted, and this will increase the possibility of looking over the shoulder and seeing whether or not someone is coming from behind, before opening the door (Figure 34).

Figure 34: Replacing the door handle further back to force passengers to look over their shoulder before opening the door

Making the design more flexible so different parts are easier to replace facilitate a longer use phase for products. When it is possible to replace broken or damaged parts, so the door panel looks new again, the parts that did not have to be replaced have a longer life instead of the need to replace the whole door panel in the case of the original PS2 door panel where all the different parts are welded/melted together (Figure 35).

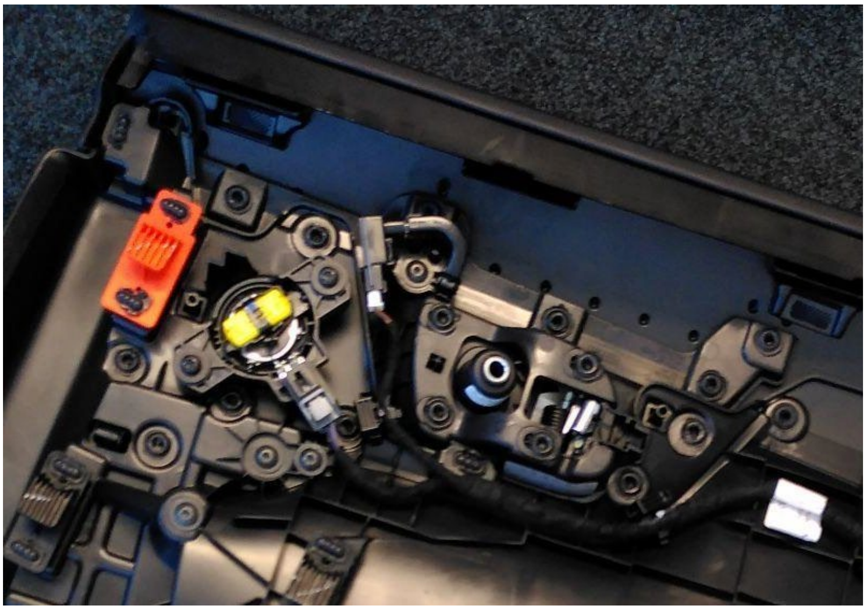

Figure 35: The back of the door panel with the parts melted together

By not gluing or melting parts that are made from different materials together, is the separation of the materials during recycling simplified.

5.4.2. Decision making

In this section of the report different methods for deciding on the new material are used and presented below.

Pugh Matrix

To decide about which materials to use in the new door panel Pugh Matrices were used. A Pugh Matrix is a criteria-based decision matrix used to compare different solutions with one another in a structured way. The current solution is used as a reference in the first matrix and every other solution is pairwise compared with the reference; positive (+), negative (-) or equal (0) in meeting the criteria. Total values of every solution are calculated and the different solutions will be ranked (Table 11). After the first Pugh Matrix the two materials that received the least number of points and the original PS2 panel were discarded. With the remaining four another Pugh Matrix was done (Table 12).

Table 11: Pugh matrix using the original door panel as a reference for evaluating the materials

Chalmers
Pugh Matrix - approach for relative decision making

Performed: 25/04 2022

Criteria	**Alternatives**						
All criteria refer directly to the materials	**PS2 panel**	**Aluminium**	**Coffee**	**Cork**	**NFPP**	**Algae**	**Plywood/ Birch**
Recyclable	**R**	+	+	0	-	+	+
Reusable	**E**	+	-	+	0	-	0
Biodegradable	**F**	0	+	+	+	+	+
Non-toxic	**E**	0	+	+	0	+	+
Non-labour intensive	**R**	0	0	-	-	-	-
Meet requirements in criteria sheet (Table 2)	**E**	-	-	0	0	-	-
Injection moldable	**N**	-	0	-	-	0	-
Aesthetically pleasing	**C**	+	+	+	-	0	+
Safety for users	**E**	0	0	0	0	0	-
Design for Longevity		+	-	0	0	-	+
Reduce the carbon footprint by half		+	+	+	-	+	+
Σ+	0	5	5	5	1	4	6
Σ 0	0	4	3	4	5	3	1
Σ -	0	2	3	2	5	4	4
Net-value	0	3	2	3	−4	0	2
Position	**5**	**1**	**3**	**1**	**6**	**5**	**3**
Decision					**discard**	**discard**	

In the matrix above the characteristics of the materials in the current door panel were compared with the possible materials' characteristics for the new door panel. In the first Pugh matrix the original door panel served as a reference for the comparison between all the materials that were discovered during the research phase. This means that materials which can be injection moulded like most plastics in the original door panel received the number 0 as the same process can be used. Materials which must be bent, glued, or rolled would receive a '-' as it is more time consuming/less effective and a major factor when wanting to reduce spillage during production of materials. The materials to be compared with the PS2 panel were aluminium, coffee, cork, NFPP, algae and plywood. These materials were analysed through following criteria:

- Recyclability: Is it possible with current methods to recycle the material?
  As stated in 5.3.2, a material's ability to be recycled is important. This can be implemented using strategies like Design for Environmental Impact and Design for Recyclability.
- Reusability: Is the material reused or will it be reused in the near future?
- Biodegradability: Is the material biodegradable and can it close the loop in the material flow?
- Non-toxic: Does the material contain or is processed using any toxic or hazardous contents? Does it contain health impacting colours or coatings or any other chemicals during manufacturing?
- Non-labour intensive: Does the material require manual (human) processing methods or processed by machines only?
- Meet the requirements from the criteria sheet (handed out for this work from Polestar)?
- Injection mouldable: Can it be moulded?
- Aesthetically pleasing: Does the material reflect good quality and standards?
- Safety for user: Is the materials safe for the driver and/or passengers in terms of physical safety or in the case of an accident?
- Design for Longevity: Is the material durable enough to last the expected lifetime of a car?
- Reduce the carbon footprint by half: Is there a 50% decrease in emissions in comparison to the original materials?

As clearly represented in the matrix above the NFPP and the algae plastic performed worse in comparison to the other materials and were therefore discarded from the materials viable for further conceptualisation.

Table 12: Pugh matrix using plywood as a reference for evaluating the materials

Chalmers **Pugh Matrix - approach for relative decision making**				
Performed: 25/04 2022				
Criteria	**Alternatives**			
All criteria refer directly to the materials	**Aluminium**	**Coffee**	**Cork**	**Plywood/Birch**
Recyclable	+	0	+	**R**
Reusable	+	0	+	**E**
Biodegradable	-	0	0	**F**
Non-toxic	-	0	0	**E**
Non-labour intensive	+	+	0	**R**
Meet requirements in criteria sheet	+	0	+	**E**
Injection moldable	0	+	0	**N**
Aesthetically pleasing	-	**-**	+	**C**
Safety for users	+	+	+	**E**
Design for Longevity	0	**-**	-	
Carbon footprint	-	**-**	-	
Σ+	5	3	4	0
Σ 0	2	5	4	0
Σ -	4	3	2	0
Net-value	1	0	2	0
Position	**2**	**3**	**1**	**3**
Decision				

After the second Pugh Matrix none of the remaining materials were discarded. The next step in the conceptualisation will be the design and form of the new door panel with these materials or a combination of those.

Bamboo as an alternative

After analysing the materials through the two Pugh matrices, wood as a material became more interesting. In past years bamboo has gained importance in a lot of industries ranging from furniture and kitchenware but is even recognised in the automotive industry. The automotive manufacturer Ford has started to implement bamboo composites in car interiors (Ford, 2022).

Bamboo, which is classified as a type of grass, can be used in various ways ranging from using the saw dusts in bioplastic production, the fibres for making natural fibre plastic or the wood on its own. Besides being able to be processed in numerous different ways the material is low-cost, biodegradable, reusable and more sustainable than other natural materials. However, for automotive parts bamboo is used to reinforce thermosets such as epoxy, vinyl ester and polyester, which are non-biodegradable yet high strength materials (Radzi et.al, 2022). A composite made from bamboo fibres and polylactic acid plastic (PLA) would create a fully bio-based and biodegradable material, which has similar properties to current plastics used in the automotive industry.

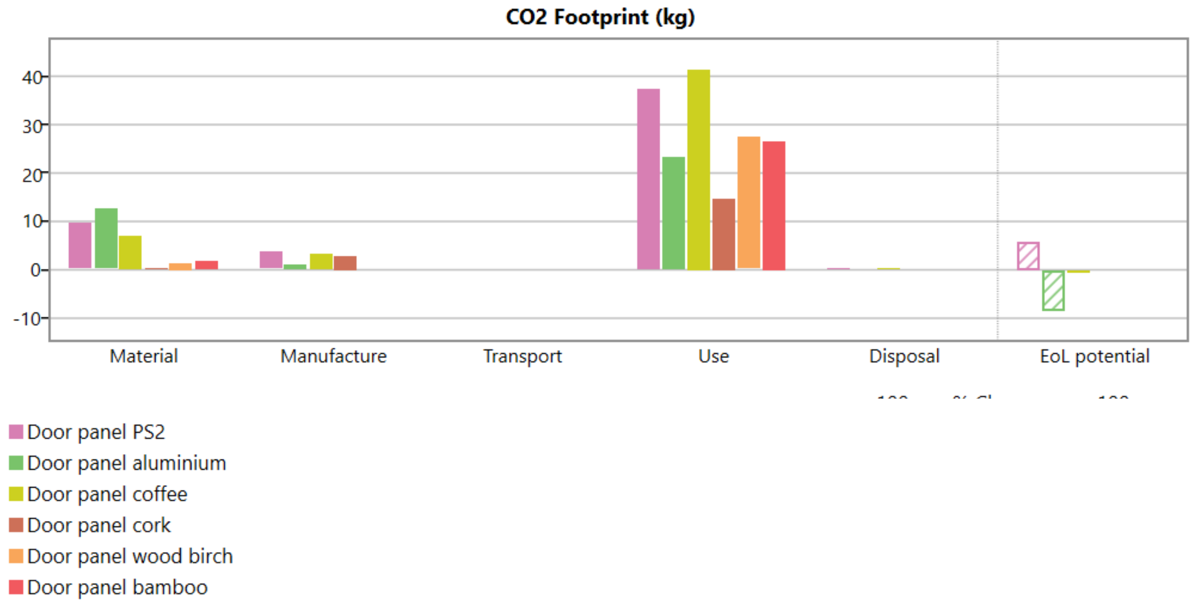

Figure 35: Bamboo's carbon footprint (red) in comparison to the other materials

Not only the previous recognition of the material within the automotive industry was taken into account yet more importantly whether it would improve the carbon footprint by 50%. To be able to quickly conclude bamboo's suitability regarding sustainability a comparison to the previous four materials was made. As shown in the bar chart (Figure 35 and Table 13) above the bamboo panel would perform better in every category besides its EoL-potential. This is because bamboo as such is not recycled or reused but downcycled, making the areas of use limited.

Tables 13: CO_2 footprint of door panel in wood and bamboo, with use-phase and change compared to the PS2 door panel

CO_2 Footprint (kg)	Material	Manufacture	Use	Disposal	EoL	Total	**Change**
Door panel PS2	9,62 kg	3,63 kg	37,7 kg	0,0887 kg	5,77 kg	56,8 kg	**0 %**
Door panel wood birch	1,4 kg	0,0449 kg	27,6 kg	0,0649 kg	-0,013 kg	29,1 kg	**-48 %**
Door panel bamboo	1,89 kg	0	26,7 kg	0,062 kg	-0,0125 kg	28,6 kg	**-50%**

For the above stated facts about bamboo, this specific material became part of the material alternatives even after the Pugh matrices.

5.4.3. Sketching and sketch models

Rapid sketching and sketch models were used in the early conceptualisation phase to understand how all the components in the interior door panel work together as well as to identify components that could be possibly removed. The sketches in figure 36 show the thought process for some of these concepts and were further developed as shown in chapter *5.5 Evaluating the new materials.* Furthermore, it should be mentioned that the original model given by Polestar in Catia V5 was the left front door interior panel. Because of this it was decided to model and sketch on front door panels instead.

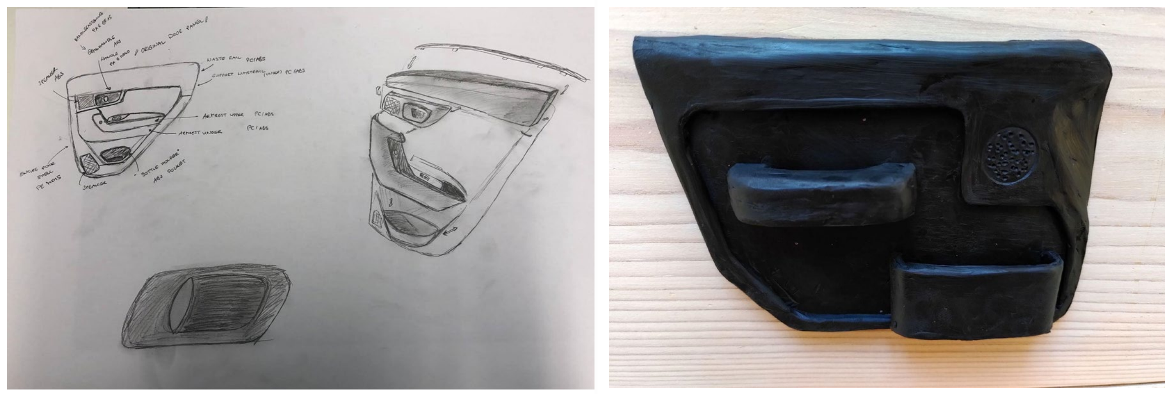

Figure 36: Sketches and sketch models in the early stages of conceptualising

5.5 Evaluating the remaining materials

PNI - Positive, Negative, Interesting

The five remaining materials were applied to digital Photoshop models to gain a better understanding of how the new materials would be perceived on a door panel. For a first evaluation, the PNI method (Positive-Negative-Interesting) was used to determine whether it was worth further considering the materials for the final design or not. The results of the PNI are presented below.

Coffee PLA

Positive	Negative	Interesting
Material with a good intention - waste to unique material	No weight reduction	Story! Coffee panel
Bioplastic, interesting/new material	Has to be made flame retardant by chemicals	New market segment for selling used coffee grounds
Easy to accept by customers, company as it is like plastic	Still plastic look	
Can be mixed with a bio-based plastic	Social responsibility to not over-consume coffee for car manufacturing	
Is fully biodegradable	Still in it's concept-phase	
Same processing method as original		

Figure 37: Door panel made of Coffee-filled PLA

Coffee filled PLA is an interesting material to use in the new door panel (Figure 37). The material has a story; the use of food waste to make a new material and the fact that it is possible to make a whole door panel out of coffee materials, coffee PLA and coffee-based leather is appealing. The door panel made of coffee would reduce the CO_2 footprint by 55%, but because of its weight as there is no weight reduction compared to the original door panel, the CO_2 reduction with the use phase taken into account is only 12%.

Cork

Positive	Negative	Interesting
Good thermal properties - does not get hot/absorbs heat	Cannot be recycled/reused after creating the material once	Can be pressed into different shapes
Low-cost material	Uses different manufacturing process	Component reduction = fewer parts
Can be dyed to make it look more fitting for a car	Unconventional	
No glue or other binders needed - mono material	Not entirely water resistant, does not age gracefully	
Mono material - easier to recycle		
Lightweight		
Stems from dead bark not actual trees - no forestry		
Granules, no spill material		

Figure 38: Door panel made of cork with a door handle of coffee filled PLA

A door panel made of cork (Figure 38) would reduce the CO_2 impact, both with and without the use phase taken into account. The material is not conventional in automotive, but because of its properties it is an interesting material. The material cannot be injection moulded, but it is possible to heat press it into shape. It is possible to make the whole door panel in the same material; only the door handle with its fastening is made from the coffee polymer.

Bamboo

Positive	Negative	Interesting
Hard material	Is not water resistant	Many possible material combinations
Can be grinded and mixed with PLA - does become injection moldable	Forming bamboo more time consuming than injection moulding	Lightweight material
Used in automotive already (like NFPP)	Not common material in automotive	
Low cost and local where the production is		
Ecological material, re-grows no need to replant		
If a full wooden sheet is used, it can be grinded into fibres and reused in bioplastic-fibre blends		
Bamboo is a fast-growing grass with good strength to weight ratio		

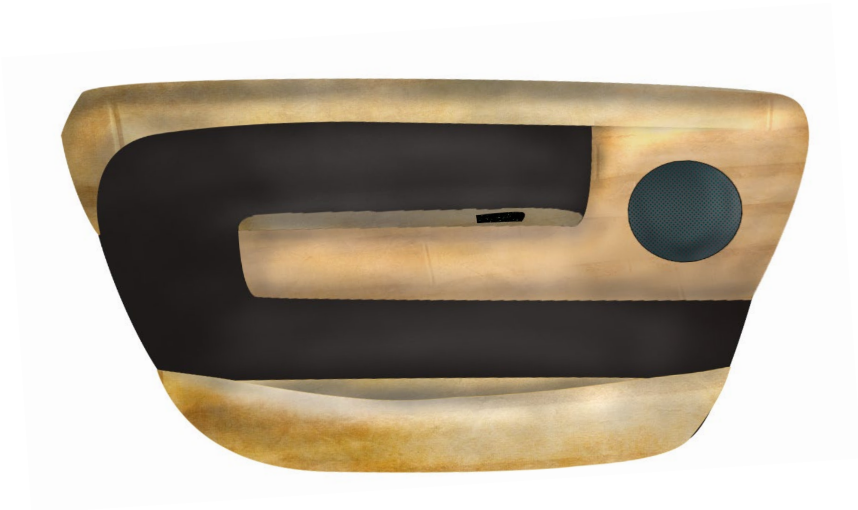

Figure 39: Door panel made from bamboo and bio-based leather

Out of a CO_2 impact perspective is bamboo a very good material to use, a fast-growing member of the grass family. New canes will grow of the same roots after being harvested and bamboo grows in China where the Polestar 2 is being produced.

Aluminium, vegan leather and plywood

Positive	Negative	Interesting
Aluminium and wood have well established recycling methods	Forming plywood more time consuming than injection moulding	Aluminium frame with holes to save material
Can use natural glues instead of chemical ones	Bio-leather glued to aluminium not easy to recycle	Revival of wood in cars - new trend like bootcut jeans
Both materials are relatively lightweight	Might be perceived as old-fashioned	
Framework makes it easier to change wooden parts	Multiple materials used - harder to recycle	
Bio leather protect against dents on aluminium		

Figure 40: Eames inspired door panel in plywood, aluminium, and coffee-based leather

Both aluminium and plywood are materials with a low CO_2 footprint and especially recycling aluminium is well established. The cladding of the aluminium shell with bio leather will make recycling the materials harder but protects the material against dents and provides passenger comfort.

Structured aluminium and plywood

Positive	Negative	Interesting
Easy recyclable, only two different materials used	Aluminium can be cold to touch	Can be perforated to obtain different surface structures
Lightweight material	Does use a different manufacturing process	
Does not get hot even if it is a metal	Forming plywood more time consuming than injection moulding	
Can be recycled with already existing methods	Material spill when pressing aluminium parts	

Figure 41: Door panel with door shell in origami (aluminium) and plywood

This concept is easier to recycle than the previous; less different materials and easier to take apart. The origami surface shall prevent the aluminium from getting visible dents as well as it creates a unique appearance.

Elimination matrix

Discussing the advantages and disadvantages of each material engaged to think through all the possibilities of the researched materials which helped in the final evaluation process. For the final evaluation, an Elimination matrix was used. To be able to eliminate the materials that would not meet the necessary criteria set in the material and design requirements in 5.1.1. Since some criteria were desirable yet not necessary these were not considered during the elimination process. The matrix below shows which and if the remaining materials meet the different criteria. If a criterion is met this is presented by a "+" as well as a "-" in case of a material that does not meet the requirement. The "+/-" is used for materials which have neither a major advantage/disadvantage (Table 14).

Table 14: Elimination matrix for making the final material decision.

NR.	Criteria	+/-	+/-	+/-	+/-	+/-
1.	**Material acquisition**	**Coffee**	**Cork**	**Bamboo**	**Aluminium 3m**	**Aluminium 2m**
1.1	Materials used should be recyclable, reusable or biodegradable	+	+	+	+	+
1.3	Materials used should not emit hazardous gases	-	+	+	+	+
1.4	Use of non-toxic chemicals during material production	+	+	+	?	?
1.6	Materials used most meet requirements described i requirements sheet: Technical regulations Door Trims	+	+	+	+	+
	Manufacturing					
2.2	Can be manufactured with already existing techniques	+	+	+	+	+
2.4	Production technique must be non-labor intensive	+	-	-/+	-	+
	Design/Form					
3.2	Ability to disassemble components of the door panel	-	+	-	-	+
3.4	Lightweight components	-	+	+/-	+	+
3.5	Does not impact the users in any negative ways regarding safety	+	+	+	+	+
3.7	Aesthetically pleasing	-	+	+/-	+	-
3.9	The new design shall be tying into the current Polestar 2's design and shape language	+	-	-	-	-
3.11	The new door panel components meet requirements in *1. Material acquisition*	-	+	+	-	-
	End-Of-Life					
4.1	Design for Assembly and Disassembly	-	+	+/-	-	+
4.4	Recyclability of all components	+	+	+	+	+
SUM		2	10	6	3	7

As presented in the table above, *coffee PLA* performed the worst in comparison to the other materials when it came to meeting the criteria. The fact that the material was not lightweight for instance would make a significant difference during the whole lifespan of the entire door panel as the weight of an electric car determines the distance one loaded battery can travel.

Further the coffee PLA panel cannot be disassembled yet decays under the circumstances. The *Aluminium 3 m(aterials)* door using aluminium, plywood and vegan leather was eliminated because of the inability to recycle all components as well as the fact that the possible old-fashioned look would not fit Polestar's design aesthetics. Furthermore, using three materials would also require more labour-intensive work. *Bamboo* and the *Aluminium 2 m(aterials)* did not meet all the criteria necessary either to make it into the final concept. Wood has been used in many luxury car brands but is not optimal when thinking about reducing the weight of car interiors as well as cutting trees for car manufacturing is not sustainable in the long run. The material that clearly outperformed all the others was cork, which was the material used in the final concept.

6. THE FINAL CONCEPT

The final concept for the new Polestar 2 interior door panel is a door panel made of cork with a door handle made of 100% bio-based, coffee-filled PLA (Figure 42).

Figure 42: Cork door panel concept

The buttons for adjusting the mirrors and those for opening and closing the windows have been moved from the door panel and their function has been added to the touch screen on the dashboard. The armrest and grab handle are combined with a small compartment. In this compartment will be a light and it will have the ability to place and charge a mobile phone via an USB-C port. Under the door handle will also be a light and those two lights will come on when the car is unlocked and when the engine is switched off, together with the interior lighting. The pocket will be big enough to contain some water bottles or a small bag and next to the pocket Polestar's logo is engraved.

6.1. The materials of the final concept

After several rounds of evaluating and discussing the advantages and disadvantages of each material a final decision had to be made. Cork was the material that outperformed the other materials even regarding an entire door panel's use phase.

Cork

Cork is a natural material made from the bark of the cork oak tree, *Quercus Suber L,* and consists of 40% suberin, 27% lignin, 12% cellulose, 4% friedelin and 17% water (Appendix 2, Granta material sheet). The oak tree lives about 300 years and after the tree has reached 25 years of age its bark can be harvested every nine years (Figure 43). Cork oaks grow in the western Mediterranean region, mostly in Portugal and Spain, but also in Morocco, Algeria, Tunisia, the south of France and on the west coast of Italy. The total area of cork oak forest is about 2.2 million hectares, more than half of that area is in Portugal and Spain (APCOR, 2015). The layer that is harvested from the cork tree is called the phellem layer, is composed of a hydrophobic (water-repelling) material that has unique characteristics: it is impermeable, buoyant, elastic, non-toxic, and fire-retardant. It is a rapidly renewable resource, and all the material taken off the tree is used for different purposes:

- Corks of natural cork.
- Corks and lids of agglomerated cork, where an adhesive is added to glue the granules together.
- Boards and furniture of expanded cork (Golenda, 2018).

Figure 43: The bark of a cork tree (Mathis, 2020)

Expanded cork

Furniture and decorative items, as well as the new PS2 door panel, are made of cork that is called expanded cork or black cork. Expanded cork is made of the bark that cannot be used to produce wine corks. It consists of branches that are pruned, fire damaged cork and cork from the first time a cork oak is harvested. This quality of cork has a high quantity of resin in it which is used as a key ingredient to process the cork. The cork bark is first grinded to produce granules (Figure 44) and thereafter placed in a mould. Pressure is applied and steam heated to 400ºC is passed through. Due to the high temperature steam the granules swell up and the resin (lignin) inside the cork will be released to form a natural kind of glue that will bind all the granules together. Expanded cork can be produced in different densities depending on how much pressure is applied (Corklink, 2013). With extra pressure the density will be higher (155 kg/m^3 up to 185 kg/m^3) and thus the produced cork can tolerate harsh circumstances.

Figure 44: Cork granules (CorkLink, n.d.).

Other material properties that have a value for the automotive industry are that cork is lightweight, durable, and impermeable to liquids and gases, thermally and acoustically insulating and hypoallergenic; it does not absorb dust or pollen and is easy to clean (Nordgröna, 2021). The thermal properties of high-density cork are also favourable; its service temperatures are between -73 ºC and 140 ºC (Granta EduPack, 2021).

However, proof for the materials functionality in a car was needed. In an article from 2017 the automotive manufacturer Hyundai had created a concept car using cork for the interior door trims. As motives for the usage of cork its cost-effectivity, good heat and UV light resistance were mentioned but also the fact that cork production does eliminate possible deforestation and cuts a part's weight by 24% in comparison to wooden interior panels (Winter, 2018). Due to cork trees not needing to be cut down to harvest cork, cork is a sustainable choice as its raw material regrows and renews itself.

Pereira (2007) states that cork is a good option for automobile interiors where thermal insulation should be maximised and the thermal distortion minimised, while the energy content of the materials should be low to comply with environmental requirements. In relation to other materials, cork has advantages related to easy recyclability, re-usability, and health friendliness (Pereira, 2007).

Coffee PLA

The coffee polymer used for the plastic details in the new door panel is the Cappuccino polymer of the Dutch company OVDesign. It is an injection moldable and 100% bio-based polymer and can degrade in the simulated environment of a waste processor. Since the Cappuccino polymer is not biodegradable in nature it can be used for long-term products. It must be made flame retardant and will require further testing until fully usable within the automotive industry. The polymer's density is 1050 kg/m³ and has a tensile strength of 30 MPa and the other properties are shown in appendix 3 (OVDesign, 2022).

6.2. Dimensions of the final concept

As aforementioned the new door panel, shown in figure 45, consists of three different materials:

- Cork for the door panel's body.
- Coffee polymer for the door handle and door fastener.
- Metals for the screws used for fastening the door panel.

The concept does not contain any fabrics or textiles. To perform the final life cycle assessment an estimation of the parts' volume and weight had to be made. The measurements from the original door panels were adapted to ensure the final concept had appropriate measurements.

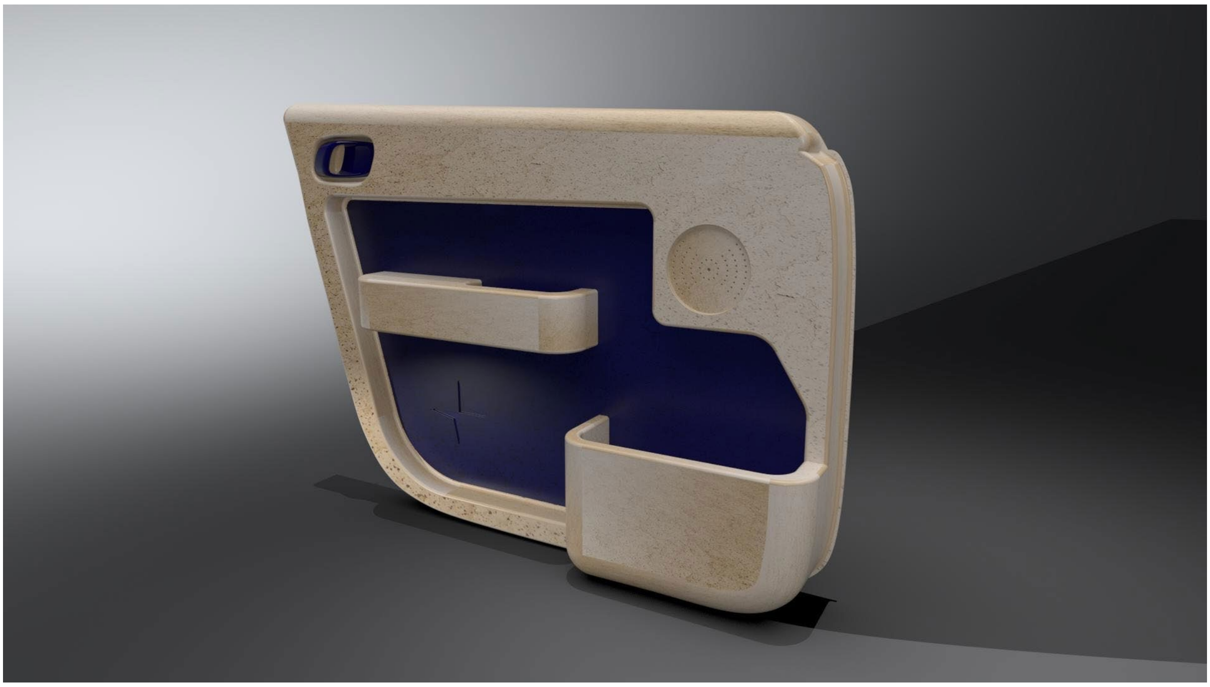

Figure 45: The new door panel in Midnight Blue.

The new door panel made from cork will have to be thicker than the plastics used in the original to sustain its physical properties such as tensile strength and crack impact. The outline shape of the original door panel is kept for it to fit even current PS2 models. For the approximation of the door shell following measurements were used:

*6400 cm² (the door shell surface area) * 1 cm (material wall thickness) * 155 kg/m³ (density of high-density cork) = 0,992 kg ~* ***1kg in weight of the whole door shell***

The grab handle and armrest were merged into one part instead of two different parts that are fused together. The initial length dimension of 40cm was kept, the width was expanded to 8cm and the material thickness for the armrest was increased to 3cm at its thickest part. The small pocket created from merging the grab handle with the armrest now has space for a mobile phone to store and has a depth of 7cm. The weight estimations of the armrest were therefore as follows.

Figure 46: Armrest and grab handle with lighting detail and USB-C charging.

*(3cm (material thickness) * 8cm (width) + 17cm (length for the elbow surface area) * 8cm (width) + (20cm (pocket compartment in the armrest) * 3cm (material thickness)) * 8 cm (in height) =* ***1760cm³ volume of the armrest***

*1760cm³ (the armrest's volume) * 155 kg/m³ (density of high-density cork) = 0,2728 kg ~* ***0,3kg in weight of the armrest***

The pocket was the last part to be fastened onto the door shell. Since the calculations were performed on a rear door the pocket had to be scaled down. Considering that a water bottle should fit comfortably into the pocket its depth had to be at least 10cm. The measurements of the new pocket insert, and its weight is shown below.

Figure 47: The pocket on the front door panel is bigger, it can hold a bottle or a smaller bag

*(2cm (material thickness) * (20cm (height of the sides) *10cm (length of the pocket insert)) * 2) + 2cm * 10cm * 20cm (bottom) + 2cm * 20cm * 20cm (front) =* ***2000cm³ volume of the pocket***

*2000cm³ (volume of the pocket) * 155 kg/m³ (density of high-density cork) = 0,310 kg ~* ***0,3kg in weight of the pocket***

The handle and handle fastening of the door kept their dimensions and volume, but the material was exchanged from mineral-reinforced plastic to coffee-ground-based PLA. The original handle weighed about 74 grams and was made from medium density PA6, while the new handle weighs approximately 50 grams as the density of the coffee PLA is 1,05 g/cm³ compared to 1,45 g/cm³ for PA6. The handle fastening is made from the same coffee PLA weighs 20 grams instead of 26 grams from PA6 glass fibre-reinforced plastic.

This resulted in a total weight of the cork interior door panel of 1,65 kg, a weight reduction of 41% in comparison to the original door panel which weighed 2,8 kg.

Another change was the number of transports for the new door panel, which increased by one more transport due to cork being harvested in Portugal and then manufactured in Asia. For this transport it was assumed that the raw material would be transported by ocean freight once again.

Apart from the above stated changes, the initial interior panel had 15 metal screws which were kept for fastening different components.

6.3. LCA of the cork door panel

Once again openLCA was used to perform the LCA of the final concept. As before for the initial PS2 door panel, the GHG-impact method was used for calculating the carbon footprint of the conceptual interior door panel. Instead of 22 kg CO_2-e as seen in the original door panel the emissions had been reduced to roughly 1,85 kg CO_2-e (Figure 48).

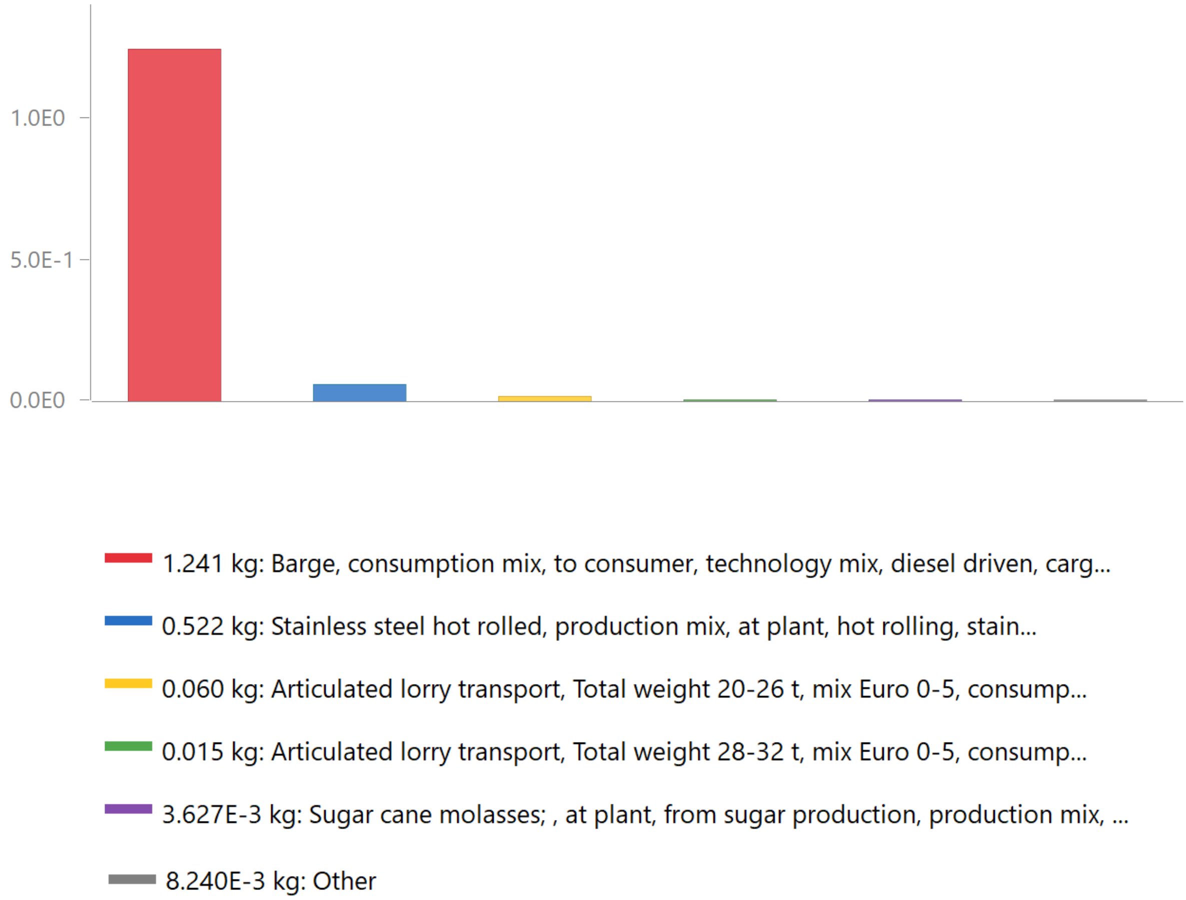

Figure 48: The LCA outcome of the conceptualised door panel

This result of having reduced the CO_2 emissions by 20,2 kg seemed unrealistic, especially due the fact that the number of transports used during the material production increased by one ocean freight. This conflicting information together with the research carried out before created the need for using another LCA tool to get a better understanding whether the concept had fulfilled the requirement of reducing the LCA outcome by 50% or not.

Limitations of the LCA

In the LCA of the cork door panel it was not possible to use the same database as in the LCA of the original door panel. Instead of the European reference Life Cycle Database (European Commission, 2015), the Environmental Footprint Database 2022 from Ecoinvent was used. The reason being was that cork was not available in the European reference Life Cycle Database. PLA or polylactide was found in neither of the databases and an estimate for the materials impact was made. The input of impact factors of the transports differentiated as well because of the use of two different databases. As in the first LCA, no data was collected about actual emissions from manufacturing plants.

Comparison in GRANTA

A comparison of the two door panels was made in GRANTA. It was not possible to use the same database in openLCA for both door panels and that together with the fact that it is not transparent in openLCA how the calculations are made, the need for a reference calculation in another program was felt.

In GRANTA the same transports were used as in the openLCA calculation, lorry transport between factories in China and ocean freighter between Shanghai and Gothenburg. The difference for the cork door panel is the transportation of the cork granules between Porto (Portugal) and Shanghai (China) by ocean freighter. The limitation in GRANTA is that it is not possible to freight parts differently, this means for example that the whole door panel will be transported from Portugal to Shanghai instead for only the cork granules in the calculation.

The outcome of the calculation in GRANTA is a reduction of the CO_2 footprint by **68%** of the cork door panel compared to the original PS2 door panel. In this comparison the use phase is not considered, but End-of-Life potential is. As shown in figure 49 the material footprint of cork and PLA is much less than the footprint of the polymers used in the PS2 panel. The impact of manufacturing is higher for the cork door panel, yet the impact of End-of-Life is higher for the original door panel. The CO_2 footprint of the cork/PLA door panel is **6,44 kg** and for the PS2 door panel **20,05 kg**. The difference with the GRANTA calculation for the PS2 door panel used as a reference when comparing new materials in chapter *5.2.3. Design concept formulation - the new materials*, is since in chapter 5.2.3 no transports are taken into account.

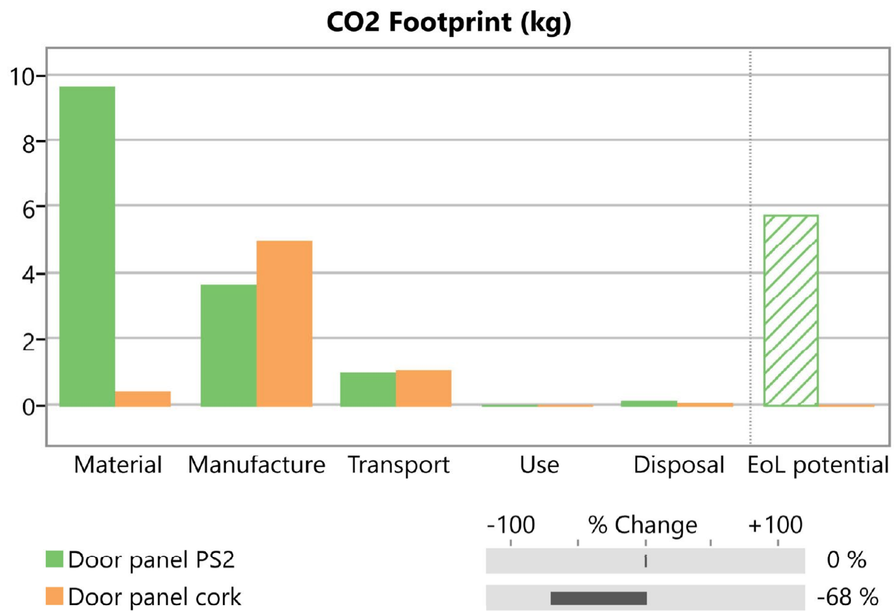

Figure 49: Comparison of the PS2 door panel and the new Cork door panel, without use phase, calculated in GRANTA.

The use phase used in the calculations was the same as in chapter *5.2.3. Design concept formulation - the new materials*, namely that the door panel is part of an electric driven family car used in Europe for 15 years, 300 days a year and 45 km per day. With the use phase the CO_2 footprint of the Polestar 2 door panel is **57,77 kg** and the footprint of the cork/PLA door panel **28,47 kg.** This means a reduction of **51%** as shown in figure 50. In **both** calculations, **with and without the use phase** considered, the thesis' goal of reducing the impact by 50% was met.

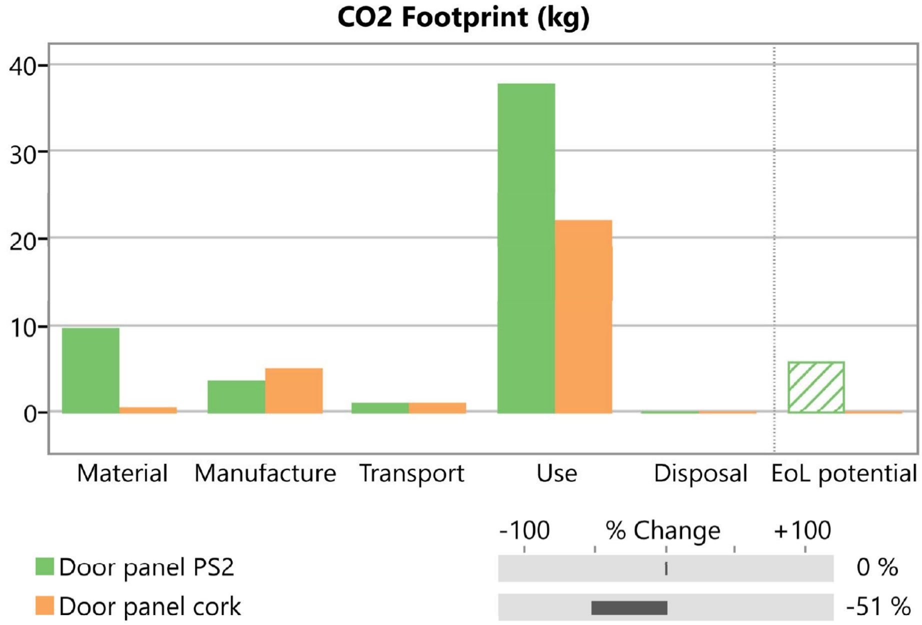

Figure 50: Comparison of the PS2 door panel and the new Cork door panel, with use phase, calculated in GRANTA.
(45 km a day, 300 days per year for 15 years in an electric family car in Europe)

7. CONCLUSION AND DISCUSSION

In this chapter the results are concluded and discussed as well as recommendations for further concept development are given.

7.1 Conclusion

To conclude it was possible to reduce the LCA outcome by half as it was asked for in the research question. The answer to this is that the use of cork would create a major positive impact on the environment, the carbon dioxide emissions as well as the possibility of designing a unique and innovative door panel. Other materials such as the coffee-based PLA would be a step towards more sustainable material manufacturing whilst giving customers the possibility to adapt to the shift in materials as well as design changes.

One advantage of the cork panel is that it does not create sharp edges in case of a collision with another vehicle. The material itself does withstand the pressure and loading which it is required to according to the technical requirements for materials, but does not break like wood or plastic, making it safer for passengers than before. When it comes to recycling the cork panel is easier to recycle than the current one as it is not clothed with a wide variety of different fabrics. As mentioned, it is difficult to remove all the materials from textiles and upholstery after having ground a car during its recycling process. Sustainable design strategies which have been implemented here are therefore Design for Environmental Impact and Design for Recyclability.

Another side effect of using cork is the payment of the workers harvesting the cork. In fact, the harvesting of cork is one of the best paid agricultural jobs in the world. (Bent & Bree, 2022) This means that the cork door panel is not only sustainable on a product level but also when it comes to adequate circumstances regarding payment and work conditions. This ties in with Polestar's fourth sustainability driver - inclusion.

Currently there is a company called Sedacor, which is supplying different manufacturers worldwide within the cork industry. The cork is used in a variety of solutions reaching from construction, decoration, and fashion to even cork material development research. After discussing this topic during research with one of their experts another interesting finding about cork was made. Agglomerated cork can be moulded which gives manufacturers extra design freedom however is an investment at first because of the special equipment needed but lowers production costs when a higher quantity of products is produced.

Innovation includes change and change requires adaptation which is the shift both automotive manufacturers and customers must accept. Cork is an unconventional choice in car interior design yet not an impossible one.

7.2 Discussion and Recommendation

Besides from the fact that the goal of reducing the carbon emissions was met, not every possible problem is resolved. Choosing new materials to improve sustainability proved itself to be a difficult task that requires extensive knowledge about materials and their properties in different situations such as alternating loading, bending or even varying temperatures of use. Being able to understand all these different factors within material science is a process and cannot be fully understood within the timeframe this project has been executed.

Receiving information about new materials proved itself to be troublesome as well. Companies rarely want to share their new materials, findings and techniques as they either worry information could be distributed or like in most cases, are not interested in engaging with students. Persistence and patience proved themselves to be necessary qualities to have when scouting new and innovative materials.

It should be said that deciding on when to stop searching for new materials was a difficulty. The variety of options during material processing and the possibilities of developing innovative materials and fabrics are almost endless, which was why new discoveries were made multiple times during the project. It can therefore be recommended to manufacturers to keep themselves in the loop of which technologies could be a step forward in sustainable manufacturing as well as enhance a material's longevity.

Furthermore, it is undeniably an interesting process to choose a material based on a Life Cycle Assessment, yet not quite easy. The programs used for calculating the LCA outcome use collocated datasets that are woven into a database. Not every database did have every process or material needed for determining the carbon footprint of the door panels. Besides not always being presented with the right option needed that one database provided yet another did not, it became obvious that the influence one has when calculating CO_2-equivalents was low. The data seemed to be vague and non-transparent due to not being able to see where the data was retrieved from.

Further it can be discussed whether cork can be used on a bigger scale than solely on a concept. How the production of cork panels should be executed to fit the demand of Polestar's car production, or automotive manufacturers in general, is debatable. The bark of which cork is made takes nine years to fully grow back and there is an uncertainty of how much cork is required to be able to produce fitting to the demand of the market. One major advantage of using cork though would be cutting down on transports from where cork is manufactured to where all the door trims are manufactured. This lowers emissions from transportation and ensures faster supply from one production location to another.

The boundaries of the study stated that the use phase of the car, and therefore the impact the interior has on this phase, would be entirely excluded, but the importance of weight of the materials used became increasingly clear during the implementation of the thesis. Heavy-weight parts mean that an electric powered car will use more energy from the battery which in turn leads to a car needing to charge more often. More charging creates the need for more electricity which should be sourced from renewable energy sources to make a car fully climate neutral. Therefore, the use-phase was used to compare different materials with each other and support decision making.

How thick the door panel must be is an estimation, in Catia V5 (Dassault Systèmes, 2019) the buoyancy of the armrest was tested, but it is not possible to change the cork density in Catia V5 from low to the higher density of the actual used cork. This means that the weight and thus the impact in the use phase in the LCA calculations also are estimations; if the door panel shell for example could be thinner in some places, 5 mm instead of 10 mm, the weight of the door panel will be reduced.

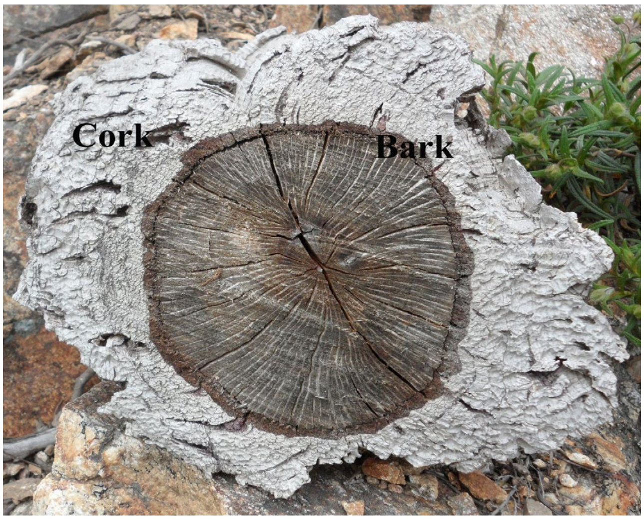

Figure 51: Section through trunk of cork oak (Wusel, 2011)

It is to mention that not all trees or tree barks can be used to produce cork. The cork oak (Figure 51) is the only tree which can be used for producing cork. Cork trees are a specific type of tree, where the dead bark can be harvested, which is done by hand and requires experience and skill. Cork is the last layer of a tree which protects all the stem and the roots from water loss, whereas the bark is the outermost layer of the wooden stem and roots and manages storing water, transporting nutrients as well as it has protective functions. Cork is essentially made from dead cells which means no harm is made to the harvested tree itself (Pediaa, 2017). Cork is neither extinct, nor endangered in any kind. Cork oaks need to be harvested to keep the trees healthy. A healthy cork oak can live up to 300 years and is never cut down but only harvested every nine years. Cork oaks do not only grow in Portugal but also in Tunisia, Algeria, the South of France as well as Italy and Morocco (Bent & Bree, 2022). It should be mentioned that the plantations are regularly looked over and new oaks are being planted to ensure that the supply is not limited but abundant which makes the material a solid sustainable choice (Bowman, 2020).

To summarise the all over work, it can be used as a framework for further material research and conceptualisation. Different materials have different properties which should be investigated further to explore the entire potential of innovative sustainable materials.

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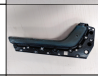
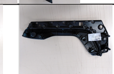
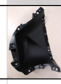
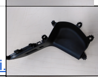
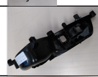
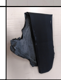
APPENDICES

Appendix 1: Bill of Materials (BOM)

Appendix 2: Cork material sheet

Appendix 3: Coffee polymer |124S

Appendix 1 - Bill of Materials

Part		Material	Weight (kg)		Part number	Supplier/manufacturer		Part image	
armrest lower part		PC/ABS	0,1122		unknown		800km		
armrest upper part		PC/ABS	0,194		2422770X		800km		
pocket		P/E MD15	0,1595		2422705X	AELXQ	800km		
upper speaker grillein		ABS	0,1278		2422704X	AELXQ	Made in China		
door shell		P/E - MD15	1,266		2422717X	AELXQ	800km		
waistrail		PC/ABS	0,2988		2422707X	AELXQ	800km		
waistrail (under)		PC/ABS	0,1251		2422706X	AELXQ	800km		
grabhandle		ABS	0,1118		2422723X (CD)	Yusei, Zhejiang China, www.yusei.			
handle (left)		PA 6- MD40	0,0736		30004597	Faurecia			
handlefastening		PA 6- GF15	0,0262			Faurecia	Shanghai 926km		
vegan leather (+foam)		Polyethylene and vegan leather	0,0724						
woven textile			0,0154						
paperlike waistrailcoating			0,0577						
leather +foam		leather and polyethylene	0,0381						
9 door fasteners		PA6- GF15	0,0372	4g/fastener					
button for decor		PA 6- MD40	0,0011						
4 metal washers		steel	0,0079						
screws		steel	0,0479						
handle screw		metal	0,0084						
handle spring		metal	0,0071						
pins for welding	läggs till doorshe	P/E MD 15	0,0073						
window button		ABS /PC PC	0,0055						
		Total weight	2,801						

Cork (high density)

General information

Ansys Name	Wood, Cork

Designation

Cork (high density)

Typical uses

Corks, stoppers, bungs for bottles, floats, lifebelts, walls, flooring, insulation, shoes, packaging, fancy goods, decoration, gaskets, road surfaces, linoleum, polishing, brake pads, vibration damping.

Included in Materials Data for Simulation	✓

Composition overview

Compositional summary

40% Suberim/27% Lignin/12% Cellulose/4% Friedelin/17% Water

Material family	Natural (wood-like)			
Base material	Wood (other: monocot, bark)			
Renewable content	100			%

Composition detail (polymers and natural materials)

Wood	100			%

Price

Price	* 23,7	-	119	SEK/kg
Price per unit volume	* 3,8e3	-	2,85e4	SEK/m^3

Physical properties

Density	160	-	240	kg/m^3
Relative density	0,14	-	0,21	
Cell type	Closed-cell			
Cells/volume	2e5	-	5e5	/mm^3
Anisotropy ratio	1,6	-	1,8	

Mechanical properties

Young's modulus	0,025	-	0,05	GPa
Specific stiffness	0,123	-	0,265	MN.m/kg
Yield strength (elastic limit)	1,1	-	2,2	MPa
Tensile strength	1	-	2,5	MPa
Specific strength	5,4	-	11,7	kN.m/kg
Elongation	20	-	70	% strain
Compressive strength	1	-	2	MPa
Compressive stress @ 25% strain	0,65	-	0,8	MPa
Compressive stress @ 50% strain	* 1,1	-	2,2	MPa
Flexural modulus	0,014	-	0,02	GPa
Flexural strength (modulus of rupture)	1	-	2,5	MPa
Shear modulus	0,004	-	0,008	GPa

Shear strength		0,55	-	1,1	MPa
Bulk modulus		0,014	-	0,02	GPa
Poisson's ratio		0,08	-	0,4	
Shape factor		2,7			
Hardness - Brinell	*	1,2	-	1,6	HB
Elastic stored energy (springs)		17,8	-	65,9	kJ/m^3
Fatigue strength at 10^7 cycles	*	0,55	-	1,1	MPa
Densification strain		0,7	-	0,8	
Work to maximum strength		20,3	-	24,8	kJ/m^3

Impact & fracture properties

Fracture toughness		0,07	-	0,1	MPa.m^0.5
Toughness (G)		0,126	-	0,311	kJ/m^2

Thermal properties

Glass temperature		77	-	102	°C
Maximum service temperature		120	-	140	°C
Minimum service temperature	*	-73	-	-23	°C
Thermal conductivity		0,04	-	0,048	W/m.°C
Specific heat capacity		1,9e3	-	2,1e3	J/kg.°C
Thermal expansion coefficient		130	-	180	µstrain/°C
Thermal shock resistance		178	-	464	°C
Thermal distortion resistance	*	2,39e-4	-	3,44e-4	MW/m

Electrical properties

Electrical resistivity	*	1e9	-	1e11	µohm.cm
Electrical conductivity	*	1,72e-9	-	1,72e-7	%IACS
Dielectric constant (relative permittivity)	*	6	-	8	
Dissipation factor (dielectric loss tangent)	*	0,02	-	0,05	
Dielectric strength (dielectric breakdown)	*	1	-	2	MV/m

Magnetic properties

Magnetic type	Non-magnetic

Optical, aesthetic and acoustic properties

Transparency	Opaque			
Acoustic velocity	344	-	525	m/s
Mechanical loss coefficient (tan delta)	0,1	-	0,3	

Healthcare & food

Food contact	No

Restricted substances risk indicators

RoHS 2 (EU) compliant grades?	✔
REACH Candidate List indicator (0-1, 1 = high risk)	0

SIN List indicator (0-1, 1 = high risk)	0

Critical materials risk

Contains >5wt% critical elements?	No

Durability

Water (fresh)	Acceptable
Water (salt)	Acceptable
Weak acids	Acceptable
Strong acids	Unacceptable
Weak alkalis	Acceptable
Strong alkalis	Unacceptable
Organic solvents	Acceptable
Oxidation at 500C	Unacceptable
UV radiation (sunlight)	Good
Flammability	Self-extinguishing

Primary production energy, CO2 and water

Embodied energy, primary production (virgin grade)		3,81	-	4,2	MJ/kg

Sources

4 MJ/kg (Hammond and Jones, 2008)

Embodied energy, primary production (typical grade)		3,81	-	4,2	MJ/kg
CO2 footprint, primary production (virgin grade)		0,192	-	0,211	kg/kg

Sources

Data reported by sources are for CO2, values were converted to CO2 footprint using the relationship: CO2 footprint = CO2 * 1.06. Relationship taken from Hammond and Jones, 2008. Note that this is only captures fuel use (i.e. not including any process related emissions). This is for the average mixture of fuels used in the UK industry.

0.19 kg/kg (Hammond and Jones, 2008)

CO2 footprint, primary production (typical grade)		0,192	-	0,211	kg/kg
Water usage	*	665	-	735	l/kg

Processing energy, CO2 footprint & water

Coarse machining energy (per unit wt removed)	*	0,544	-	0,601	MJ/kg
Coarse machining CO2 (per unit wt removed)	*	0,0408	-	0,0451	kg/kg
Fine machining energy (per unit wt removed)	*	1,16	-	1,28	MJ/kg
Fine machining CO2 (per unit wt removed)	*	0,087	-	0,0962	kg/kg
Grinding energy (per unit wt removed)	*	1,85	-	2,04	MJ/kg
Grinding CO2 (per unit wt removed)	*	0,138	-	0,153	kg/kg

Recycling and end of life

Recycle		✗			
Recycle fraction in current supply		0,1			%
Downcycle		✓			
Combust for energy recovery		✓			
Heat of combustion (net)	*	19,8	-	21,3	MJ/kg
Combustion CO2	*	1,69	-	1,78	kg/kg

Landfill	✓
Biodegrade	✓

Notes

Warning

Cork has a wide range of densities and properties.

Links

ProcessUniverse

Producers

Reference

Shape

Appendix 3: Product Data Sheet - Coffee Polymer |124S

Product Data Sheet

Coffee Polymer I124S

Revision date	16 April 2020
Page	1 of 2
Date previous version	March 22 2019
Version & language	I124S/002 - EN
Product availability	Global
Product status	Commercial

PRODUCT DATA SHEET
COFFEE POLYMER I124S

Interested in the applications of Coffee Polymers? Feel free to contact us at
www.ovdesigns.nl info@ovdesigns.nl

DESCRIPTION
Coffee Polymer I124S is a 100% biobased polymer from natural resources and 30% coffee based. Only used coffee grounds are being used in this material. Coffee Polymer I124S is a medium flow composite suitable for injection moulding.

TYPICAL PROPERTIES[1]

Physical properties	Method	Typical value
Density	Literature value	1,30 g/cm^3
Melt flow index	ISO 1133-A (210°C/2.16kg)	24 g/10 min
Melt flow index	ISO 1133-A (190°C/2.16kg)	10 g/10 min
Appearance	Visual	Coffee brown pellets
Water / moisture	Coulometric Karl-Fischer	≤ 400 ppm
Melting temperature	DSC	165°C
Glass transition temperature	DSC	55-60°C
Mechanical properties	**Method**	**Typical value**
Tensile modulus 40°C mould	ISO 527-2	4300 MPa
Tensile modulus 110°C mould	ISO 527-2	4600 MPa
Tensile strength 40°C mould	ISO 527-2	33 MPa
Tensile strength 110°C mould	ISO 527-2	32 MPa
Elongation at break 40°C mould	ISO 527-2	1%
Elongation at break 110°C mould	ISO 527-2	1%

[1] Typical properties, not to be interpreted as specifications

Processing information & Recommendations

Coffee Polymer I124S can be processed on conventional injection moulding equipment. To prevent leakage due to gas formation a lockable nozzle is recommended. To prevent or reduce the degradation of the material during processing, it is recommended to use a screw with an L/D ratio of at least 20:1 and if applicable low shear hot runners in the mould. Pre-drying of the compound is necessary.

Injection moulding processing recommendations	
Predrying	4-6 hours at 70°C
Feed zone	145°C
Compression zone	155°C
Metering zone	170°C
Nozzle	170°C
T_{melt}	150-210°C
$T_{mold, amorphous}$	20-30°C
$T_{mold, crystalline}$	90-100°C
Back pressure (Bar, specific)	50-100 bar
Screw speed	As slow as possible

Typical settings, may require optimization

Start-up and shutdown

1. Propper cleaning of the equipment is needed to prevent cross contamination.
2. Purging the system with a polyolefin or a purging compound (e.g. Dyna-purge, Clean LDPE) followed by purging with Coffee Polymer I124S is recommended.
3. Using a purging compound after completion of the run is recommended to prevent degradation or cross contamination.

After completion of the run, Coffee Polymer I124S must be removed from the whole system. Coffee Polymer I124S Can degrade into lactic acid causing corrosion of the equipment (e.g. die plates).

Designs

Product Data Sheet
Coffee Polymer

Revision date	16 April 2020
Page	2 of 2
Version & language	I124S/002 - EN

Moisture & Pre-Drying
Coffee Polymer I124S pre-drying is recommended. Drying should be done for 4-6 hours at 85°C. Drying of Coffee Polymer I124S can be performed in a desiccant hot air dryer, with a dew point of -40°C or less. Reducing the moisture content to a level less than 250ppm and preferably less than 100ppm is recommended. Predrying is in particular important prior to injection moulding, film and sheet production. Moisture causes hydrolysis of the Coffee Polymer I124S during melt processing, resulting in reduced mechanical performance in the final part.

Packaging & Storage Conditions
Coffee Polymer I124S is available in 25kg bags and in 1000kg big bags. Coffee Polymer I124S should be stored in its closed, original moisture-barrier packaging at a temperature below 50°C. Storage in direct sunlight should be avoided. The supplied Coffee Polymer I124S pellets are typically semi-crystallin unless otherwise stated.

Compostability
Composting of organic waste helps to divert organic waste from landfill or incineration. Composting is a biological process in which organic wastes are degraded by microorganisms into carbon dioxide, water and humus, a soil nutrient.
As the compostability of the end product is also dependent on the geometry of the product, it is the responsibility of the manufacturer of the end product to ensure compliance with the regulations.

Biobased content
Coffee Polymer I124S has a biobased content of 100%.

Notice Regarding Use Restrictions
Coffee Polymer I124S pre-drying is recommended. Drying should be done for 4-6 hours at 85°C. Drying of Coffee Polymer I124S can be performed in a desiccant hot air dryer, with a dew point of -40°C or less. Reducing the moisture content to a level less than 250ppm and preferably less than 100ppm is recommended. Predrying is in particular important prior to injection moulding, film and sheet production. Moisture causes hydrolysis of the Coffee Polymer I124S during melt processing, resulting in reduced mechanical performance in the final part.