Creating a framework for material selection of polymers to use in trucks

Master Thesis in Innovative and Sustainable Chemical Engineering

Ingibjörg Anna Hjartardóttir
Roshni Vijaykumar Makam

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

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Report no. E2023:137
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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SUMMARY

An in-depth analysis of the creation of a material selection framework, specifically highlighting the transition from fossil-based polymers to renewable alternatives. Volvo Group Trucks requires a sustainability-driven material selection tool that takes material properties into consideration, enabling informed choices within a shorter time frame. The data utilized for constructing the framework was obtained from structured interviews.

This material selection represents a systematic analysis that impacts product performance, expenses, and environmental repercussions. It underlines the importance of choosing polymeric materials, emphasizing the criteria used in the selection process and its contribution to achieving sustainability goals. By considering aspects like mechanical properties, cost-effectiveness, accessibility, and environmental implications, this approach can narrow down the most fitting polymeric materials for Volvo truck components. This approach symbolizes a structured material selection method, advancing sustainable practices and responsible resource utilization within the Volvo Group.

The report's structure begins with the theoretical and research methodology. Subsequently, a section dedicated to the interview findings that played an important role in shaping the material selection framework. Later in the report, there is a comprehensive explanation of the framework's structure, and its effectiveness is assessed through a dedicated case study. Finally, the discussion section involves an analysis of the case study results and an explanation of the findings.

Keywords: Material selection framework, Sustainable polymer selection,

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1 Introduction

The automotive industry has a significant influence on the climate, contributing to emissions and environmental degradation. To mitigate this impact, automobile companies can adopt a more comprehensive and sustainable approach. However, one aspect that is often overlooked is the selection of materials and products that have a positive rather than negative impact on the environment and human well-being. To effectively navigate the market of sustainable materials and work towards achieving climate targets such as reducing embodied carbon footprint, automobile companies need to take into account various certifications, labels, and declarations that have been developed to assess and classify the environmental impact of each truck. By considering these indicators, companies can make informed choices and prioritize materials that align with their sustainability goals. This holistic approach to material selection plays a vital role in promoting environmentally friendly practices within the automotive sector and working towards a more sustainable future [1].

Material selection is an essential component of the design process for physical objects. When it comes to product design, the primary objective of material selection is to balance cost and performance requirements. The systematic process of choosing the most suitable material for a particular application starts by evaluating the properties and costs of various candidate materials. George E. Dieter[2] highlights that material selection is often enhanced by employing material indexes or performance indexes that are applicable to the desired material properties. These indexes serve as helpful tools in facilitating the material selection process.

Several sustainable polymer materials can be utilized in the manufacturing of trucks, offering improved environmental performance. One example is bio-based polymers derived from renewable resources such as plants or biomass. These polymers, including bio-based polypropylene (PP), reduce dependence on fossil fuels and have a lower carbon footprint. Another option is recycled polymers obtained from post-consumer or post-industrial plastic waste. Recycled PP can be used in truck components as it reduces plastic waste and energy consumption. Additionally, biodegradable polymers, offer an environmentally friendly alternative that can reduce plastic pollution. These sustainable polymer materials contribute to greener and more eco-friendly trucks[3].

Renewable materials offer superior environmental advantages compared to fossil-based alternatives in manufacturing. They effectively reduce the carbon footprint, utilize renewable resources, minimize environmental impact, and improve waste management practices. Increasing the use of renewable content in products can significantly reduce the impact on the climate [4]. However, there is controversy surrounding the feasibility of utilizing renewable polymers in automotive applications. Companies like Volvo Trucks are uncertain about the potential cost implications of transitioning to renewable materials. To address this, it is essential to bridge the knowledge gap and provide companies with the necessary information to assess the sustainability of these materials. This requires a shift in thinking and working, considering various approaches to improve sustainability. Factors such as assessing long-term effects, adhering to regulations, and designing and producing for recyclability, including closed-loop circularity, need to be considered. This entails evaluating every chemical and material used in the product and during the production stages. By addressing these considerations, they can make informed decisions and work towards a more sustainable future in the automotive industry [5].

Volvo trucks core values are Quality, Safety, and Environmental care. They are part of the cornerstones of product development. Volvo believes quality is about continuous efforts to go beyond the expected and leave nothing to chance and they start by using superior materials and components. The current challenge is to reduce the environmental and climate impact of goods while the demand for transport continues to increase. Volvo Trucks is providing services that can help customers reduce waste for circularity [6]. Volvo is also aiming towards zero emissions and is moving in a fossil-free direction to reduce its carbon footprint [7]. The Department of Fossil-free Material Purchasing was formed in early 2022 and focuses on developing partnerships with raw material manufacturers to drive fossil-free material for current products and prepare/secure the capacity of Fossil-free materials for future AB Volvo projects. Another approach is to utilize the use of renewable energy to reduce carbon footprint in the overall process of production. Various projects and working groups within the AB Volvo team (Trucks brands like Volvo and Renault, Volvo Buses, Volvo Penta, and Volvo Construction Equipment) are presently investing their resources to create processes that do not utilize fossil-based energy to generate materials with a lower carbon footprint for their product line.

> ” Material selection encompasses the procedure of identifying the optimal material for a truck that aligns with the objective of choosing a more sustainable option, with the intention of benefiting the environment [8].”

Different materials possess unique properties such as strength, durability, and conductivity. By carefully selecting materials that align with the desired performance requirements, the functionality and longevity of the truck can be enhanced. It is cost-efficient. The choice of materials can significantly influence the overall cost of a project. By considering factors such as material availability, production processes, and life cycle costs, Volvo Group can identify cost-effective materials that meet the necessary performance standards. Lastly, it contributes to sustainability and environmental considerations. With increasing awareness of environmental issues, selecting sustainable materials is vital. By evaluating factors such as carbon footprint, recyclability, and environmental certifications, Volvo can minimize its environmental impact and contribute to a greener future. It also ensures safety and reliability. In conclusion, material selection is essential for achieving optimal product performance [9].

1.1 Purpose

This thesis aims to develop a screening tool to aid in the selection of polymer materials and to observe how the alternative material will reduce the use of fossil-based polymers, and its influence on the truck's environmental impacts. The tool will focus on narrowing down sustainable materials for future utilization and will perform specific steps to identify the most suitable material from a given list. The main emphasis of this project revolves around exploring alternatives for Polypropylene (PP). Its purpose is to assist in choosing materials like bio-polymers and recycled polymers for trucks. This tool will specifically concentrate on aspects related to design, manufacturing, cost, and environmental criteria. Additionally, it is essential to understand whether bio-polymers can be recycled as it also contains fossil fuel-based polymers. Although bio-based polymers are not currently used in automotive products, their adoption is advantageous due to their lower carbon footprint and renewable sources [10]. However, the implementation of bio-polymers in trucks and their potential for recycling present challenges that need to be understood and addressed. Material selection is a complex design process that requires accuracy in order to enhance the likelihood of success. Understanding the transition from fossil-based polymers to renewable-based and its implications for truck design, manufacturing, and costs are still in the early stages of development.

1.2 Research Questions

The objective of this thesis is to create a screening tool for material selection with the aim to assist with evaluating the transition from fossil-based to renewable-based polymers in the automotive industry. The research aims to address the following inquiries:

- Is it possible to create a screening framework for the selection of sustainable polymers, such as bio-based to be used in trucks?
    - Which renewable-based polymers comply with Volvo standards, with regards to mechanical properties, costs, and quality? Can they be recycled without contaminating the closed polymer waste stream, and thus effectively replace fossil-based for interior applications?
    - How would a transition to an increased usage of renewable content in polymers impact the carbon footprint of trucks?
- Can the results obtained from the material selection framework be considered reliable and utilized for subsequent decision-making purposes?
- Additionally, what are the hotspots for the carbon emissions throughout the different polymer's production cycles?

1.3 Limitations

Due to the nature of the project and lack of primary data, a few limitations are set and are presented in the following list.

- We limit the study to PP as this is the most used polymer in Volvo trucks
- Some of the properties and costs considered for the framework are obtained from the literature papers
- For the material selection it is limited to finding a sustainable alternative PP
- Due to the lack of necessary data to accurately calculate the manufacturing cost, assumptions are made for the case study
- Only the primary polymer composition is considered for the analysis and other components such as fillers and additives are not considered
- The LCA is performed for Cradle-to-Gate which also includes the storage time of the assembled trucks in the Volvo Warehouses until the customer collects the truck
- Primary data about the production of the polymers is not available, therefore the Ecoinvent database is used

2 Theory

2.1 Material selection

Material selection is a significant component of product design and production. The choice of materials for the truck should significantly impact the part's performance, sustainability, and overall lifecycle of the material within the truck's operation. It is a systematic procedure that takes into account the criteria such as functional needs, ecological concerns, economic issues, and production restrictions [2]. It helps in determining the functionality, durability, and environmental performance of a product. The right choice of materials can enhance product performance, reduce energy consumption, minimize waste generation, and improve recyclability. It influences factors such as strength, weight, corrosion resistance, thermal conductivity, electrical properties, and aesthetic appeal. Moreover, selecting sustainable and environmentally friendly materials can contribute to the overall sustainability goals of an organization or project [11].

It begins with the identification and prioritization of critical design criteria. Subsequently, several types of renewable polymers that resemble fossil-based PP will be narrowed down. Tools such as Ashby plots can be employed for both types of materials to aid in their selection for specific applications. When comparing the selection of renewable polymers to other materials, it is important to consider similar material properties. These properties commonly considered include tensile strength, failure strain, elastic modulus, thermal conductivity, diffusivity, density, toughness, melt behavior, and cost [8]. For this project focusing on the PP polymer, the properties taken into consideration are Density, Tensile strength, Tensile Modulus, Strain at the break, Flexural Modulus, Impact strength, Notched impact, and Cost when assessing materials for potential use in trucks.

Ashby material selection methodology is a systematic approach for choosing the most suitable polymer material for a given application. It was developed by Professor Mike Ashby and is widely used in the field of materials science and engineering. The goal of the Ashby material selection process is to identify the material that optimally balances the desired functional requirements with the constraints imposed by the application. The methodology involves several steps. The first step is to define the functional requirements of the application, such as mechanical properties, thermal stability, chemical resistance, and electrical conductivity. These requirements are essential in determining the performance criteria that the selected material must meet. Next, the material property charts developed by Ashby are utilized. These charts plot various material properties against each other, providing a visual representation of the trade-offs between different properties. For polymer materials, properties such as tensile strength, density, and cost are commonly considered [8].

Ashby charts have drawbacks, including their simplistic two-dimensional representation that oversimplifies the complex combinations of material properties. This can lead to inaccuracies in material selection by not considering the interplay between multiple properties. Additionally, these charts focus on a limited set of properties, potentially neglecting important factors for specific applications. The charts rely on average values and trends, limiting exploration of new materials. Human judgment plays a role, introducing subjectivity and inconsistency. The static nature of the charts ignores dynamic changes in material properties under varying conditions, leading to inaccuracies when conditions change. Figure 1 illustrates the primary criteria that are commonly employed in material selection, while Ashby material selection methodology considers only Durability, Adaptivity, and Low-cost factors.

Figure 1: Common criteria for Material selection

Considering these limitations, the Ashby method was not employed for this project. Accurate results necessitated the utilization of alternative tools and methods. Methods and tools provide systematic approaches to evaluate and compare different materials based on their properties, performance, and suitability. One of the fundamental methods in material selection is the use of material property databases. These databases provide a vast repository of information on the properties of a wide range of polymer materials. Material property databases enable efficient evaluation and selection of materials by providing comprehensive data [12]. In the specific context of this project, which revolves around Volvo Trucks, the relevant material properties are sourced specifically from an internal database. The Multi-Criteria Decision Analysis (MCDA) is a decision-making technique used in material selection to evaluate and compare different materials based on multiple criteria or factors chosen for the material selection framework. It helps in systematically assessing the alternatives and identifying the most suitable material for a specific application[13].

In order to identify the most appropriate material for a specific application across various fields, MCDM methods like VIKOR, AHP, and TOPSIS are utilized. These tools have been employed both individually and in combination to effectively address material selection challenges and provide optimal solutions[14]. Table 1 provides an overview of the significance and various factors associated with each method.

Table 1: Multi-Criteria Decision Analysis methods description

MCDA methods	**Principle of decision making**	**Merits**	**Demerits**
AHP	It combines subjective judgments with mathematical calculations to facilitate rational and informed decision-making processes [15]	It does not require an additional tool for criteria and weight determination [15]	Subjectivity, bias, sensitivity to small changes, complex implementation, lack of consistency, limited transparency, and difficulty in handling large decision problems [15]
VIKOR	The technique determines the optimum solution by comparing alternatives with respect to the measure of closeness to the ideal alternative. It incorporates measures of both maximization and minimization to find a compromise solution that balances multiple objectives [16]	Compromise solution, simplicity, consideration of multiple objectives, flexibility in threshold setting, and structured evaluation of alternatives [16]	It's potential for inconsistent rankings due to the compromise solution approach [16]
TOPSIS	The method utilizes distance measures to determine the overall similarity or closeness of each alternative to the ideal solution, allowing for the identification of the best option [17]	The process is quite simple and the solution procedure does not change irrespective of the number of decision criteria and alternatives [17]	The correlation between criteria are not considered in the evaluation of Euclidean distance. In addition, vector normalization may be required in solving problems that are multidimensional [17]

Considering the various grades of renewable polymer available, the most suitable approach for this project is to proceed with the utilization of the VIKOR method. This method offers advantages such as the ability to find compromise solutions, provide a ranking order of alternatives, handle multiple criteria evaluations, flexibility in application across various fields, and consideration of stakeholder preferences. It helps in making well-informed decisions by balancing conflicting criteria and accommodating the needs of different stakeholders involved in the material selection of polymers for the Trucks [18]. As a result, the VIKOR method is utilized in this framework.

3 Methodology

The methodology section of this thesis presents the systematic approach undertaken to address the research objectives. It outlines the chosen research paradigm, design, data collection methods, and data analysis techniques. By detailing these methodological choices, this section provides insight into the thoroughness and reliability of the research process, ensuring the validity of the findings and their implications.

3.1 Data gathering through Structured Interviews

To collect information on sustainable actions related to material development, around 30 structured interviews with Volvo Group employees and some polymer part suppliers were conducted. The employees at Volvo were from the Fossil free materials purchasing team, Cross-functional polymer team, Materials technology lab and testing lab. The compiled list of questions can be found in Section B in the Appendix. The interviews covered various aspects of sustainable material development, including Volvo's standard properties of PP, available resources, working groups related to material development and sustainability, greenhouse gas emissions, and cost. The progress of material development goals, achieved milestones, upcoming projects, and challenges in sustainability discussions were also discussed, along with potential solutions.

Internal discussions focused on sustainability roadmaps, greenhouse gas emissions during production, raw material sourcing, specific process steps, recycling, reusing, and refurbishing of products. The interviews explored the manufacturing process, including electricity sources and efficiency. Properties related to material selection, such as mechanical integrity and durability, were examined. Additionally, the interviewees were asked about their communications with suppliers concerning decarbonization and related goals.

The interviews with Volvo Group suppliers of PP raw materials and parts aimed to understand the different grades of raw materials supplied, including bio and renewable-based alternatives. Supplier goals towards sustainability, progress made, and accomplishments were discussed. The presence of a sustainability roadmap and its alignment with Volvo's roadmap, as well as suppliers' plans for increasing decarbonization, were addressed. Definitions of key terms related to sustainability were examined to ensure a common understanding. The suppliers' use of LCAs for their materials was discussed, including the scope of the assessments, benchmarking practices, and factors considered. Finally, the suppliers' approach to product recyclability was explored. Detailed interview questions can be found in section B in the appendix.

The structured interviews with Volvo Group employees and suppliers aim to gather significant data on sustainable material development and related subjects. This data is crucial for conducting a thorough analysis of design requirements, environmental impact, and sustainability considerations for the criteria categories defined in section 5 below. The structure of the material selection framework was set with the assistance of the data gathered from the interviews. Additionally, the interviews will provide insights into Volvo's decision-making process for part manufacturing and supplier selection, thereby enhancing understanding of their practices in these areas.

3.2 MATLAB

MATLAB is an abbreviation of "MATrix LABoratory" and is a proprietary programming language and numeric computing environment developed by MathWorks. MATLAB is widely used for various scientific and engineering applications, offering capabilities for matrix manipulations, plotting functions and data, implementing algorithms, creating user interfaces [19].

In this project, MATLAB is utilized as the primary tool for conducting calculations within the framework. Its powerful numerical computing capabilities make it suitable for handling the complex calculations involved in the material selection process.

3.3 Creating a Framework for Material Selection

The material selection process focuses on promoting sustainability and reducing environmental impacts in the production of polymers and polymer parts. In order to make informed decisions regarding material selection, several factors were considered based on the gathered information and assessments.

This process of material selection involves assessing the sustainability performance of various materials. This evaluation encompasses factors such as the environmental impacts associated with production. The outcomes of these assessments offer valuable insights into the environmental impacts of different material options. Moreover, the material selection process considers the goals and objectives of material development within the study's scope. This entails evaluating the progress made towards these goals and acknowledging achievements as well as future projects aimed at further enhancing material sustainability. By aligning material selection with the overall objectives of the Volvo Group and its suppliers, a cohesive and strategic approach to sustainable material development is pursued.

Collaboration and communication with Volvo Group Trucks Purchasing (GTP), Volvo Group Trucks Technology (GTT) and but not limiting to polymer part suppliers also play a significant role. Regular discussions are conducted to exchange information on sustainability, material properties, and the availability of alternative materials. This collaborative approach facilitates a comprehensive understanding of the available material options and enables the identification of sustainable alternatives. Based on the information gathered and the assessments performed, the material selection process ultimately aimed to prioritize materials with lower environmental impacts, good mechanical properties, durability, and high recyclability. By considering these factors holistically and aligning them with the goals of sustainable material development, the selected materials contribute to the overall efforts in reducing the environmental footprint and promoting sustainable practices in the production of PP parts [20].

The process incorporates a comprehensive methodology that considers multiple criteria to ensure an effective evaluation of the candidate materials. Four main categories are utilized: design/structure, manufacturing cost, system integration, and sustainability/environmental impact. These categories provide a framework for assessing and comparing the materials based on various factors. Figure 2 was created by incorporating elements from existing material selection frameworks while giving particular emphasis to the specific factors highlighted in this report [20].

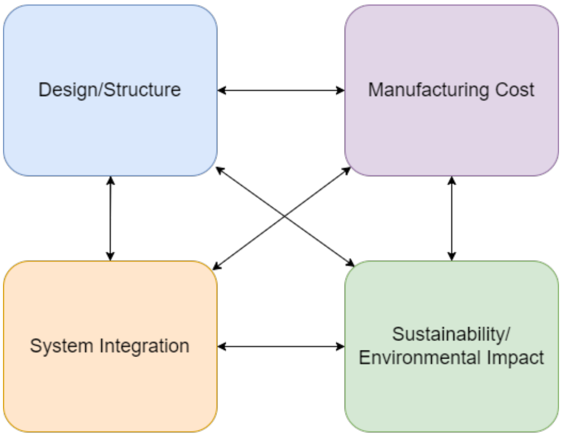

Figure 2: Categories and Interrelationships

3.3.1 Preselection/prescreening of materials

In the preliminary screening phase of polymer material selection for Volvo Trucks, a thorough assessment is conducted to examine the innate properties and attributes of potential materials. This includes validating the technical datasheets provided by suppliers. This step ensures the accuracy and reliability of the information before proceeding to further evaluation and testing. Exploring the different types of PP materials available in the market as it can have various grades, each offering different properties and characteristics. Considering factors like biocomposites, copolymer or homopolymer PP, fillers or reinforcements, and additives used in the material composition. Factors such as durability, performance, safety, aesthetics, and sustainability are considered. The goal is to identify materials that can withstand the demanding conditions of Volvo Trucks while delivering optimal functionality and visual appeal. Through careful evaluation and shortlisting, Volvo Trucks ensures that only the most suitable options are considered for further evaluation and testing. This diligent approach contributes to the high-quality and reliable designs that Volvo Trucks is renowned for.

It is important to note that the prescreening process may vary depending on the specific requirements of the truck and its components. Consulting with material experts, engineers, and suppliers can provide valuable insights and guidance throughout the process.

3.3.2 Key requirements at focus for plastic parts in trucks

Safety Requirements for Plastic Parts in Volvo Trucks

Safety is of paramount importance in Volvo Trucks, and plastic parts play a crucial role in ensuring the overall safety of the vehicles. The following requirements are vital in this regard. Plastic parts must possess high mechanical strength to withstand various loads and impacts, ensuring the structural integrity of the truck. The parts should have excellent fire resistance properties to minimize the risk of fire propagation and ensure the safety of the occupants and cargo. Plastic parts should be designed to absorb and dissipate energy during a collision, enhancing the truck's crashworthiness and protecting the driver and passengers. Plastic parts must maintain their integrity and functionality over the vehicle's lifespan, ensuring long-term safety and reliability [6].

Recyclability Requirements for Plastic Parts in Volvo Trucks

Environmental care and sustainability are key values at Volvo Trucks. Plastic parts should meet the following requirements for recyclability. Preference should be given to recyclable plastics, PP, and high-density polyethylene (HDPE), promoting a circular economy and reducing waste. Plastic parts should be designed with ease of disassembly in mind, facilitating efficient separation of different materials for recycling purposes. Clear labeling and identification, with appropriate recycling codes and instructions help streamline the recycling process. Collaboration with suppliers and recycling facilities is essential to ensure that plastic parts are designed and manufactured with recyclability in mind, allowing for efficient recycling and minimizing environmental impact [6].

Cost Efficiency Requirements for Plastic Parts in Volvo Trucks

While maintaining quality and safety, achieving cost efficiency is crucial in the production of plastics parts for Volvo Trucks. The following requirements contribute to cost optimization. Choosing cost-effective plastics materials that meet the required specifications and performance standards without compromising safety and quality. Utilizing efficient and cost-effective manufacturing processes, such as injection molding, to ensure high production volumes, minimize waste, and reduce production costs. Designing plastics parts with optimal geometry and lightweight materials, without compromising safety and performance, helps reduce fuel consumption and overall vehicle weight, leading to cost savings. Plastics parts should be designed for durability, minimizing the need for frequent replacements or repairs, thus reducing maintenance costs over the vehicle's lifespan. By adhering to these requirements, Volvo Trucks ensures that plastics parts not only align with the company's core values of quality, safety, and environmental care but also contribute to overall cost efficiency in the production and operation of their vehicles [6].

3.3.3 Design Properties

This category focuses on the specific interior requirement of the truck design and its intended functionality. Factors such as mechanical properties, chemical compatibility, thermal stability, and dimensional tolerances are considered. The goal is to select materials that meet the design specifications, ensuring that the chosen material would provide the necessary structural integrity and performance for the truck.

Table 2 illustrates the properties that have been taken into account for this particular project.

Table 2: Properties for Material selection Framework

Property	**Description**
Density	It represents the mass of a material per unit volume. Low-density materials offer advantages such as lightweight design, improved fuel efficiency, ease of handling, and reduced transportation costs. On the other hand, high-density materials may provide benefits such as increased durability, resistance to deformation, and enhanced shielding properties [21].
Tensile strength	It is the maximum stress a material can withstand before breaking under tension. High tensile strength is advantageous as it indicates the material's ability to withstand stretching or pulling forces without failure. This property is crucial in truck applications as resistance to mechanical loads is essential [22].
Tensile Modulus	In the process of material selection this allows for evaluating the stiffness and rigidity of different materials. It measures a material's resistance to deformation under tensile (pulling) forces. Higher Tensile Modulus values indicate greater stiffness, which can be advantageous in scenarios in truck components. This is important for dimensional stability [23].
Strain at the break	It is essential for assessing the ductility and resilience of material and refers to the amount of deformation a material can undergo before it fractures. It provides information about the material's ability to absorb energy and withstand sudden impacts or loads. Higher value exhibits greater ductility and is better equipped to withstand excessive stretching or bending without fracturing. This offers the necessary balance between strength, flexibility, and resistance to fracture, ensuring the longevity and reliability of truck components [24].
Flexural Modulus	It is an intensive property that is computed as the ratio of stress to strain in flexural deformation or the tendency for a material to resist bending. A higher value indicates a stiffer material that can withstand greater bending forces without experiencing excessive deflection or failure. This will help in understanding how the resistance to bending or flexural stresses is crucial for preventing deformation or failure in trucks [25].
Impact strength	It measures the material's resistance to sudden shocks or collisions. A higher impact strength indicates a material's greater ability to absorb and dissipate the energy generated during impact, thereby reducing the risk of failure or damage. This helps to minimize the risk of premature failure or damage, contributing to the overall performance and longevity of the truck. By considering this the chosen material can withstand the dynamic forces encountered in truck applications and maintain its structural integrity, even under challenging conditions [26].
Notched impact	It is also known as Izod or Charpy impact strength, measures a material's ability to resist fracture or failure when subjected to impact loads on a notched or pre-cracked specimen. It assesses the material's toughness and its ability to absorb energy at a localized stress concentration point, such as a notch or a pre-existing crack. A higher value indicates a better resistance to fracture under notched conditions, implying increased toughness and resilience. In material selection for trucks, considering this is essential for components that may experience localized stress concentrations or have inherent notches or cracks [27].
Cost	This is the economic consideration of material selection. It encompasses factors such as material availability, production costs, processing expenses, and long-term maintenance or replacement costs. Selecting a material with a favorable cost can lead to cost-effective manufacturing, reduced production expenses, and overall economic viability of the final product or structure [8].

After identifying the relevant properties to material selection and creating a short list of different PP material grades for a specific application in the truck, the VIKOR method is employed to rank and select the most suitable PP-grade material for the truck. Widely accepted and developed for multi-criteria optimization in complex systems is VIKOR which is particularly useful when dealing with conflicting criteria that have different units of measurement[28]. The VIKOR approach involves a compromise ranking based on the measure of proximity to the ideal alternative, with compromise denoting an agreement reached through mutual concessions. To address numerical challenges associated with the traditional VIKOR method, Chang[29] developed a modified version, which incorporates a novel normalization technique. The proposed comprehensive and compromising model offers advantages over traditional VIKOR as it encompasses all objectives within the MCDM process.

To begin, the VIKOR method requires the creation of a decision matrix. This matrix is structured such that each row corresponds to PP grade alternatives under consideration, denoted by 'i', while each column represents a specific criterion such as properties, denoted by 'j'. The decision matrix is then populated by inputting the performance values for each alternative-criterion combination as shown in Table 10. In this matrix, all the properties are assigned numerical values. For this specific project, the matrix comprises a total of 8 properties, denoted by 'j', representing the number of properties in the matrix. Each grade from suppliers is assigned a numerical value, denoted by 'i', representing the total number of grades available. Subsequently, each property is assigned values of "Max," "Min," and "Target." These designations indicate the level of importance for each property, with "Max" representing properties of the highest importance, "Min" for the least important, and "Target" for properties aligned with Volvo's standard fossil-based PP. The important properties of PP are considered for comparison with the result from the framework as shown in Table 3. To carry out the material selection process, the properties of PP are obtained from the Volvo database.

Table 3: PP properties [30]

Properties	Value
Tensile Strength, MPa	55.9
Flexural Modulus, MPa %	1200
Tensile Modulus, MPa	1700
Density, g/cm^3	0.91
Strain at break, %	12
Impact strength, kJ/m^2	78.7
Notched impact, kJ/m^2	54
Cost €	1.2

After considering the properties and other relevant factors, nine different grades of biocomposites and recycled PP have been carefully shortlisted from different suppliers. These selected options represent the most suitable choices based on their properties and other evaluated criteria. The properties considered during the evaluation process are presented in Case Study chapter 6.

Next ensuring a common scale for the criteria values through normalization is necessary due to the potential variations in units or scales across the criteria. Normalization facilitates meaningful comparison and aggregation of these values, enabling a comprehensive analysis. Numerous normalization techniques, such as min-max normalization or standardization, can be employed to achieve this goal. But for this project, the decision matrix is normalized by dividing each element by the sum of the respective column elements. Additionally, weights are assigned to each criterion to reflect their relative importance. These weights, denoted by 'w_j' and all properties in the matrix are assigned values based on their maximum, minimum, and target importance, ensuring that the sum of these values equals 1. Properties with minimum importance will have smaller 'w_j' values, while those with maximum importance will have larger 'w_j' values. These weighted values are presented in Table 10.

'T_j' represents target property values required. For this particular project, the target property values are set according to the Volvo standard fossil-based PP. This step is taken to assess whether the material under consideration can be a viable replacement for the fossil-based PP currently used in Volvo Trucks. Subsequently, the value of 'A_j' is computed, representing the difference between the maximum and minimum values for each property, which also incorporates the target property values. The values of each 'T_j' and 'A_j' are presented in Table 11.

Following that, 'r_{ij}' is compiled, representing the elements of the decision matrix, table 10, that pertain to alternative 'i' concerning criteria 'j' for each specific grade. The properties for each grade are presented in their respective 'r_{ij}' rows. Subsequently, 'S_i' and'R_i' are computed, and the equations (1-3) for these notations are provided below:

$$S_i = \sum_{j=1}^{n} w_j \left(1 - e^{\frac{|r_{ij}-T_{ij}|}{-A_j}}\right) \tag{1}$$

Where 'w_j' represents the weight of each criterion; 'r_{ij}' represents value for criterion 'i' and alternative 'j'; 'T_{ij}' represents Target values for criteria 'i','j'

$$R_i = Max_j \left[w_j \left(1 - e^{\frac{|r_{ij}-T_{ij}|}{-A_j}}\right]\right) \tag{2}$$

Where 'w_j' represents the weight of each criterion; 'r_{ij}' represents represents value for criterion 'i' and alternative 'j'; 'T_{ij}' represents Target values for criteria 'i','j'

After obtaining the 'S_i' and 'R_i' values, the next step involves calculating the 'Q_i' values. These values indicate the alignment of the chosen alternative with the level of risk to be taken. A conservative approach is represented by a low value of 'ν' of 0.1, an optimistic approach by a high value of 'ν' of 0.9, and a moderate approach by ' $\nu = 0.5$ '. The 'Q_i' values provide insights into how much risk is involved in selecting a particular alternative based on the chosen approach. For this project moderate approach of ν value was chosen. The equation to calculate 'Q_i' is resented below.

$$Q_i = \begin{cases} \left[\frac{R_i-R^-}{R^+-R^-}\right] & \text{if } S^+ = S^- \\ \left[\frac{S_i-S^-}{S^+-S^-}\right] & \text{if } R^+ = R^- \\ \left[\frac{S_i-S^-}{S^+-S^-}\right]\nu + \left[\frac{R_i-R^-}{R^+-R^-}\right](1-\nu) & \text{otherwise} \end{cases} \tag{3}$$

Where $S^- =$ Min S_i, $S^+ =$ Max S_i, $R^- =$ Min R_i, $R^+ =$ Max R_i, and ν is used to weigh the importance

Lastly, after obtaining the 'Q_i' values, ranks are assigned based on the values, from lowest to highest. The alternative with the highest 'Q_i' value receives the least rank, while the one with the lowest 'Q_i' value gets the highest rank. Subsequently, a compromise solution of the alternative '$Q_{A(1)}$' which is the best-ranked according to the 'Q' measure (minimum), is provided if certain conditions are met. Once the 'Q_i' values are obtained, they should be subtracted from the previous ranks to get 'X' values. Then 'X' values should be further subtracted with 'DQ' and it is calculated as follows

$$DQ = \frac{1}{(M-1)} \tag{4}$$

where M is the number of alternatives.

If the resulting value is lesser than 'DQ', then it satisfies the C1 condition which represents the Acceptable advantage. Then for the C2 condition, the alternative $A^(1)$ should also be the best ranked by S or/and R. In this way, the compromise solution of alternative 'A(1)' can be determined based on whether it meets this condition. Consequently, the alternative that achieves the highest rank and fulfills the criteria is advanced to the next stage for assessment regarding its ability to satisfy the other criteria.

In addition, it is important to explain the rationale behind selecting the alternative and provide insights into the trade-offs between criteria. This helps stakeholders understand the reasoning behind the chosen alternative and the compromises made during the decision-making process. By effectively communicating the findings, stakeholders gain a comprehensive understanding of the stability of rankings, the robustness of the selected alternative, and the underlying trade-offs between criteria.

3.3.4 Manufacturing Cost

This category evaluated the economic feasibility of using different materials. Factors such as raw material costs, processing costs, tooling expenses, and production efficiency are assessed. The aim is to identify materials that not only met the design requirements but also offered cost-effectiveness in terms of manufacturing and overall production. The manufacturing cost of the grade is based on theoretical values, as the original cost from the supplier is not available.

Firstly, the initial step involves identifying Direct Materials Costs, which entails determining the necessary quantities of raw materials to manufacture one unit of the product. Subsequently, the unit cost of each raw material is acquired from the suppliers. This material is taken into account to determine the overall cost incurred for the manufacturing process. It's important to note that the specific raw materials used in PP manufacturing can vary depending on the production process as seen in equation (5).

$$\text{Direct Materials Cost} = \text{Cost of Material} * \text{Quantity of material produced per day} \tag{5}$$

Moving on, the second step revolves around calculating Direct Labor Costs, which necessitates identifying the labor hours required for producing a single unit of the product. Later, the labor rate per hour for each type of labor involved is established as seen in equation (6).

$$\text{Direct Labor Cost} = \text{Labor rates} * \text{Working labor hours per day} \tag{6}$$

The next stage involves calculating Manufacturing overheads, which encompass various expenses such as electricity, rent, heating, maintenance, and utilities essential for the production process as seen in equation (7). Later the Allocation overheads are determined. This step involves allocating both variable costs and fixed costs across the entire manufacturing process as seen in equation (8).

$$\text{Manufacturing Overhead} = \text{Electricity} + \text{Rent} + \text{Utilities} \tag{7}$$

$$\text{Allocation Overheads} = \text{Variable Cost} + \text{Fixed Cost} \tag{8}$$

Finally, the Total Cost is calculated by summing up all the aforementioned components, including Direct Materials Costs, Direct Labor Costs, Manufacturing Costs, and Allocation Costs as seen in equation (9). This comprehensive figure represents the total expenditure incurred in producing the specified quantity of the product [31].

$$\begin{aligned}\text{Total Manufacturing Cost} &= \text{Direct Material Cost} + \text{Direct Labor Cost}\\ &\quad + \text{Manufacturing Overheard}\end{aligned} \tag{9}$$

The cost per kg provides a valuable metric for pricing decisions, cost comparison, and budgeting purposes, which allows one to evaluate the cost-effectiveness of their production processes as seen in equation (10).

$$\text{Cost per Kg} = \text{Total Manufacturing Cost/Quantity of PP produced per day in Kgs} \tag{10}$$

3.3.5 Environmental Impacts

In the material selection process, evaluating the environmental implications and sustainability performance of materials plays a crucial role. Factors such as life cycle environmental impacts, recyclability, resource depletion, energy consumption, and CO_2 eq emissions are to be assessed to select materials with minimized negative environmental impacts, promoting resource efficiency and supporting circular economy principles [32]. To compile comprehensive information regarding CO_2 eq emissions, it is most effective to focus on screening LCAs that specifically target the manufacturing phases. This approach ensures a nuanced understanding of emissions stemming from the production process.

The goal of the screening LCA in this study is to evaluate the environmental impact of shifting to more sustainable polymer alternatives in trucks. The assessment analyzes various stages of the polymer's life cycle, encompassing sourcing, processing, and application in the trucking industry to provide insights into its environmental performance. The findings is be presented section 6.6 of this Case Study. The LCA's scope is precisely delineated to facilitate a comprehensive evaluation and provide recommendations for material selection criteria that effectively reduce environmental footprints, following the ISO 14040 and 14044 standards. In the case study, a flow chart showcasing the manufacturing of a renewable material-based part is presented in 6.5, while the flow chart illustrating the manufacturing of fossil-based polypropylene parts is included in Appendix A.

One limitation encountered was obtaining primary data directly from the companies evaluated. Due to the nature of the assessment and the specific data requirements, it was necessary to rely on the information that was publicly available or provided through sustainability reports, product specifications, or other available sources. To overcome this limitation, screening LCA were performed using the available information. While the aim was to gather as much accurate and reliable data as possible, it is important to acknowledge that accessing primary data directly from the manufacturer would have provided more precise and specific information for the assessment. Lastly, for the purpose of demonstrating the use of screening LCAs the CO_2 eq emissons are only considered.

By following this approach, we aim to conduct a comprehensive evaluation of the environmental consequences linked to the usage of fossil-based polymer parts in trucks, with a particular emphasis on material selection. Considering the entire life cycle within European production sites will provide valuable information to support the transition to renewable based polymers through informed material selection. Ultimately, this approach not only promotes sustainability but also contributes significantly to reducing the environmental impact in the truck manufacturing industry.

3.3.6 System Integration

This category evaluates the compatibility of the chosen materials with the overall product system. Factors such as ease of assembly, compatibility with other components, and integration with existing manufacturing processes are taken into consideration. The primary objective is to guarantee the seamless integration of the selected material into the manufacturing and assembly procedures of the truck. This integration aims to minimize disturbances and enhance system performance, all while maintaining efficiency and productivity. Furthermore, the evaluation encompasses factors such as the availability and accessibility of resources needed for material processing, which can include molds, machinery, or specific production techniques. Additionally, Volvo Trucks acknowledges the significance of evaluating the capabilities of its suppliers. This evaluation comprises assessing whether suppliers possess the essential resources, expertise, and infrastructure to deliver the selected materials effectively. By taking into account the capabilities of suppliers, Volvo Trucks ensures the successful provision of materials in terms of quality, quantity, and timeliness. This evaluation also extends to the suppliers' capacity to support system integration, which includes any essential modifications or adjustments required for equipment or processes [33].

4 Results from interviews

4.1 Current way of working at Volvo

The current procedure for material selection involves several steps to ensure a comprehensive evaluation and decision-making process. Firstly to initiate contact with the supplier. During this first step, the focus is on determining if the company aligns with sustainability goals, particularly in terms of having a decarbonization plan in place. This ensures that potential suppliers are committed to environmentally friendly practices. Information sharing is a crucial aspect of the material selection process. It involves exchanging specific details about the supplier's processes, manufacturing data, and capacity. This information allows Volvo to assess the supplier's capabilities and determine if they can meet the required specifications. Once the necessary information is shared, testing and material data sheet verification take place at Volvo. This step involves conducting tests on the raw materials or parts provided by the supplier. The objective is to verify the accuracy and reliability of the material data sheets and ensure that the materials meet Volvo's quality standards. This is where the involvement of the polymer testing lab at Volvo comes in, by conducting tests to verify the supplier-provided TDS/MDS. Additionally, the material selection process involves identifying the suitable areas where the polymer can be used in the specific truck parts. This may involve suggestions from the supplier or collaboration with design engineers at Volvo. The goal is to determine the optimal applications for the polymer and maximize its effectiveness in enhancing the truck's performance and sustainability. Then the material lab can assess the need for additional tests that may be required. This thorough process ensures that the materials chosen align with Volvo's sustainability goals and meet the necessary quality standards for integration into their trucks.

The work procedure for addressing **new topics** involves a comprehensive approach that takes into account sustainability considerations and explores new, promising materials with lower carbon footprints. The key aspect is to ensure efficient knowledge sharing within the teams at Volvo, ensuring that the right information reaches the right person at the right time. The procedure begins with the identification of new topics that align with Volvo's sustainability goals. Research is conducted to explore innovative materials that offer lower carbon footprints and enhanced sustainability performance. The gathered information is then shared within the teams at Volvo through effective communication channels. To facilitate efficient knowledge sharing, it is important to identify the appropriate individuals or teams who need to be informed about the new topics. By ensuring that the right person receives the information at the right time, Volvo can maximize the potential for collaboration, brainstorming, and decision-making. Moreover, the procedure emphasizes the need to document and disseminate the information effectively. Allowing for easy access to the knowledge and enables teams to stay informed about the latest developments related to sustainability and new materials with lower carbon footprints.

The work procedure for evaluating **new materials** involves a meticulous approach that takes into consideration the reasons for their selection, their intended applications, and the need to target the appropriate laboratory tests. The procedure begins by understanding the rationale behind the selection of the new materials. This involves conducting thorough research and analysis to determine the specific attributes and advantages that led to their consideration. By understanding the motivations for choosing these materials, a more informed evaluation can be carried out. Next, the procedure focuses on identifying the intended applications for the new materials. This involves closely examining the requirements, specifications, and performance expectations for different components or systems where the materials are proposed to be utilized. By understanding the specific application areas, a targeted evaluation can be performed to assess the suitability and effectiveness of the materials in meeting the desired objectives. Furthermore, the procedure emphasizes the importance of targeting the right laboratory tests. This involves aligning the testing protocols with the unique characteristics and properties of the materials under evaluation. By selecting and conducting the appropriate tests, including mechanical, chemical, thermal, or other relevant analyses, a comprehensive assessment of the materials can be obtained, providing valuable insights into their performance and potential limitations.

The key words from the interviews are displayed in a word bubble in Figure 3 below.

Figure 3: Key words from interviews

4.2 Ways to improve the current way of working

In order to enhance the material selection process and ensure its effectiveness, there is a recognized need to increase communication and collaboration between different departments at Volvo, specifically involving the testing lab and design engineers from the beginning stages. By involving the testing lab early on, there can be a better understanding of the specific requirements and performance characteristics of the materials being evaluated. This early collaboration allows for more accurate and comprehensive testing protocols to be developed, ensuring that the materials undergo rigorous evaluation based on the intended application. Similarly, involving the design engineers from the start enables a deeper integration of their expertise and insights into the material selection process. Their input can provide valuable guidance in terms of the specific design considerations, functional requirements, and compatibility of the selected materials with the overall product system. By fostering this cross-departmental communication and collaboration from the beginning, Volvo can leverage the collective knowledge and expertise of different teams, resulting in a more efficient and informed material selection process. Furthermore, a comprehensive documentation can be compiled to list all plastic parts used, the corresponding materials, and the respective suppliers. This documentation will serve as a reference to obtain the necessary technical data sheets from suppliers, enabling a thorough evaluation and comparison of the materials. By investigating the reasons behind the choice of a particular polymer for a specific application, factors such as mechanical properties, chemical resistance, durability, and cost-effectiveness can be better understood.

In summary, the following list outlines ways to enhance the working process.

- Involve the testing lab early on to better understand the requirements and performance characteristics of materials being evaluated, allowing for more accurate and comprehensive testing protocols to be developed.

- Engage design engineers from the start to integrate their expertise and insights into the material selection process, considering specific design considerations, functional requirements, and compatibility with the overall product system.
- Foster cross-departmental communication and collaboration to leverage the collective knowledge and expertise of different teams, resulting in a more efficient and informed material selection process.
- Compile a comprehensive documentation listing all plastic parts used, corresponding materials, and respective suppliers for easy reference and obtaining necessary technical data sheets.
- Investigate the reasons behind the selection of specific polymers for particular applications to better understand factors such as mechanical properties, chemical resistance, durability, and cost-effectiveness.
- Emphasize sustainability considerations throughout the material selection process to align with Volvo's sustainability goals and reduce environmental impacts.

5 Framework for Material Selection

In order to help Volvo Trucks in their endeavor to choose a polymer material that is more sustainable, whether, through non-fossil-based options or recycled alternatives, the implementation of a material selection framework can be highly beneficial. By employing this framework, Volvo Trucks can make informed decisions when selecting a polymer material that aligns with its sustainability goals, promotes the principles of a circular economy, and contributes to reducing environmental impacts throughout the entire life cycle of its trucks.

In cases where an existing product is in a way being modified, the material selection process involves a hands-on approach. The primary focus was to optimize the material selection for improved sustainability without compromising the product's performance and functionality. The process began by evaluating the existing material used in the product. Its properties, environmental impacts, and availability were assessed. The alternative materials were identified and assessed for their compatibility with the product's specifications and requirements. Considerations were given to factors such as compatibility with existing manufacturing processes, cost implications, and the feasibility of incorporating the new material into the product design. Figure 4 shows a flow chart of how the developed framework works and in the following sections, a detailed description of each step can be found.

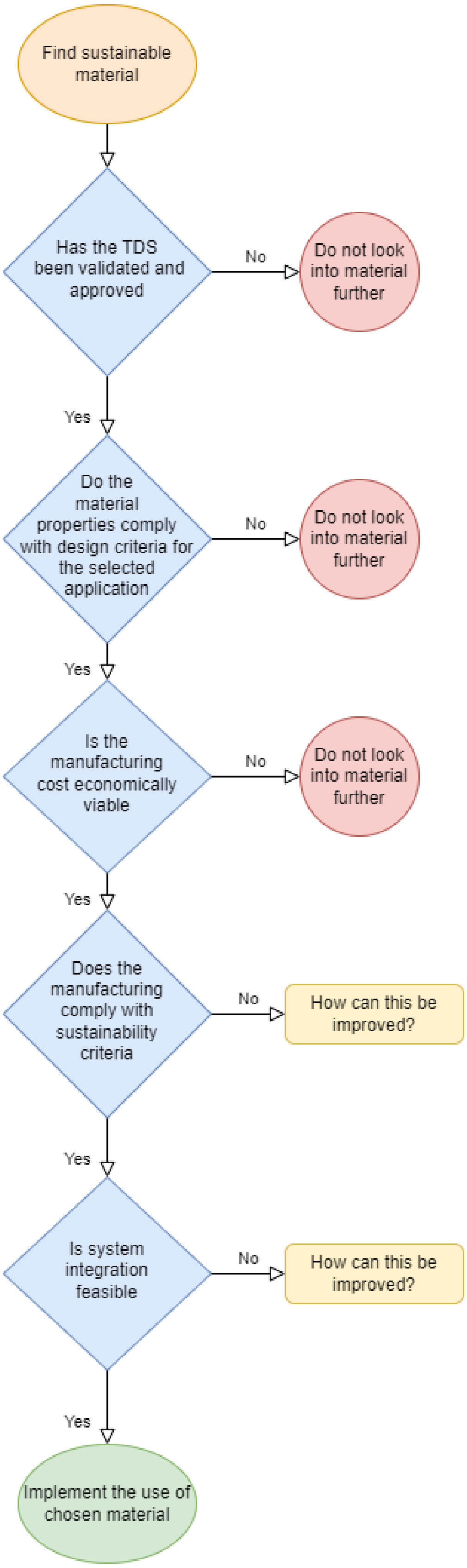

Figure 4: Flow chart of the Material Selection Framework, (TDS stands for Technical Data Sheet)

5.1 Design Properties - Criteria category

The process of material selection is a crucial aspect of the design and engineering of any part of the Volvo truck. Engineers and designers face the complex task of evaluating numerous materials for the truck, each with its unique set of properties and characteristics. The design criteria encompass various factors, including function and structural demands, market or user demands, and whether a totally new design or improvements are required. Figure 5 demonstrates the various factors taken into account within the design criteria of this material selection framework.

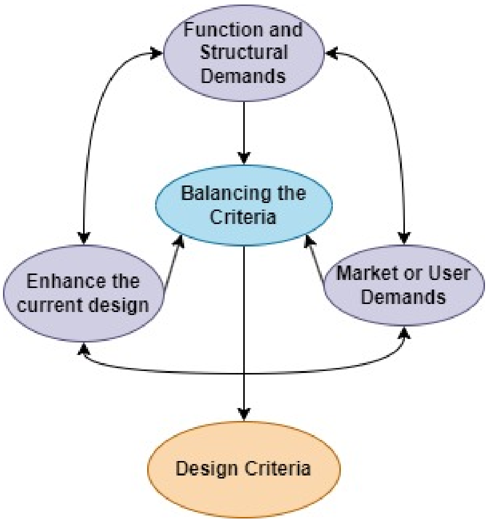

Figure 5: Factors for design criteria

Functional requirements involve conducting a comprehensive examination of the mechanical properties while ensuring structural integrity is of equal importance as materials must retain the integrity of the design over its lifespan. Apart from functionality, achieving success in design also relies on satisfying market and user demands. It is crucial to comprehend customer requirements to develop products that resonate with the intended audience. Material selections impact various aspects such as aesthetics, color options, and surface finish, all of which contribute to the overall user experience and the perceived quality of the product [34].

For a comprehensive understanding of the detailed steps and equations, refer to C.1.1. The design criteria for material selection vary depending on whether the project calls for a totally new design or improvements to an existing product. In total new designs, innovative materials are explored to achieve novel functionalities or address unique challenges that conventional materials may not satisfy. In contrast, when making improvements to existing designs, the focus is on enhancing specific performance characteristics or addressing limitations. Evaluating alternative materials with superior properties or introducing reinforcements and additives to upgrade the existing material is vital. This approach allows for iterative progress, capitalizing on the strengths of established designs while refining their weaknesses. While innovative solutions in entirely new designs can enhance competitiveness and provide distinct market advantages, it is essential to note that the scope of this project is limited to material selection for an existing part [35].

Finding the right balance between the design criteria is required for the success of material selection. Importance must weigh functional requirements against user demands, ensuring that the final product performs optimally while meeting customer expectations. At times, trade-offs are inevitable, as fulfilling stringent market demands may require compromises in other areas. The aim of this framework is to choose a material that demonstrates environmental sustainability.

5.2 Manufacturing Cost - Criteria category

By considering the manufacturing cost alongside other factors such as material properties, performance, and sustainability, engineers and designers can make well-informed decisions during the material selection process. Striking a balance between cost and desired material attributes ensures that the chosen material aligns with the project's budget, production capabilities, and market competitiveness. A comprehensive evaluation of manufacturing cost enables the selection of materials that meet functional requirements while optimizing cost-efficiency in the production process. For a comprehensive understanding of the detailed steps and equations, refer to C.2.

5.3 Environmental Impacts - Criteria category

The Screening LCAs can be performed using the following steps.

- Assessing the system boundaries and streams
- Stream setup
- Connecting process streams
- Calculation of CO_2 eq emissions
- Result analysis and interpretation
- Decision-making and optimization

The performance of screening LCAs involves multiple detailed steps. System boundaries are defined, considering both input and output streams, with a preference for primary data. Clear process stream names ensure accurate connections. The overall CO_2 eq emissions are calculated and for each manufacturing step respectively. Result analysis identifies emissions contributors, aiding in decision-making and optimization efforts to reduce the carbon footprint of the product manufacturing.

5.4 System integration - Criteria category

Collaborating with capable suppliers is crucial for Volvo Trucks to successfully integrate the chosen materials into their existing infrastructure. It helps guarantee a smooth transition and minimizes any potential disruptions or delays in production. Moreover, supplier capability plays a vital role in maintaining consistent material quality, reliability, and adherence to sustainability standards. Through a thorough assessment of supplier capabilities, Volvo Trucks ensures a reliable and efficient supply chain that can effectively support the seamless integration of selected materials into their systems, fostering a smooth transition towards sustainable practices.

Table 4: Criteria for Assessing System Integration and Supplier Capability

Criteria	**Description**
Resources and Capacity	Evaluating whether suppliers have the necessary resources, manufacturing facilities, equipment, and skilled workforce to meet material demands.
Quality Control	Assessing the supplier's quality management systems to ensure consistent and reliable material production that aligns with Volvo's standards.
Technical Expertise	Considering the supplier's technical knowledge and expertise in material manufacturing, including their understanding of industry regulations, specifications, and best practices.
Supply Chain Reliability	Evaluating the supplier's track record in terms of on-time delivery, responsiveness, and ability to maintain a stable supply chain.
Financial Stability	Assessing the supplier's financial health and stability to ensure a long-term partnership and reliable material supply.
Sustainability Practices	Examining the supplier's sustainability initiatives and practices, such as waste management, energy efficiency, and reduction of environmental impacts.
Collaboration and Communication	Considering the supplier's willingness to collaborate, provide transparent information, and engage in open communication regarding material specifications, availability, and potential challenges.

Through a careful consideration of the system integration criteria delineated in Table 4, Volvo Trucks try to ensure the harmonization of the chosen materials with both their internal infrastructure and that of their suppliers. This strategic assessment would guarantee that the materials could be effectively employed without causing substantial disruptions or necessitating extensive additional investments. By adopting this approach, Volvo Trucks can achieve a seamless transition to sustainable materials while upholding their production standards and mitigating potential impediments or complexities during the implementation phase [36].

5.5 Validation and Implementation

To conclude, the material selection process culminates in the steps of validation and implementation throughout. This final phase involves several essential activities. Firstly, researching and evaluating suitable options, conducting laboratory testing, and performing rigorous performance validation. Additionally, comprehensive assessments of environmental impacts through life cycle assessments are carried out. Following this, seamless integration into the supply chain is pursued, accompanied by feasible optimization of manufacturing processes. Finally, ongoing monitoring of performance is conducted to drive continuous improvement. The overarching objective of this meticulous process is to ensure that eco-friendly polymers not only meet the required performance standards but also significantly reduce the environmental impact associated with truck manufacturing [37].

An action plan for the above-mentioned steps is displayed in Figure 6 below.

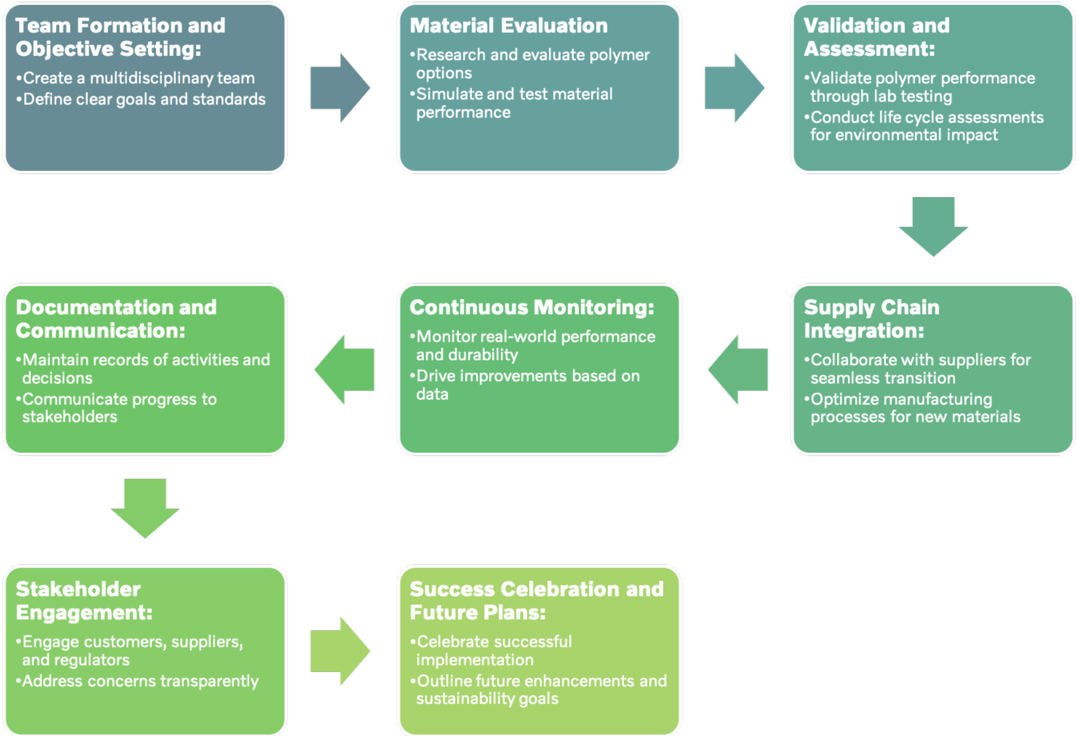

Figure 6: Action plan for validation and implementation

6 Case study - Selection of Renewable Polymer using the Framework

6.1 Case Study - Theory

6.1.1 Volvo fossil based PP - material to find substitute for

PP is a versatile thermoplastic polymer that is extensively utilized in various industries due to its wide range of applications. It is a type of plastic belonging to the polyolefin family and is produced through the polymerization process involving propylene monomers. It possesses a multitude of characteristics that contribute to its extensive usability. It exhibits exceptional resistance to a diverse range of chemicals, making it highly suitable for deployment in corrosive environments. Additionally, its low density allows for easy handling and transportation. It also showcases excellent impact resistance, making it an optimal choice for applications requiring toughness. Moreover, its malleability enables it to be molded into various shapes and forms, facilitating the production of a wide variety of products. It has impressive thermal stability, with a high melting point and heat resistance, makes it well-suited for applications exposed to elevated temperatures. Its favorable electrical insulation properties further enhance its value in electrical and electronic applications. Furthermore, PP's recyclability promotes sustainability and reduces environmental impact [38]. Figure 7 represents a basic structure of PP.

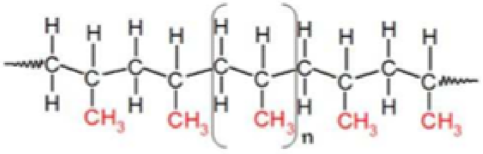

Figure 7: Polypropylene structure

Given its advantageous combination of properties, PP finds extensive usage across numerous industries such as automotive to make components. The versatility and performance of PP make it a favored choice in many manufacturing processes, contributing to the efficiency and functionality of various products [39].

The most common type is homopolymer PP, known for its high melting point, excellent chemical resistance, and impressive tensile strength. This makes it suitable for automotive parts, packaging materials, and consumer goods. Hence, this particular type of PP is chosen for this project. Another type, random copolymer PP, incorporates small amounts of comonomers, such as ethylene, to enhance clarity, impact resistance, and flexibility. It finds application in food containers, housewares, and medical components. Block copolymer PP combines the toughness of ethylene copolymers with the stiffness and heat resistance of propylene homopolymer, making it ideal for automotive bumpers, pipes, and industrial containers. High crystalline PP exhibits enhanced stiffness, strength, and dimensional stability, making it well-suited for automotive parts, furniture, and industrial components. Polypropylene can also be compounded with materials like glass fibers or minerals to create composites with improved properties. For example, glass fiber-reinforced polypropylene (PP-GF) offers increased strength and rigidity, while mineral-filled polypropylene (PP-MF) provides improved flame resistance and dimensional stability. Understanding the different types of polypropylene enables manufacturers to choose the most suitable variant for their specific applications, ensuring optimal performance and desired characteristics [39].

6.2 Prescreening

In the material selection process, the framework initiates a **prescreening** stage to narrow down the list and identify materials that are most suitable for the intended purpose, as described in Section 3.3.1.

Various material types were evaluated, and among them, biocomposite and recycled PP were selected as potential candidates due to their sustainability, aesthetics, performance, and durability. All the suppliers considered are based in Europe to take into account carbon emissions and their sustainability goals related to PP. The properties were thoroughly verified and tested within Volvo Trucks, and only after this step, the suppliers were shortlisted for further evaluation.

Table 5: Prescreening of suppliers

Supplier	A	B	C	D
Name	Stora Enso	Paper Shell	Fortum	Environment 48
Location	Sweden	Sweden	Denmark	France
Product	Biocomposite	Biocomposite	Recycled PP	Recycled PP
Aesthetics	Average	Average	Good	Good
Verified attributes	Yes	Yes	Yes	Yes

Stora Enso and Paper Shell biocomposites were shortlisted as they claim to have promising applications for the automotive industry and offer promising grades of biocomposite and have demonstrated the capacity and ability to provide bio-based material for the trucks. One of their other reasons is their commitment to sustainable practices. Specifically, three grades from the Prime family of Stora Enso were shortlisted, while Paper Shell had one grade available.

Recycled PP has emerged as a prominent candidate as it emerges as a versatile, eco-friendly, and cost-effective raw material, facilitating a greener future for the automotive industry. Processing recycled materials requires less energy and resources, resulting in reduced greenhouse gas emissions. By incorporating recycled PP into the manufacturing process, a circular economy approach is fostered, promoting the continual reuse of materials, extending their lifespan, and minimizing waste generation [40]. Fortum and Environment 48 quality of the recycled grades are acceptable according to the Volvo standards and they claim to be the leading companies in the field of recycling and sustainable solutions as they employ state-of-the-art recycling techniques and stringent quality control measures to produce recycled PP that meets industry standards and specifications. Additionally, they have demonstrated their dedication to reducing their carbon footprint and supporting a circular economy.

6.3 Introduction of alternative Grades

Stora Enso's Prime biocomposites grade is advertised specifically for injection moulding applications, with a wood-fiber-reinforced polymer matrix. They claim that the material offers the flexibility of choosing between biobased or fossil-based polymer options, with the Eco-version being an eco-friendly alternative and it can easily be colored using standard masterbatches, ensuring a wide array of visual possibilities. The Prime grades allege to excel in replacing traditional PP polymers and find ideal applications in the automotive and industrial sectors and it is their highest-performing material, providing excellent impact while maintaining stiffness and strength. With its sustainable composition and versatility, Stora Enso's Prime biocomposites pave the way for greener and more environmentally conscious manufacturing practices. They have various grades with varying fiber content ranging from 20-40% [41].

The properties of each grade in the Stora Enso biocomposites family vary, and a range was provided in the TDS. The selection of properties was on the wood content and it is important to note that the properties shown in the report are not accurate and are used primarily to test the framework for these PP alternatives. The goal is to determine if the biocomposites meet the necessary criteria and function as viable replacements for conventional PP polymers, offering a sustainable and eco-friendly solution for various applications. The 3 grades are considered and are listed in the table 6 with their respective properties. The cost of the grades is entirely speculative since it was not available.

Table 6: Stora Enso grades [41]

Grade Name	Prime 20	Prime 30	Prime 40
Fiber content, %	20%	30%	40%
Density, g/cm^3	0.96	1.015	1.07
Tensile strength, MPa	46	58	70
Tensile Modulus, MPa	2600	3550	4500
Strain at break, %	12	8	4
Flexural Modulus, MPa	2400	2900	3400
Impact strength, $\mathrm{kJ/m^2}$	80	55	30
Notched impact, $\mathrm{kJ/m^2}$	20	15	10
Cost, €	2	2.1	2.2

PaperShell states at the forefront of creating eco-friendly solutions rooted in cellulose fibers, actively leading the way in the transition towards a circular society. They claim to specialize in crafting a natural fiber composite that possesses the distinctive trait of being hydrophobic, UV, weather, and heat resistant which also demonstrates composite-like properties, which surpasses the strength of plastics and press-molded veneer, allowing for reduced weight and decreased material usage. As a result, they emerge as an alternative effectively replacing wood, plastics, fiber composites, and, in certain instances, even metal sheets across various markets and applications [42].

This grade is entirely free from fossil carbon, ensuring that during its "End of Life" stage, it only releases carbon back into the atmosphere that the tree or plant had previously absorbed. By substituting any fossil-based materials, the amount of fossil CO2 eq emissions entering the atmosphere can be effectively reduced [42]. This company offers a single grade, and all properties are derived from the TDS, in table 7 the properties are shown . The cost of the grade is entirely speculative since it was not available.

Table 7: Papershell Grades [42]

Grade Name	Papershell
Fiber content, %	Unknown
Density, g/cm^3	1.34
Tensile strength, MPa	90
Tensile Modulus, MPa	1000
Strain at break, %	1
Flexural Modulus, MPa	1680
Impact strength, kJ/m^2	11
Notched impact, kJ/m^2	3.53
Cost, €	2.3

Fortum Circo compounds claim to be crafted from recycled plastic sourced from post-consumer waste, and enhanced with carefully chosen additives to elevate both technical and environmental characteristics and to serve as a sustainable alternative to virgin plastics, these compounds allege to exhibit improved properties, including heightened stiffness, rigidity, and impact strength. Meticulously designed to fulfill the demands of various applications, Fortum compounds fulfill technical, aesthetic, and haptic requirements. While offering pre-selected material series, customization options are also available to tailor the compounds to specific needs, encompassing mechanical and environmental attributes, processability, color, and other features. With basic grades like PP, High-Density Polyethylene, and Low-Density Polyethylene granules, Fortum alleges to ensures products of uncompromised quality, making it a dependable and secure raw material fit for diverse applications [43].

Two grades of recycled PP are being evaluated for this framework, and the properties listed have been obtained from the TDS. The cost of the grades is entirely speculative since it was not available. In table 8, the grades and their respective properties are shown.

Table 8: Fortum Circo Grades [43]

Grade Name	PP 11-1000%	PP 22-1000%
Recycled content , %	100	100
Density, g/cm^3	0.92	0.91
Tensile strength, MPa	26	19
Tensile Modulus, MPa	1300	1070
Strain at break, %	8.6	6
Flexural Modulus, MPa	1300	1160
Impact strength, kJ/m^2	63	65
Notched impact, kJ/m^2	4.2	4.3
Cost, €	1.6	1.6

Environnement 48 claims primary objective is to provide raw materials sourced from recycling, thereby actively promoting the principles of the circular economy by dedicating time to the collection, sorting, and treatment of waste materials, transforming them into valuable secondary raw materials. They are limiting the amount of waste sent to landfills and the use of fossil fuels [44].

Three grades of recycled PP were considered. It is important to note that the properties shown in the report are not accurate and are used primarily to test the framework for this recycled PP alternative. The cost of the grades is entirely speculative since it was not available. In table 9, the grades and their respective properties are shown.

Table 9: Environnement 48 grades [44]

Grade Name	PP E48 1	PP E48 2	PP E48 3
Recycled content, %	Unknown	Unknown	Unknown
Density, g/cm^3	0.93	0.92	0.94
Tensile strength, MPa	26	35	25
Tensile Modulus, MPa	1250	1550	1300
Strain at break, %	17	30	15
Flexural Modulus, MPa	1050	1100	1150
Impact strength, kJ/m^2	6.5	7.5	8
Notched impact, kJ/m^2	6.9	6.9	6.9
Cost, €	1.6	1.6	1.6

6.4 Design Properties

Once the raw materials undergo prescreening, they proceed to the Design Criteria stage, where the first step involves creating a decision matrix. Table 10 represents the decision matrix for this case study. See the methodology section 3.3.3, which contains a detailed explanation of how the design criteria is formulated.

Table 10: Decision matrix of properties for VIKOR calculation

Objectives of design	Min	Max	Target	Max	Target	Max	Max	Min
Subjective weight, 'w_j'	0.1	0.13	0.13	0.14	0.09	0.16	0.16	0.09
Properties	Density	Tensile Strength	Tensile Modulus	Strain at break	Flexural Modulus	Impact Strength	Notched Impact Strength	Cost
Units	$\frac{g}{cm^3}$	MPa	MPa	%	MPa	$\frac{kJ}{m^2}$	$\frac{kJ}{m^2}$	$\frac{euro}{\text{per kg}}$
Reference PP								
Volvo PP unfilled	0.91	55.9	1700	12	1200	78.7	54	2.016
Biocomposite								
Prime 20	0.96	46	2600	12	2400	80	20	2
Prime 30	1.015	58	3550	8	2900	55	11	2.1
Prime 40	1.07	70	4500	4	3400	30	10	2.2
Papershell	1.34	90	1000	1	1680	11	3.53	2.3
Recycled								
PP 11-1000	0.92	17	1300	8.6	1300	63	4.2	1.6
PP 22-1000	0.91	19	1070	6	1160	65	4.3	1.6
PP E48 1	0.93	26	1250	17	1050	6.5	6.9	1.6
PP E48 2	0.92	35	1550	30	1100	7.5	6.9	1.6
PP E48 3	0.94	25	1300	15	1150	8	6.9	1.6

Next the values of each 'T_j' and 'A_j' are presented in Table 11 and the values of R and S: max and min are present in Table 12.

Table 11: Values of 'T_j' and 'A_j'

T_j	0.91	90	1700	30	1200	80	20	1.6
A_j	0.43	73	3500	29	2350	73.5	16.47	0.7

Table 12: Values of R and S, max and min

R and S	Values
R^+	0.091
R^-	0.007
S^+	0.569
S^-	0.042

$$DQ = \frac{1}{(9-1)} = 0.125 \tag{11}$$

Using equation 4 the value of 0.125 is obtained. In Table 13 S_i, R_i and Q_i are solved using equation 1, equation 2 and equation 3 respectively.

Table 13: Results from VIKOR calculations and evaluation

Grade Name	S_i	R_i	Q_i	Ranking	X	X-DQ	Compromised Alternative
Prime 20	0.285	0.046	0.461	7	0.303	0.178	
Prime 30	0.445	0.071	0.764	8	0.236	0.111	
Prime 40	0.569	0.091	1	9			
Papershell	0.183	0.029	0.266	6	0.195	0.070	C1 satisfied
PP 11-1000	0.088	0.014	0.087	3	0.029	-0.096	
PP 22-1000	0.122	0.019	0.150	5	0.116	-0.009	
PP E48 1	0.103	0.017	0.116	4	0.035	-0.090	
PP E48 2	0.042	0.007	0	1	0.076	-0.049	C2 satisfied
PP E48 3	0.082	0.013	0.076	2	0.011	-0.114	

As seen in Table 13 both C1 and C2 conditions are satisfied. C1 is satisfied at Rank 6, therefore the first 5 ranked grades are acceptable alternatives and C2 is satisfied for the best-ranked grade which is PP E48 2. In this framework, Environment 48 grade **PP E48 2** secures the highest rank in the Design criteria and Stora Enso's grade Prime 40 has the lowest rank. PP E48 2 also fulfills one of the key requirements for the Trucks, which is Safety. It stands out as the best alternative according to the evaluation as seen in table 13.

The detailed calculations and methodology are presented in the appendix section D.2, which includes the Matlab code for reference. Each step is thoroughly explained, providing a comprehensive understanding of the process.

To assess the framework's results and gain a comprehensive understanding, various scenarios were explored. In some scenarios, the cost property was omitted, while in others, the reference PP property was incorporated within the framework. By comparing the outcomes of these different scenarios, the framework's effectiveness and sensitivity to these factors can be better understood. Detailed explanations and findings for each scenario are provided in the Appendix section D.2.

6.5 Manufacturing Cost

The first step in the production of recycled PP involves the collection of post-consumer or post-industrial PP waste from diverse sources, including recycling centers, households, and manufacturing facilities. To achieve the desired quality and purity of recycled PP, the collected waste undergoes a rigorous cleaning process. Contaminants such as dirt, labels, adhesives, and food residue are removed meticulously. Once cleaned, the PP waste is shredded into small pieces or granules to facilitate further processing. The shredded PP is then melted and fed into an extruder, where it undergoes heating and mixing to form a homogenous melt. During this extrusion process, any remaining impurities or additives are eliminated, and the material is shaped into a continuous stream. The molten PP is forced through a die to create long strands, which are then cut into small pellets as they cool down. These recycled PP pellets, also known as regrind, are subjected to rigorous quality control measures. Physical properties such as tensile strength, melt flow index, and density are tested to ensure that the recycled PP meets the required specifications for different applications [45]. Figure 8 illustrates the common production process of Recycled PP [46].

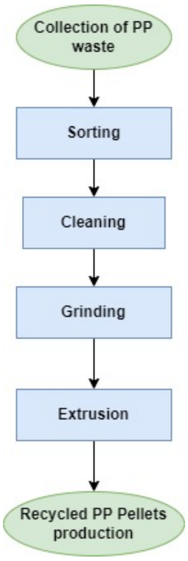

Figure 8: Process of Recycled PP

After ranking PP E48 2 as the best alternative in the Design criteria, the next step involves performing calculations under the Manufacturing Criteria to assess whether the manufacturing cost is comparable to the given cost or if it justifies the price. This evaluation will help determine the feasibility and economic viability of PP E48 2 in the manufacturing process. As the required information was not supplied, the values for these calculations are derived from research papers and other reliable sources. By using this external data, the assessments for the Manufacturing Criteria can be made with reasonable accuracy and validity.

Due to a lack of data, a substantial portion of it was sourced from literature papers. In Table 14 includes all the basic assumptions made for the manufacturing calculations.

Table 14: Basic Assumptions considered

Basic Assumptions	Values
PP material Price per ton	450 €/ton
PP material Price per kgs	0.45 €/kg
Quantity of PP produced per day in tons	6 tons/day
Quantity of PP produced per day in kgs	6000 kgs/day
Labor rates	30 €/hour
Working labor hours per day	8 hours
Electricity rate per hour	28.3 €/ kwh
Electricity price per day	226.4 €/ kw
Rent per month	45000 €
Rent per day	1500 €
Utilities per day	500 €/ kw
Fixed Cost	544.6 €
Variable Cost	547 €
Production Capacity per year	60 tons/ year €
Production Capacity per day	6 tons / day €

In-depth procedure and equations for this criterion can be found in the methodology section 3.3.4. In the first step, the Direct Materials Cost is computed using equation 5. Next, the direct labor costs are calculated using equation 6. Finally, the expenses for Manufacturing overheads and Allocation overhead incurred during the production process are determined using equations 7 and 8 respectively.

$$\textbf{Direct Materials Cost} = = \mathbf{0.45 * 6000 = 2700} \text{ €}$$

$$\textbf{Direct Labor Cost} = \mathbf{30 * 8 = 240} \text{ €}$$

$$\textbf{Manufacturing Overhead} = \mathbf{226.4 + 1500 + 500 = 2226.4} \text{ €}$$

$$\textbf{Allocation Overheads} = \mathbf{544.6 + 547 = 1091.6} \text{ €}$$

Lastly, the Total Manufacturing Cost and Cost per Kg can be calculated using equation 9 and equation 10 respectively.

$$\textbf{Total Manufacturing Cost} = \mathbf{2700 + 240 + 2226.4 + 1091.6 = 6258} \text{ €}$$

$$\textbf{Cost per Kg} = \mathbf{6258 \ / \ 6000 = 1.043} \text{ €}\mathbf{/kg}$$

The calculated cost per kg of PP E48 2 amounts to 1.043 €/kg , which closely aligns with the selling price of 1.6 €/kg. This similarity indicates that the grade meets the key requirement criteria for cost efficiency. PP E48 2 can be further evaluated against environmental criteria.

6.6 Environmental Impacts

Due to the limitations mentioned in section 3.3.5 and the lack of data regarding exact compositions and renewable content, the evaluation was limited to a comparison of the fossil based unfilled PP from Volvo to the 3 biocomposite grades from Stora Enso for demonstrative purposes.

The system boundaries encompass the entire manufacturing life cycle of the polymer parts, with a specific focus on European production sites. The functional unit chosen for assessment is the mass of parts produced (measured in kilograms of parts produced) to enable direct material comparison. The screening LCAs are conducted using OpenLCA and the EcoInvent 3.9 database, providing an overview of potential environmental impacts associated with the life cycles of the polymer parts. The results are analyzed to identify significant environmental hotspots and iterative processes is employed to refine the models, ensuring the robustness and reliability of the findings [47].

The impact assessment method selected in OpenLCA is the IPCC 2021 methodology, focusing on Global Warming Potential over a 100-year timeframe (GWP100) to quantify CO_2 eq emissions associated with the production cycles of the polymer parts. The total amount calculated is always a total of 1 kg of material/part produced, considering the density range for the bio composites is 0.96 - 1.07 g/cm^3 which is similar to pure grade fossil based PP as shown in Table 3. A summary of the results is displayed in Table 15 below.

Table 15: Results from screening LCA

Grade Name	Total emissions $[\frac{CO_{2-eq}}{\text{kg part produced}}]$	From polypropylene granulate production	From injection molding	From wood fibers
Volvo PP unfilled	2.77	1.88	0.89	0
Prime 20	2.40	1.50	0.90	0.005
Prime 30	2.22	1.32	0.90	0.007
Prime 40	2.03	1.13	0.90	0.01

The results in table 15 suggest that replacing a portion of the primary fossil polypropylene with wood fibers to create an enhanced engineered bio composite represents a significant environmental improvement when compared to using 100% fossil-based materials.

6.7 System integration

Based on the information publicly available on the company Environnement 48 and criteria for System Integration and Supplier Capability assessment in table 4, the following table table 16 shows an analysis of how Environnement 48's operations align with each criterion.

Table 16: Results from System Integration Assessment

Resources and Capacity	Environnement 48's site encompasses 21 hectares, including 26,000 m^2 of covered buildings, indicating a substantial resource base. Their various platforms for metal, scrap metal, wood, green waste, and plastic sorting showcase their manufacturing capacity. The presence of a recycling center and a dedicated logistics platform for Waste Electrical and Electronic Equipment (WEEE) further highlights their capabilities.
Quality Control	To fully assess this criterion, additional data would be required to ensure their material production aligns with high-quality standards.
Technical Expertise	Their investment in innovative processes for recycling printing waste and using advanced technologies in plastic washing, crushing, and extrusion suggests technical expertise in material manufacturing and recycling.
Supply Chain Reliability	Additional information would be needed to evaluate this aspect thoroughly.
Financial Stability	A thorough financial assessment would require more specific financial data.
Sustainability Practices	As mentioned prior in section – it was assessed that the companies demonstrates commitment to sustainable practices.
Collaboration and Communication	They have demonstrated willingness by providing Volvo with data such as TDS´s and MDS´s. Further communication would be required to assess their willingness to collaborate, provide transparent information, and engage in open communication regarding material specifications and availability.

Overall, the information in table 16 showcases their efforts in waste recycling, energy recovery, and material sorting, which aligns with some of the criteria mentioned for assessing system integration and supplier capability. However, a comprehensive assessment would require more detailed data and information from Environnement 48 to evaluate each criterion thoroughly.

6.8 Validation and Implementation

A prototype of the part made from PP E48 2 material needs to be created for conducting tests. These tests are essential in Volvo Group to determine the viability of using PP E48 2 grade in their Trucks for long-term usage. The validation process includes conducting thorough tests on the prototype, such as wear and tear, aging, and other relevant tests, to assess the suitability of this material for implementation in the Trucks. Any failures or deviations observed during testing will be carefully analyzed, and efforts will be made to address design flaws, material issues, or manufacturing defects to enhance the part's performance. Additionally, the part will be installed in the truck interiors for real-world testing, evaluating its performance under actual driving conditions and customer usage scenarios. This comprehensive testing and validation procedure is essential in ensuring that the PP E48 2 material meets the high-quality and reliability standards required for Volvo Group's Trucks.

6.9 Chosen alternative

According to the framework's evaluation, PP E48 2 emerges as the selected alternative for implementation. It surpasses other alternatives in terms of meeting the desired criteria, making it the preferred choice based on the assessment conducted. The framework demonstrates that using recycled PP is a superior choice for Volvo Trucks when considering environmental impact, design criteria, and cost factors. It highlights the benefits of incorporating recycled PP in terms of sustainability, product design, and economic feasibility for the company.

7 Discussion

To ensure environmental sustainability in the material selection, it is essential to consider two primary aspects. These aspects involve staying informed about and adhering to regulations, as well as actively pursuing sustainable practices [48].

It would enhance the material selection tool if it would also take into account additional elements such as regulatory compliance, the conservation of resources, energy usage, the presence of renewable components, and evaluations of recyclability. This analysis could to determine the material's suitability for prolonged utilization and its alignment with governmental regulations to ensure a cautious approach. The accessibility of the chosen material holds significant importance in the truck manufacturing process.

7.1 Regulations

Regulations and compliance play a crucial role in managing the environmental impacts of industrial activities, including the manufacturing of trucks. By adhering to specific guidelines and standards, companies can ensure that their operations minimize harm to the environment. Some relevant regulations and initiatives include: REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals): REACH applies to the use of chemicals in the production of automotive grade plastics. Manufacturers must comply with REACH requirements to ensure the safe use of chemicals and minimize risks to human health and the environment[49]. RoHS (Restriction of Hazardous Substances Directive): RoHS restricts the use of certain hazardous substances in electrical and electronic equipment, including components and parts used in automobiles. Manufacturers of automotive grade plastics need to comply with RoHS regulations to ensure the restriction of hazardous substances [50]. Lastly, ISO 14001: While not a regulation, ISO 14001 is an international standard for environmental management systems. Many automotive manufacturers and suppliers adopt ISO 14001 to establish and maintain effective environmental management practices, including the responsible use and disposal of automotive grade plastics [51]. Compliance with these regulations helps reduce pollution, protect natural resources, and promote sustainable practices.

Table 17: Regulations and Initiatives in Truck Manufacturing [49] [50] [51]

Regulation/ Initiative	**Description**
REACH	Applies to the use of chemicals in automotive grade plastics production. Compliance ensures safe chemical use and minimizes risks to human health and the environment.
RoHS	Restricts the use of hazardous substances in electrical and electronic equipment, including automotive components. Compliance ensures restricted substance usage.
ISO 14001	International standard for environmental management systems. Adopted by automotive manufacturers and suppliers to establish effective environmental management practices.

Conforming to regulations is paramount in ensuring environmental sustainability during material selection. Regulations serve as vital guidelines, promoting responsible practices and minimizing environmental impacts. Compliance with these regulations demonstrates a commitment to ethical and sustainable operations, mitigating pollution, and conserving natural resources.

Ensuring that the chosen materials comply with regulations helps avoid potential legal issues and supports ethical and responsible manufacturing practices. In this report, we will demonstrate the importance of adhering to specific regulations relevant to the automotive industry and material selection processes. By examining the role of regulations governing chemical usage, hazardous substance restrictions, and environmental management systems, the is to highlight their impact on promoting environmentally conscious decisions.

Furthermore, exploring how compliance with these regulations influences material choices and manufacturing processes, contributing to reduced environmental footprints in the automotive sector. Understanding the implications of adhering to regulations will enable the identification of best practices and strategies for achieving greater sustainability in material selection. By emphasizing the significance of regulations and their role in fostering environmentally responsible practices, this report aims to advocate for the integration of sustainability principles into the decision-making processes of industries. Through comprehensive analysis and discussion, we seek to underscore the benefits of regulatory compliance and the positive impact it can have on the environment, society, and the overall long-term success of automotive manufacturing [52].

7.2 List of additional environmental criteria

Depending solely on CO2e emissions may lead to less effective decisions, as it fails to encompass the complete environmental context. Certain processes release non-CO_2 greenhouse gases and pollutants with significant global warming potentials. By evaluating the location of raw material resources, opportunities for sustainable sourcing can be identified and the carbon footprint associated with material extraction and transportation can be minimized. Additionally, assessing energy consumption in the manufacturing processes enables pinpointing energy-intensive stages and exploring ways to optimize energy usage or transition to renewable energy sources. Transportation is another crucial aspect that influences CO_2 eq emissions. By considering the logistics and distance between manufacturing facilities and distribution centers, possibilities to improve transportation efficiency can be identified, potentially reducing emissions through optimized routes, alternative transportation modes, or regional sourcing strategies [47].

Another important consideration is the recyclability of materials used in truck manufacturing. Designing trucks with components that can be easily recycled at the end of their life cycle helps reduce waste and conserve resources. This includes the consideration of chemicals used in the products and in the production processes [53]. Additionally, incorporating a higher percentage of renewable content in truck manufacturing, such as bio-based or recycled materials, contributes to a more sustainable approach [54].

The criteria mentioned in table 18 are identified through active engagement with internal and external stakeholders at Volvo Trucks to gain insight into their sustainability practices, promote transparency, and encourage the adoption of environmentally conscious production methods.

Table 18: Criteria for in-depth Sustainability and Environmental Impact Assessment

Criteria	**Description**
CO_2 eq emissions	Measurement of carbon dioxide equivalent emissions throughout the manufacturing process using screening LCAs. GWP100 is used as a metric, accounting for emissions from various sources.
Resource depletion	Utilizing recycled or bio-based materials, helps minimize the consumption of finite resources like fossil fuels and raw minerals, preserving these valuable resources and lessening the environmental impact of their extraction.
Energy consumption	Implementing energy-efficient measures in the manufacturing process involves optimizing energy mixes and prioritizing the use of renewable energy sources, such as solar and wind power, while also exploring advancements in energy-saving technologies.
Recyclability	Designing truck components for easy recycling at the end of their life cycle to reduce waste and conserve resources.
Renewable content	Incorporating a higher percentage of renewable materials, such as bio-based or recycled materials, in truck manufacturing for a more sustainable approach.

7.3 Key takeaways

To achieve accurate results, obtaining more precise data is necessary. Currently, there is a significant amount of information concerning costs and properties that is unavailable for various grades. Therefore, emphasizing the importance of gathering accurate data becomes essential to ensure the reliability and accuracy of the chosen alternative from the Framework. With information gathering consistently increasing, this effort towards obtaining accurate data will play a crucial role in advancing sustainable practices.

By having a roster of sustainable materials and validating the TDS early on, Volvo Trucks can streamline the material selection process, saving time and resources. It eliminates the limitations of evaluating materials in isolation and enables a thorough analysis of their compatibility with Volvo Trucks' commitment to delivering high-quality, reliable, and environmentally conscious products.

Adopting such a framework empowers Volvo Trucks to make informed decisions based on a holistic understanding of the available sustainable materials. This approach enables Volvo Trucks to consider multiple factors such as durability, performance, safety, aesthetics, recyclability, and cost efficiency in a systematic manner. By evaluating these criteria within the framework, the most suitable material for a specific application can be identified, ensuring optimal functionality, environmental sustainability, and cost-effectiveness.

8 Conclusions

In conclusion, the technological capabilities of biocomposite manufacturers are still in the early stages and therefore their implementation in the automotive industry is still developing. Although it is a promising step in the near future. With the information gathering consistently increasing with the increasing understanding of how improvements can be made towards sustainable products. Based on the present technologies, recycled PP exhibits promising outcomes when compared to other alternatives. It demonstrates remarkable similarities with respect to Volvo standard PP in terms of properties, cost, and quality. Moreover, the recycling process for these materials is well-established and does not contaminate the waste stream.

The usefulness and reliability of the framework has been demonstrated in the case study by getting appropriate results for the alternatives provided. The results obtained from this framework indicate that recycled PP can effectively replace a portion of fossil-based PP in Volvo trucks. The findings from the screening LCAs indicate that the major environmental impact hotspots during the manufacturing of both PP parts and bio-similar parts are primarily related to the sourcing of raw materials for fossil-based PP and the energy-intensive injection molding process. The results also highlight that incorporating a higher proportion of renewable content can significantly reduce the carbon footprint of the truck by decreasing the reliance on fossil materials.

This framework was developed for material selection for sustainable polymer alternatives but would need further improvement for other material categories. An adjustment of criteria in for example the design category for specific applications. Using sustainable and renewable materials is better for the long run of the Truck industry. Regulations within Europe and outside will continue to push manufacturers to increase the circularity of their products.

9 Open Questions and Further work

Whilst testing the framework during the case study a few questions have come up and they have been summarized in the following list.

- How can this framework be modified to accommodate other materials utilized in the trucks?
- How can the user-friendliness of this material selection framework be improved?
- What additional criteria can be integrated into this framework and what other elements can be included to enhance the framework's overall effectiveness?
- How can the focus on sustainable options be strengthened?
- How can we effectively create a distinct criterion solely focused on materials among the available options within the framework?

Further work encompasses engaging in further research and investigation to delve deeper into the subject matter and incorporate practical applications for the newfound knowledge. This involves early collaboration with industry stakeholders to ensure the appropriate information is gathered on their part for a more efficient evaluation using the framework. It also entails conducting additional testing and detailed life cycle assessments in collaboration with stakeholders. Furthermore, for a more effective approach, increased communication and collaboration between different departments at Volvo, particularly involving the testing lab and design engineers from the beginning stages, is required to develop sustainable parts with the intended application in mind during the early stages of the project. Additionally, it should be examined whether the presence of additives affects the outcomes of the framework.

APPENDIX

Chapter A

Flowcharts

A.1 Flowchart for fossil based Polypropylene parts manufacturing

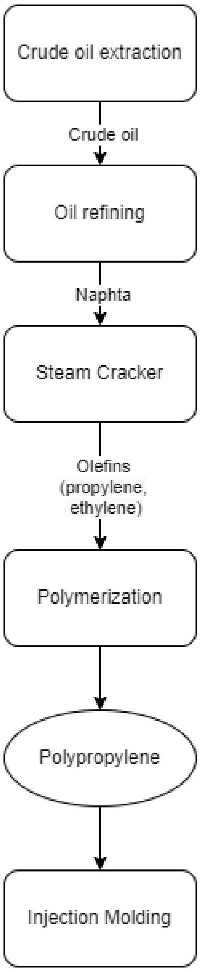

Figure A.1.1: Initial flow chart for fossil based PP parts: Depicting the sequential steps involved in the manufacturing stage

A.2 Flowchart for bio-composite manufacturing process

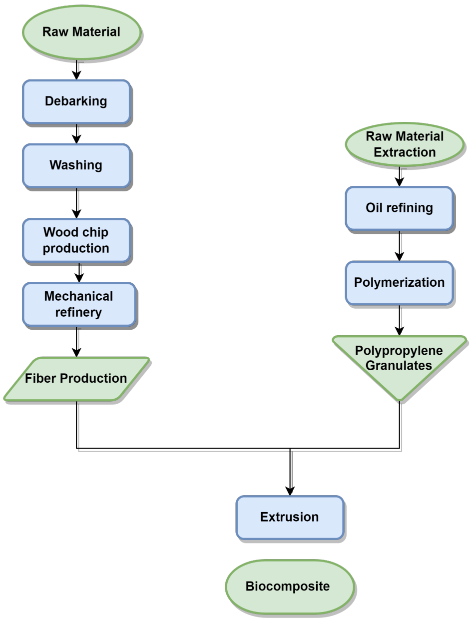

Figure A.2.1: Flowchart of bio-composite manufacturing process: Depicting the sequential steps involved in the manufacturing stage

CHAPTER B

Interview Questions

The subsequent questions posed during the interviews serve as fundamental queries. These lead to additional discussions and supplementary points that won't be elaborated upon here.

B.1 Internal interviews

What department are you from?

What is your function?

Your view on current communication within Volvo teams and Suppliers? (regarding collaboration)

What are your goals in sustainable material development in your current projects?

How is the progress of the prior mentioned goals?

Mention future projects towards sustainable material development.

How do you feel would be the most efficient way to communicate the work that you and your team are doing to the rest of Volvo?

What is the priority of information for you?

Mention specific problems that can occur in material development and solutions if applicable.

Where/who can you support at Volvo?

What sustainability definitions do you feel are unclear and have resulted in issues due to that?

B.2 Follow up internal interviews

Could you mention and describe partnerships with Volvo suppliers?

What certifications do these suppliers have?

Which of these suppliers are what you call "Green" suppliers?

Have these suppliers provided, LCA reports, CO2 eq emission graphs etc.?

B.3 Supplier interviews

What types of bio-based raw materials do you use?

What grades are being supplied to Volvo?

Is each material recyclable?

If yes, how can it be recycled?

What are your goals towards sustainability?

How is the progress of the prior mentioned goals?

What are the future plans to achieve the goals?

What certifications do you have?

Could you provide us with information on different grades of raw materials?

Can you provide property data sheets and material data sheets?

Could you provide LCA reports from your production?

How early do you start from in your LCA calculations? (if applicable)

How are you calculating green house gas (GHG) emissions?

Are the scope 1, 2 and 3 of the GHG emissions calculated?

What are the factors considered?

Chapter C

Framework

C.1 Design / Structures - Criteria category

C.1.1 VIKOR technique for Design criteria

VIKOR which stands for VlseKriterijumska Optimizacija I Kompromisno Resenje is one of the methods for making decisions about the materials based on multiple criteria, known as multi-criteria decision-making (MCDM). It was developed by Yugoslav researchers Zavadskas and Turskis. The purpose of VIKOR is to find the best accommodating solution when faced with conflicting and non-commensurable criteria in the selection of alternative materials. By considering both the best and worst values for each criterion, this method allows for the ranking and comparison of different options. The primary objective is to identify a solution that closely resembles the ideal choice while minimizing the distance to the worst possible choice. It was originally developed by Serafim Opricovic, VIKOR was created to tackle decision problems involving conflicting and non-commensurable criteria, where compromise is deemed acceptable for conflict resolution. The method assumes that the decision-maker seeks a solution that is closest to the ideal and evaluates alternatives based on all established criteria. VIKOR ranks the alternatives and determines a compromise solution that best approximates the ideal choice [55].

The VIKOR method involves several key steps. The first step is to determine the criteria relevant to the decision-making problem. These criteria should encompass the essential attributes or factors that need to be considered when evaluating alternative options. For instance, in the context of material selection, criteria such as mechanical properties, cost, availability, environmental impact, and manufacturability could be taken into account. Figure C.1.1 represents the steps of this method [18].

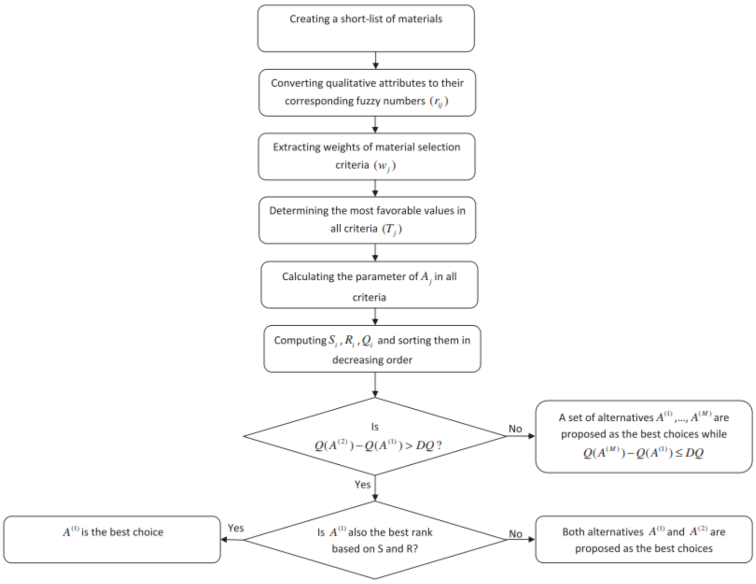

Figure C.1.1: VIKOR technique

Once the criteria have been identified, the next step is to normalize the data associated with each criterion. Normalization ensures that all criteria are on a comparable scale, facilitating meaningful comparisons. Common normalization techniques include min-max normalization, which scales the data between 0 and 1, and standardization, which transforms the data to have zero mean and unit variance [56].

Assigning appropriate weights to the criteria is crucial to reflect their relative importance. The weights capture the decision-maker's preferences and can be determined using various methods. With the criteria and weights established, T , the VIKOR values for each alternative can be calculated. These values are derived from the best and worst values of each criterion across all alternatives. The VIKOR values provide a comprehensive assessment of each alternative, taking into account both favorable and unfavorable performances.

$$T = \{T_1, T_2, .., T_j, .., T_n\} \tag{C.1}$$

Where, T represents the Target values for criteria j

Next, the S-values are calculated, representing the "closeness" of each alternative to the ideal solution. The S-values indicate the level of compromise achieved by each alternative. They are computed using a formula that considers the best and worst values for each criterion and their respective weights. This step helps decision-makers identify alternatives that strike a balance between the ideal and worst choices.

$$S_i = \sum_{j=1}^{n} w_j \left(1 - e^{\frac{|r_{ij}-T_{ij}|}{-A_j}}\right) \tag{C.2}$$

Where W_j represents the weight of each criterion; r_{ij} represents value for criterion i and alternative j; T_{ij} represents Target values for criteria i,j

Following the calculation of S-values, the R-values are determined to represent the "rank" of each alternative. The R-values gauge the overall performance of each alternative relative to others. They are calculated based on the S-values and an "optimism" coefficient, denoted as Q, which reflects the decision-maker's attitude towards risk. The R-values help in establishing a final ranking order, with the alternative possessing the highest R-value is considered the most favorable or the best compromise solution.

$$R_i = Max_j \left[w_j \left(1 - e^{\frac{|r_{ij} - T_{ij}|}{-A_j}} \right] \right) \tag{C.3}$$

Where W_j represents the weight of each criterion; r_{ij} represents represents value for criterion i and alternative j; T_{ij} represents Target values for criteria i,j

When determining the appropriate value for Q in the VIKOR method, it is crucial to consider the level of risk and the specific context of the decision problem. A lower Q value close to 0 is chosen to minimize risk, reflecting a conservative approach that focuses on avoiding unfavorable outcomes. Conversely, a higher Q value close to 1 is more suitable for reduced risk and aims to maximize potential gains, representing an optimistic approach that strives for the best possible outcomes. For a balanced approach between risk and reward, a Q value of 0.5 is used, taking into account both positive and negative aspects. It is important to acknowledge that the choice of Q is subjective and depends on personal preferences, risk tolerance, and the unique circumstances of the decision. Once the Q value is determined, it is incorporated into the calculation of R-values, which determine the overall rankings of alternatives in the VIKOR method. By combining the S-values, which represent the proximity of each alternative to the ideal solution, with the Q value, a balance is achieved between optimistic and pessimistic decision-making. Adjusting the Q value allows decision-makers to influence the trade-off between best-case and worst-case scenarios, offering flexibility to accommodate different risk attitudes. This flexibility facilitates the identification of a compromise solution that aligns with individual preferences.

$$Q_i = \begin{cases} \left[\frac{R_i - R^-}{R^+ - R^-}\right] & \text{if } S^+ = S^- \\ \left[\frac{S_i - S^-}{S^+ - S^-}\right] & \text{if } R^+ = R^- \\ \left[\frac{S_i - S^-}{S^+ - S^-}\right]\nu + \left[\frac{R_i - R^-}{R^+ - R^-}\right](1-\nu) & \text{otherwise} \end{cases} \tag{C.4}$$

Where $S^- = \text{Min } S_i$, $S^+ = \text{Max } S_i$, $R^- = \text{Min } R_i$, $R^+ = \text{Max } R_i$, and ν is used to weigh the importance

Subsequently, the results obtained from the VIKOR method are ranked by sorting the values of S, R, and Q in descending order. This ranking process allows for a systematic evaluation of the alternatives based on their respective S-values, R-values, and Q-values. By sorting the values in decreasing order, the alternatives with higher S-values, indicating greater proximity to the ideal solution, are given higher rankings. Similarly, alternatives with lower R-values, signifying better overall performance, are assigned higher rankings. The Q-values, representing the decision-maker's risk preference, are also taken into account, with alternatives having higher or lower Q-values being ranked accordingly.

In order to propose a compromise solution within the VIKOR method, the alternative $A^{(1)}$ is chosen as the top-ranked option based on the Q-value, given that it satisfies two specific conditions. Firstly, $A^{(1)}$ must have the minimum Q-value among all the alternatives under consideration. This condition indicates that the chosen alternative aligns with the decision-maker's risk attitude, be it a conservative approach with a low Q-value, an optimistic approach with a high Q-value, or a moderate approach with Q=0.5. Secondly, $A^{(1)}$ must have the maximum S-value among all the alternatives. This condition signifies that $A^{(1)}$ is the alternative that is closest to the ideal solution, taking into account the defined criteria and their respective weights.

By fulfilling these two conditions, the alternative $A^{(1)}$ emerges as the proposed compromise solution, striking a balance between the decision-maker's risk preference and the proximity to the ideal solution. It is important to note that the selection of the compromise solution relies on the specific values of S, R, and Q for each alternative. The ranking process ensures a systematic evaluation and enables the identification of the optimal alternative according to the decision-maker's preferences and the criteria employed within the VIKOR method.

- 1. Acceptable advantage: $\mathrm{Q}(\mathrm{A}^{(2)})$ - $\mathrm{Q}(\mathrm{A}^{(1)}) \geq$ DQ

  where $\mathrm{A}^{(2)}$ represents the alternative with second place in the ranking list by Q;

  DQ = 1/(M - 1)

  Where M represents the number of alternatives.

- 2. Acceptable stability in decision making:

  The alternative $\mathrm{A}^{(1)}$ should also be the best ranked by S or/and R.

A set of compromise solutions is proposed as follow, if one of the conditions is not satisfied.

- Alternatives $\mathrm{A}^{(1)}$ and $\mathrm{A}^{(2)}$ if only the C2 is not satisfied
- Alternatives $\mathrm{A}^{(1)}$, $\mathrm{A}^{(2)}$, ... , $\mathrm{A}^{(M)}$ if the C1 is not satisfied; $\mathrm{A}^{(M)}$ is determined by the relaQ($\mathrm{A}^{(M)}$) - Q($\mathrm{A}^{(1)}$) < DQ for maximum M.

The LOP (Lexicographic Order Preference) approach is a technique used in the VIKOR method to determine the best alternative among a set of options. In the VIKOR method, alternatives are evaluated based on multiple criteria, and the LOP approach helps in achieving a compromise solution.

The LOP approach follows a step-by-step procedure. First, the criteria are ranked in a lexicographic order, meaning they are prioritized based on their importance. The most critical criterion is given the highest priority, followed by the second most important criterion, and so on. Next, the alternatives are evaluated based on these ranked criteria. For each alternative, the evaluation starts with the most significant criterion. If there is a clear difference between the alternatives based on this criterion, the alternative with the better performance is selected. If there is no clear difference, the evaluation moves on to the next criterion in the lexicographic order. This process continues until a clear distinction is made between the alternatives or all the criteria have been considered.

In this method, the merit parameter "m" is calculated for each material, and a lower value of "m" indicates a better material choice. The calculation of "m" involves considering various factors and criteria that are important for the material selection process.

$$m_i = \sum_{j}^{n_l} w_j \frac{L_j}{r_{ij}} + \sum_{j}^{n_u} w_j \frac{r_{ij}}{U_j} + \sum_{j}^{n_t} w_j \left| \frac{Min(r_{ij}, T_j)}{Max(r_{ij}, T_j)} \right| i = 1, 2, 3, ..., m \tag{C.5}$$

Where L_i, U_j and T_j are lower limit, upper limit and target values of criteria respectively.

The VIKOR method offers several advantages. It allows decision-makers to handle decision problems involving conflicting and non-commensurable criteria, providing a comprehensive framework for analysis. By considering both the best and worst scenarios, the method enables a balanced decision-making process. Moreover, the VIKOR method yields a compromise solution that accommodates conflicting objectives, further enhancing its applicability in real-world decision-making scenarios.

However, the VIKOR method also has its limitations. It heavily relies on the accuracy of weight assignment, which is subjective and prone to biases. Additionally, the method assumes that compromise is acceptable, which may not always align with the preferences and objectives of decision-makers. Furthermore, the VIKOR method does not consider uncertainties and does not account for the potential risks associated with the alternatives, limiting its ability to address complex decision scenarios.

In conclusion, the VIKOR method provides decision-makers with a valuable tool for multi-criteria decision-making. By incorporating a systematic approach and considering both the best and worst performances for each criterion, the method enables a comprehensive evaluation of alternatives. While acknowledging its limitations, future research could focus on enhancing the method's robustness, addressing uncertainties, and incorporating risk analysis to further improve its applicability in real-world decision-making scenarios.

C.2 Manufacturing cost - Criteria category

Manufacturing cost plays a critical role in material selection, as it directly impacts the overall cost and profitability of the truck. Evaluating manufacturing costs when selecting materials involves considering various factors that contribute to the cost of producing the truck. By carefully assessing these factors, informed decisions can be done to optimize cost efficiency. One crucial factor to assess is the price of the polymer material itself. Different polymer materials vary in price due to factors such as availability, production processes, and market demand. Comparing the prices of these provides an initial understanding of their cost implications [57].

These costs are the expenses incurred during production and can be categorized into three main components: direct materials costs, direct labor costs, and manufacturing overhead costs. Calculating manufacturing costs involves several detailed steps.

Firstly, **Direct materials** costs are determined by identifying the polymer used in the production process, such as raw materials and components. The quantity of each material required for production is determined, and their respective costs based on purchase prices, including any additional fees like shipping or handling, are recorded. The total direct materials cost is calculated by multiplying the quantity of each material by its corresponding cost[58].

$$\textbf{Direct Materials Cost} = \textbf{(Quantity of Material 1 x Cost of Material 1)} + \textbf{(Quantity of Material n x Cost of Material n)}$$

Secondly, **Direct labor** costs are calculated by identifying the labor necessary to produce the goods or services. The number of labor hours or units required for each task or process is determined, along with the labor rate, which includes wages, salaries, benefits, and other labor-related expenses. The total direct labor cost is obtained by multiplying the labor hours or units by the labor rate[58].

$$\textbf{Direct Labor Cost} = \textbf{(Number of Labor Hours/Units for Task 1 x Labor Rate)} + \textbf{(Number of Labor Hours/Units for Task n x Labor Rate)}$$

Next, **Manufacturing overhead** costs are considered. These costs represent the indirect expenses associated with the production process, such as factory rent, utilities, equipment depreciation, maintenance, and indirect labor. The total cost of each overhead expense is determined based on actual or estimated amounts. The overhead costs are allocated to the production process using an appropriate method, such as direct labor hours, machine hours, or material costs. By multiplying the allocation rate by the allocation base (e.g., labor hours) for each product or process, the manufacturing overhead cost is calculated[58].

Figure C.2.1: Manufacturing Cost

Finally, **the Total Manufacturing costs** are calculated by summing up the total direct materials costs, direct labor costs, and manufacturing overhead costs obtained in the previous steps. Any additional relevant costs associated with manufacturing, such as packaging, shipping, or quality control expenses, are also included in the calculation. The resulting sum represents the total manufacturing costs for the goods or services produced. It is worth noting that manufacturing costs can vary depending on factors like production volume, economies of scale, and the complexity of the production process. Therefore, regular monitoring and analysis of manufacturing costs are crucial for businesses to optimize operations, enhance profitability, and make well-informed pricing decisions [58].

Total Manufacturing cost = Direct materials + Direct labor + Manufacturing overhead

Efficient material usage is another important consideration. Waste generated during the manufacturing process can significantly impact costs. Certain materials may produce more waste or require additional processing steps, increasing manufacturing costs. Selecting materials that minimize waste generation and optimize material utilization helps reduce manufacturing costs. The choice of processing techniques also affects manufacturing costs. Different polymer materials may require specific processing methods, such as extrusion, blow molding, Injection Molding, Compression Molding, or Thermoforming. Each technique incurs costs related to equipment, labor, energy, and tooling. Assessing the compatibility of materials with cost-effective processing techniques is essential. Labor costs are an integral component of manufacturing costs. Certain materials may demand skilled labor, specialized training, or extended processing time, all of which affect costs. Assessing the availability of skilled labor and associated costs is crucial when selecting materials. The need for specialized tooling and equipment is another consideration. Some materials require specific tools or equipment for processing plastic. These tools and equipment come with upfront costs and ongoing maintenance expenses. Evaluating the investment required for tooling and equipment is vital in assessing manufacturing costs.

Post-processing and finishing requirements also impact manufacturing costs. Some polymers may necessitate additional steps which contribute to the overall manufacturing cost. While cost is a significant consideration, it should be balanced with desired material properties and performance. Opting for cheaper materials without meeting performance requirements can lead to quality issues, rework, or product failures, which can incur additional costs in the long run.

Chapter D

Case Study

D.1 Manufacturing Cost

D.1.1 Matlab code for calculations

```
%given

Mpt = 450 % euro / ton (Material Price per ton)
Mpkg = 0.45 % euro / kg (Material Price per kg)
Qt =  6 % tons / day (Quantity per day in tons)
Qkg = 6000 % kg/day  (Quantity per day in kgs)
L = 30 % euro / hour (Labour rates in euro / hour)
W = 8 % hours (Working hours / day)
Er = 28.3 % euro / kwh (Electricity rate in Euro)
E = 226.4 % euro / kw (Electricity Rate)
Rm2 = 300 % euro / m^2 (Rent / m^2)
A = 150 % m^2 (Available Space)
Rmonth = 45000 % euro / month (Rent / month)
Rday = 1500 % euro / day (Rent / day)
U = 500 % euro / kw (Utilities / day)
FC = 544.6 % euro (Fixed Cost)
VC = 547 % euro (Variable COst)


DMC = Mpkg * Qkg % euro / kg (Direct Material Cost)
DLC = L*W % euro (Direct Labour Cost)
MO = E+Rday+U % euro (Material Over head)
AO = FC+VC % euro (Allocation Over head)
TMC = DMC+DLC+MO+AO % euro (Total Manifacturing Cost)


CpU = TMC / Qkg  %(Cost per Unit)
```

D.2 Design

To observe the framework's performance under various scenarios, several factors were modified to examine their impact on the results. In Case 1, the cost property was considered, but the Reference PP property was excluded from the calculations. In Case 2, the cost property was not taken into account during the calculations. Lastly, in Case 3, the reference PP, specifically the fossil component, was included in the calculations. These changes were made to analyze how the results differed across different cases.

D.2.1 Matlab code for calculations

Case 1

```
i = [1,2,3,4,5,6,7,8,9]
j=1:8;

%properties:
% density
% tensile strength
% tensile modulus
% strain at break
% flexural modulus
% impact strength
% notched impact strength
% cost

r1j = [0.96 46 2600 12 2400 80 20 2] %storaenzo prime 20
r2j = [1.015 58 3550 8 2900 55 11 2.1] %storaenzo prime 30
r3j = [1.07 70 4500 4 3400 30 10 2.2] %storaenzo prime 40
r4j = [1.34 90 1000 1 1680 11 3.53 2.3] %papershell
r5j = [0.92 17 1300 8.6 1300 63 4.2 1.6] %fortum pp 11-1000
r6j = [0.91 19 1070 6 1160 65 4.3 1.6] %fortum pp 22-1000
r7j = [0.93 26 1250 17 1050 6.5 6.9 1.6] %E48 1
r8j = [0.92 35 1550 30 1100 7.5 6.9 1.6] %E48 2
r9j = [0.94 25 1300 15 1150 8 6.9 1.6] %E48 3

% Tj ideal values
Tj = [0.91 90 1700 30 1200 80 20 1.6]

% wj weighing
wj = [0.1 0.13 0.13 0.14 0.09 0.16 0.16 0.09]

Aj = [0.43 73 3500 29 2350 73.5 16.47 0.7]

S1 = sum(wj*(1-exp((abs(r1j-Tj))/(-Aj))), j)
S2 = sum(wj*(1-exp((abs(r2j-Tj))/(-Aj))), j)
S3 = sum(wj*(1-exp((abs(r3j-Tj))/(-Aj))), j)
S4 = sum(wj*(1-exp((abs(r4j-Tj))/(-Aj))), j)
S5 = sum(wj*(1-exp((abs(r5j-Tj))/(-Aj))), j)
S6 = sum(wj*(1-exp((abs(r6j-Tj))/(-Aj))), j)
S7 = sum(wj*(1-exp((abs(r7j-Tj))/(-Aj))), j)
S8 = sum(wj*(1-exp((abs(r8j-Tj))/(-Aj))), j)
S9 = sum(wj*(1-exp((abs(r9j-Tj))/(-Aj))), j)

R1 = max(wj*(1-exp((abs(r1j-Tj))/(-Aj))))
R2 = max(wj*(1-exp((abs(r2j-Tj))/(-Aj))))
R3 = max(wj*(1-exp((abs(r3j-Tj))/(-Aj))))
```

```
R4 = max(wj*(1-exp((abs(r4j-Tj))/(-Aj))))
R5 = max(wj*(1-exp((abs(r5j-Tj))/(-Aj))))
R6 = max(wj*(1-exp((abs(r6j-Tj))/(-Aj))))
R7 = max(wj*(1-exp((abs(r7j-Tj))/(-Aj))))
R8 = max(wj*(1-exp((abs(r8j-Tj))/(-Aj))))
R9 = max(wj*(1-exp((abs(r9j-Tj))/(-Aj))))

% Create tables with chosen results
S_resultsTable = table(S1, S2, S3, S4, S5, S6, S7, S8, S9);
R_resultsTable = table(R1, R2, R3, R4, R5, R6, R7, R8, R9);

% Display the tables
disp(S_resultsTable);
disp(R_resultsTable);

% v is ranging from 0-1 so we choose 0.5
v = 0.5

Q1 = ((S1-S8)/(S3-S8))*v+((R1-R8)/(R3-R8))*(1-v)
Q2 = ((S2-S8)/(S3-S8))*v+((R2-R8)/(R3-R8))*(1-v)
Q3 = ((S3-S8)/(S3-S8))*v+((R3-R8)/(R3-R8))*(1-v)
Q4 = ((S4-S8)/(S3-S8))*v+((R4-R8)/(R3-R8))*(1-v)
Q5 = ((S5-S8)/(S3-S8))*v+((R5-R8)/(R3-R8))*(1-v)
Q6 = ((S6-S8)/(S3-S8))*v+((R6-R8)/(R3-R8))*(1-v)
Q7 = ((S7-S8)/(S3-S8))*v+((R7-R8)/(R3-R8))*(1-v)
Q8 = ((S8-S8)/(S3-S8))*v+((R8-R8)/(R3-R8))*(1-v)
Q9 = ((S9-S8)/(S3-S8))*v+((R9-R8)/(R3-R8))*(1-v)

% Create a table with final results
Q_resultsTable = table(Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9);
disp(Q_resultsTable);
```

In Case 1, among all the grades, PP E48 2 exhibited properties most closely resembling the target properties, which were those of the reference Volvo PP.

Case 2

```
i = [1,2,3,4,5,6,7,8,9]
j=1:8;

% HERE the cost property is not included in the calculations

%properties:
% density
% tensile strength
% tensile modulus
% strain at break
% flexural modulus
% impact strength
% notched impact strength

r1j = [0.96 46 2600 12 2400 80 20] %storaenzo prime 20
r2j = [1.015 58 3550 8 2900 55 11] %storaenzo prime 30
```

```
r3j = [1.07 70 4500 4 3400 30 10] %storaenzo prime 40
r4j = [1.34 90 1000 1 1680 11 3.53] %papershell
r5j = [0.92 17 1300 8.6 1300 63 4.2] %fortum pp 11-1000
r6j = [0.91 19 1070 6 1160 65 4.3] %fortum pp 22-1000
r7j = [0.93 26 1250 17 1050 6.5 6.9] %E48 1
r8j = [0.92 35 1550 30 1100 7.5 6.9] %E48 2
r9j = [0.94 25 1300 15 1150 8 6.9] %E48 3

% Tj ideal values
Tj = [0.91 90 1700 30 1200 80 20]

% wj weighing
wj = [0.11 0.16 0.14 0.15 0.1 0.17 0.17]

Aj = [0.43 73 3500 29 2350 73.5 16.47]

S1 = sum(wj*(1-exp((abs(r1j-Tj))/(-Aj))), j)
S2 = sum(wj*(1-exp((abs(r2j-Tj))/(-Aj))), j)
S3 = sum(wj*(1-exp((abs(r3j-Tj))/(-Aj))), j)
S4 = sum(wj*(1-exp((abs(r4j-Tj))/(-Aj))), j)
S5 = sum(wj*(1-exp((abs(r5j-Tj))/(-Aj))), j)
S6 = sum(wj*(1-exp((abs(r6j-Tj))/(-Aj))), j)
S7 = sum(wj*(1-exp((abs(r7j-Tj))/(-Aj))), j)
S8 = sum(wj*(1-exp((abs(r8j-Tj))/(-Aj))), j)
S9 = sum(wj*(1-exp((abs(r9j-Tj))/(-Aj))), j)

R1 = max(wj*(1-exp((abs(r1j-Tj))/(-Aj))))
R2 = max(wj*(1-exp((abs(r2j-Tj))/(-Aj))))
R3 = max(wj*(1-exp((abs(r3j-Tj))/(-Aj))))
R4 = max(wj*(1-exp((abs(r4j-Tj))/(-Aj))))
R5 = max(wj*(1-exp((abs(r5j-Tj))/(-Aj))))
R6 = max(wj*(1-exp((abs(r6j-Tj))/(-Aj))))
R7 = max(wj*(1-exp((abs(r7j-Tj))/(-Aj))))
R8 = max(wj*(1-exp((abs(r8j-Tj))/(-Aj))))
R9 = max(wj*(1-exp((abs(r9j-Tj))/(-Aj))))

% Create tables with chosen results
S_resultsTable = table(S1, S2, S3, S4, S5, S6, S7, S8, S9);
R_resultsTable = table(R1, R2, R3, R4, R5, R6, R7, R8, R9);

% Display the tables
disp(S_resultsTable);
disp(R_resultsTable);

% v is ranging from 0-1 so we choose 0.5
v = 0.5

Q1 = ((S1-S8)/(S3-S8))*v+((R1-R8)/(R3-R8))*(1-v)
Q2 = ((S2-S8)/(S3-S8))*v+((R2-R8)/(R3-R8))*(1-v)
Q3 = ((S3-S8)/(S3-S8))*v+((R3-R8)/(R3-R8))*(1-v)
Q4 = ((S4-S8)/(S3-S8))*v+((R4-R8)/(R3-R8))*(1-v)
```

```
Q5 = ((S5-S8)/(S3-S8))*v+((R5-R8)/(R3-R8))*(1-v)
Q6 = ((S6-S8)/(S3-S8))*v+((R6-R8)/(R3-R8))*(1-v)
Q7 = ((S7-S8)/(S3-S8))*v+((R7-R8)/(R3-R8))*(1-v)
Q8 = ((S8-S8)/(S3-S8))*v+((R8-R8)/(R3-R8))*(1-v)
Q9 = ((S9-S8)/(S3-S8))*v+((R9-R8)/(R3-R8))*(1-v)

% Create a table with final results
Q_resultsTable = table(Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9);
disp(Q_resultsTable);
```

In Case 2, even without factoring in the cost property, PP E48 2 grade remained the result. This indicates that the cost of the grades held relatively less significance in the calculation.

Case 3

```
i = [1,2,3,4,5,6,7,8,9,10]
j=1:8;

% HERE the reference PP the fossil IS included in the calculations

%properties:
% density
% tensile strength
% tensile modulus
% strain at break
% flexural modulus
% impact strength
% notched impact strength
% cost

r1j = [0.96 46 2600 12 2400 80 20 2] %storaenzo prime 20
r2j = [1.015 58 3550 8 2900 55 11 2.1] %storaenzo prime 30
r3j = [1.07 70 4500 4 3400 30 10 2.2] %storaenzo prime 40
r4j = [1.34 90 1000 1 1680 11 3.53 2.3] %papershell
r5j = [0.92 17 1300 8.6 1300 63 4.2 1.6] %fortum pp 11-1000
r6j = [0.91 19 1070 6 1160 65 4.3 1.6] %fortum pp 22-1000
r7j = [0.93 26 1250 17 1050 6.5 6.9 1.6] %E48 1
r8j = [0.92 35 1550 30 1100 7.5 6.9 1.6] %E48 2
r9j = [0.94 25 1300 15 1150 8 6.9 1.6] %E48 3
r10j = [0.91 55.9 1700 12 1200 78.7 54 2.016]

% Tj ideal values
Tj = [0.91 90 1700 30 1200 80 54 1.6]

% wj weighing
wj = [0.1 0.13 0.13 0.14 0.09 0.16 0.16 0.09]

Aj = [0.43 73 3500 29 2350 73.5 50.47 0.7]

S1 = sum(wj*(1-exp((abs(r1j-Tj))/(-Aj))), j)
S2 = sum(wj*(1-exp((abs(r2j-Tj))/(-Aj))), j)
S3 = sum(wj*(1-exp((abs(r3j-Tj))/(-Aj))), j)
```

```
S4 = sum(wj*(1-exp((abs(r4j-Tj))/(-Aj))), j)
S5 = sum(wj*(1-exp((abs(r5j-Tj))/(-Aj))), j)
S6 = sum(wj*(1-exp((abs(r6j-Tj))/(-Aj))), j)
S7 = sum(wj*(1-exp((abs(r7j-Tj))/(-Aj))), j)
S8 = sum(wj*(1-exp((abs(r8j-Tj))/(-Aj))), j)
S9 = sum(wj*(1-exp((abs(r9j-Tj))/(-Aj))), j)
S10 = sum(wj*(1-exp((abs(r10j-Tj))/(-Aj))), j)

R1 = max(wj*(1-exp((abs(r1j-Tj))/(-Aj))))
R2 = max(wj*(1-exp((abs(r2j-Tj))/(-Aj))))
R3 = max(wj*(1-exp((abs(r3j-Tj))/(-Aj))))
R4 = max(wj*(1-exp((abs(r4j-Tj))/(-Aj))))
R5 = max(wj*(1-exp((abs(r5j-Tj))/(-Aj))))
R6 = max(wj*(1-exp((abs(r6j-Tj))/(-Aj))))
R7 = max(wj*(1-exp((abs(r7j-Tj))/(-Aj))))
R8 = max(wj*(1-exp((abs(r8j-Tj))/(-Aj))))
R9 = max(wj*(1-exp((abs(r9j-Tj))/(-Aj))))
R10 = max(wj*(1-exp((abs(r10j-Tj))/(-Aj))))

% Create tables with chosen results
S_resultsTable = table(S1, S2, S3, S4, S5, S6, S7, S8, S9, S10);
R_resultsTable = table(R1, R2, R3, R4, R5, R6, R7, R8, R9, R10);

% Display the tables
disp(S_resultsTable);
disp(R_resultsTable);

% v is ranging from 0-1 so we choose 0.5
v = 0.5

Q1 = ((S1-S10)/(S3-S10))*v+((R1-R10)/(R3-R10))*(1-v)
Q2 = ((S2-S10)/(S3-S10))*v+((R2-R10)/(R3-R10))*(1-v)
Q3 = ((S3-S10)/(S3-S10))*v+((R3-R10)/(R3-R10))*(1-v)
Q4 = ((S4-S10)/(S3-S10))*v+((R4-R10)/(R3-R10))*(1-v)
Q5 = ((S5-S10)/(S3-S10))*v+((R5-R10)/(R3-R10))*(1-v)
Q6 = ((S6-S10)/(S3-S10))*v+((R6-R10)/(R3-R10))*(1-v)
Q7 = ((S7-S10)/(S3-S10))*v+((R7-R10)/(R3-R10))*(1-v)
Q8 = ((S8-S10)/(S3-S10))*v+((R8-R10)/(R3-R10))*(1-v)
Q9 = ((S9-S10)/(S3-S10))*v+((R9-R10)/(R3-R10))*(1-v)
Q10 = ((S10-S10)/(S3-S10))*v+((R10-R10)/(R3-R10))*(1-v)

%{ Create a table with final results
Q_resultsTable = table(Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9, Q10);
disp(Q_resultsTable); }
```

In Case 3, considering the reference Volvo PP, the outcome remained the same grade. This underscores the strong influence of target properties on the final results.

D.3 Environmental Impact

Base case: Pure PP part

Pure PP, injection molding The LCA results for the entire process shows that around **2.77 kg** CO_{2-eq} are emitted per 1 kg of PP part produced. With the primary polypropylene granulate production contributing to **1.88 kg** CO_{2-eq} per 1 kg of PP part produced.

Bio composites To demonstrate the % of the impact coming from the wood fibers in the entire production the following equation is used.

$$\%_{\text{impact from wood fibers}} = \frac{kgCO_{2-eq} \text{ from wood fiber production}}{kgCO_{2-eq} \text{ from entire process}} x100\% \tag{D.1}$$

Bio composite with 80 % primary PP and 20 % wood fibers This means using less of primary PP according to the % of wood fibers added. The emissions of the wood fibers are additionally calculated. The LCA results for the entire process shows that around **2.40 kg** CO_{2-eq} are emitted per 1 kg of bio composite produced. With the primary polypropylene granulate production contributing to **1.50 kg** CO_{2-eq} per 1 kg of bio composite produced. From equation D.1 we get 0.21% of the entire impact from the wood fibers.

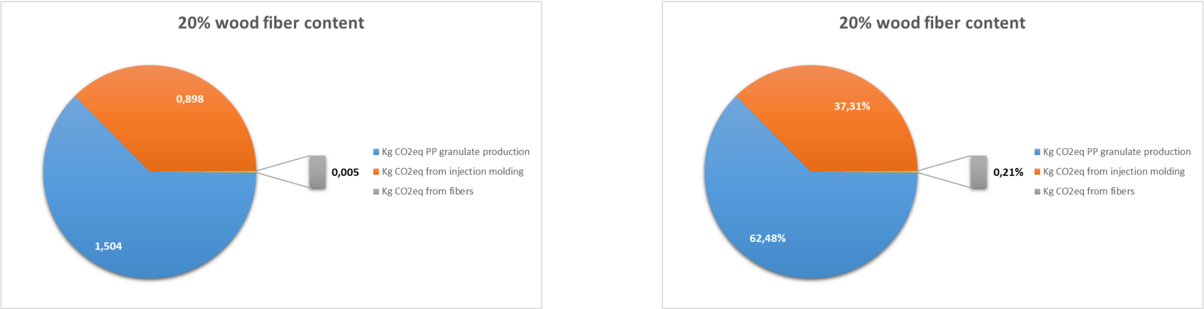

Figure D.3.1: LCA results for 20% wood fiber content

Bio composite with 70 % primary PP and 30 % wood fibers This means using less of primary PP according to the % of wood fibers added. The emissions of the wood fibers are additionally calculated. The LCA results for the entire process shows that around **2.22 kg** CO_{2-eq} are emitted per 1 kg of bio composite produced. With the primary polypropylene granulate production contributing to **1.32 kg** CO_{2-eq} per 1 kg of bio composite produced. From equation D.1 we get 0.34% of the entire impact from the wood fibers.

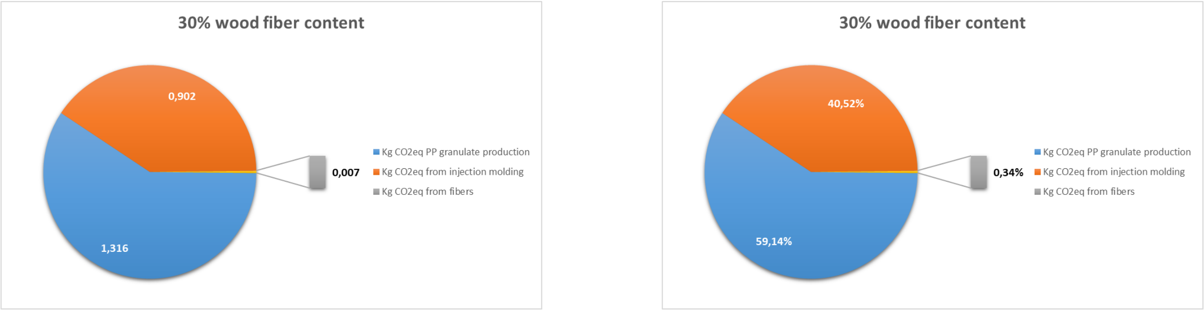

Figure D.3.2: LCA results for 30% wood fiber content

Bio composite with 60 % primary PP and 40 % wood fibers This means using less of primary PP according to the % of wood fibers added. The emissions of the wood fibers are additionally calculated. The LCA results for the entire process shows that around **2.03 kg** CO_{2-eq} are emitted per 1 kg of bio composite produced. With the primary polypropylene granulate production contributing to **1.13 kg** CO_{2-eq} per 1 kg of bio composite produced. From equation D.1 we get 0.49% of the entire impact from the wood fibers.

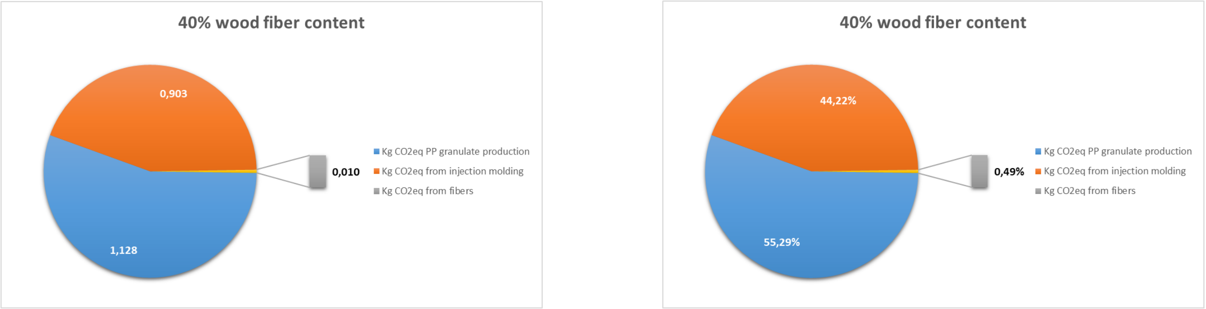

Figure D.3.3: LCA results for 40% wood fiber content

Transportation is another crucial aspect that influences CO_2 eq emissions. By considering the logistics and distance between manufacturing facilities and distribution centers, possibilities to improve transportation efficiency can be identified, potentially reducing emissions through optimized routes, alternative transportation modes, or regional sourcing strategies [47].

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DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

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