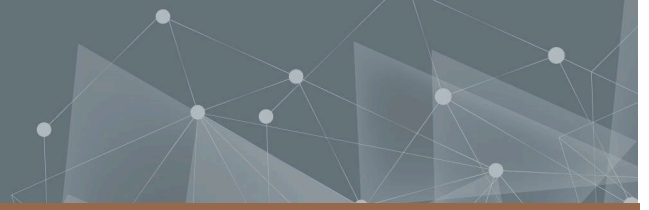




CHALMERS
UNIVERSITY OF TECHNOLOGY



A Business Model-LCA of turbochargers

Comparing BorgWarner remanufacturing and traditional
manufacturing business models

Master's thesis in Industrial Ecology

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SUMMARY

This study explores whether remanufacturing turbochargers in the automotive industry can help decouple economic growth from environmental impact. The principle is to reuse older components and minimize the need for parts made of virgin raw materials. While remanufacturing reduces material consumption, it also introduces additional processes and reverse logistics. To evaluate these trade-offs, the study compares two business models: remanufacturing (REMAN) and traditional manufacturing (business as usual, BAU). Rather than using a conventional product-level life cycle assessment (LCA), the analysis employs the Business Model Life Cycle Assessment (BM-LCA) method to assess environmental performance at the business model level, analyzing both materials and financial flows in combination. The results show that REMAN outperforms BAU environmentally, with significant reductions in raw material use, particularly of critical materials, and overall environmental performance. For example, titanium use, the most critical metal assessed, decreased by 70.8%, and global warming potential was reduced by 44%. These environmental benefits were not offset by the added processes in REMAN, nor did they compromise economic performance. A sensitivity analysis revealed that production in Poland currently results in the highest global warming potential compared to four other potential locations, provided that comparable profitability is maintained. The study supports remanufacturing as a viable circular economy (CE) strategy that improves environmental performance while maintaining profitability. The findings suggest that, for this case, remanufacturing can contribute to decoupling economic value creation from environmental harm, offering a competitive advantage for companies committed to sustainable industrial practices.

Keywords: Business Model Life Cycle Assessment, Remanufacturing, Turbocharger, Circular Economy, Reverse supply chain, Environmental Impact, Life Cycle Assessment, Sustainable Business Model

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Glossary of Terms and Abbreviations

For the sake of making it easier to write and avoid cluttered sentences, abbreviations and adapted terms are used. These are listed below so that the text is easier to follow as a reader.

Abbreviation	Description
BM-LCA	Business model - Life Cycle Assessment, A traditional LCA adapted to the business model perspective instead of the product perspective.
CRM	Critical Raw Materials, materials with too high demand relative to available crustal reserves.
CSI	Crustal Scarcity Indicator
CSP	Crustal Scarcity Potential, measurement of CSI.
DDT	Dichloro-diphenyl-trichloroethane is a synthetic organochlorine compound.
GWP	Global warming potential, a measurement of the climate change impact in CO2 equivalent.
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
Key Terms	Definition
BAU	Business as usual, referencing the case of traditional manufacturing of turbocharger business model.
Core	A product that has reached the end of its life, may be used as a resource, scavenging restorable components for remanufacturing. It is used to refer to old turbochargers collected for REMAN.
REMAN	Referencing the case of turbocharger remanufacturing business model.

1. Introduction

The world is facing severe environmental threats that endanger both the future of the planet and human well-being. Increasing pollution is putting immense strain on ecosystems, as evidenced by the global spread of harmful substances such as lead and DDT. At the same time, the depletion of natural resources is hindering sustainable development opportunities and limiting our long-term growth potential (Meadows et al., 1972).

This unsustainable course is driven by an increasing consumption and the pursuit of economic growth, increasing pressure on the world's systems. These are further worsened by both ecological processes and decision-making delays. Technical fixes alone will not be sufficient; it will require radical changes in societal values to achieve a sustainable global equilibrium with a stable population and capital. Recognizing these complex issues, along with adopting a long-term vision and planning, would be the first step necessary to avoid an imminent collapse and ensure a sustainable future (Meadows et al., 1972).

The globalized world is currently often in the hands of multinational companies to make the choice in pursuing the path of sustainable development in a developing economy (Sorrell, 2016). This highlights the weight of company decisions and their choice of strategy. In order to mitigate the environmental impact, companies first need to know why their choices matter. Such a method is life cycle assessment (LCA), which assesses the environmental impact caused throughout a service or product's lifecycle. Identifying what is problematic with a product might be the first step in being able to plan for a more sustainable future (Environmental Impact Academy, n.d.). However, a conventional LCA doesn't revolve around the business itself, as both socio-technical and economic dimensions are missing, which means that it might not represent the company and its business model in the first place, limiting the ability to support decision making regarding the business model (Böckin et al., 2022).

To meet these challenges, Business Model Life Cycle Assessment (BM-LCA) can be conducted. Whereas conventional LCA uses the function of the product as a basis for the functional unit, BM-LCA instead bases it on the economic performance of the business. This makes the business the basis of comparison, which can potentially better guide green decisions made by companies while maintaining competitive advantage (Böckin et al., 2022).

The automotive industry is one of the largest industries and is a critical sector for addressing sustainability challenges. It is characterized by significant resource use, including critical raw materials, and substantial environmental impacts throughout its lifecycle, from raw material extraction to vehicle production, use, and end-of-life disposal. Traditionally, the industry has relied on linear production models, where materials are extracted, transformed into products, and ultimately discarded as waste. However, as demand for sustainable solutions grows and environmental regulations tighten, the sector faces increasing pressure to transition to circular

principles. This involves rethinking the business model, embracing waste as a valuable input in new processes, and adopting innovative strategies such as remanufacturing, recycling, and extended producer responsibility (Orsato & Wells, 2007). Further strategic insight could ease the transition while maintaining a competitive advantage over traditional businesses, such as by conducting a BM-LCA.

1.1. Aim

The aim is to assess the environmental impact from the perspective of producing profit, of the business models, by conducting a BM-LCA. Having two cases, consisting of remanufacturing and traditional manufacturing of turbochargers, the comparative study aims to highlight the benefits and drawbacks of applying the remanufacturing strategy in turbocharger production.

Research question 1

- How does the environmental performance of BorgWarner's remanufactured turbocharger business model compare to the traditional linear model, according to the BM-LCA?

The assessment aims to identify existing impact hotspots, so that the cases can be evaluated to find potential areas of improvement, while giving a full picture of the environmental performance of Borg Warner's business models.

Research question 2

- How sensitive are the environmental impacts to aspects relating to changes, such as labour, reverse logistics, and technology?

By conducting a sensitivity analysis, the evaluation aims to find implications in changing scenarios, which can represent the case of expanding or changes in the market.

Research question 3

- In what way did the BM-LCA exceed a traditional LCA?

For the case of the academic contribution of this thesis, comparing the insight brought by the BM-LCA with the results of the LCA would create a better understanding of when BM-LCA is the more suited method.

1.2. Limitations

There will only be one case of remanufacturing business model assessed, along with the traditional version of the business model, of a single model of a turbocharger and one consistent customer, which is a service center of a truck company.

This specific product has different aftermarkets in the two cases, and assumptions are made to adapt the sales price to be equivalent to each other. The set sale prices are the amount allocated to the production site, as they trade between the site and aftermarkets no matter whether it is within the same company or not.

The results are influenced by the limited data available, both primary and secondary data, e.g., even though there was access to the exact material composition, the lack of environmental impact data available forced the use of simplified data of similar material and manufacturing.

2. Background

This section covers the thematic context for the study, connecting: the urgent push for sustainability; the operationalization of the circular economy through remanufacturing business models; and the academic and practical relevance of applying BM-LCA. Positioning decoupling, circular economy, and remanufacturing at the center of attention for the study, will provide the context needed to understand the relevance of the thesis.

2.1. Sustainability and decoupling

Sustainability has been generally defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). To achieve sustainability, it is important to balance economic prosperity, social well-being, and environmental protection in a way that ecosystems remain resilient and society thrives long term. Decoupling is defined as breaking the link between 'environmental bads' and 'economic goods', where economies can grow without increasing resource use or pollution (Evoiding, 2021).

In a society where economic growth is desired with the belief that the current state of emissions and resource use is unsustainable, decoupling refers to decoupling economic growth from environmental impact, such that we may continue growing the economy. Applying this to a business means that decoupling is to be able to increase profit on a product without increasing environmental harm in the same proportion. There are 2 different types of decoupling, absolute and relative (Vadén et al., 2020).

Relative decoupling is that economic development occurs at a faster rate than the development of environmental damage or resource consumption, even if the environmental damage or resource consumption is still increasing (Vadén et al., 2020). For instance, an example of relative decoupling can be that EU statistics show that GDP per capita rose by nearly 19% between 2010 and 2022, even though waste generation per person increased, it was far from the same extent as the GDP. As waste did not grow as fast as the economy, the EU considers this to be a case of relative decoupling (EEA, 2024).

On the other hand, absolute decoupling means that total environmental pressures decline while the economy grows. Relative decoupling is not automatically linked to absolute decoupling, as it can continue for years without turning into absolute decoupling. Figure 1 illustrates decoupling. An example of absolute decoupling can be the case of Sweden, where, since adopting its CO₂ tax in 1991, it has risen from €29 to €125 per tCO₂. During the time between 1990-2013, Sweden's annual greenhouse gas emissions fell in absolute terms while the GDP saw a growth of 58%. With strong policy initiatives, like high carbon pricing, an economy can grow while reducing its overall CO₂ emissions (Andersson & Lövin, 2015).

Decoupling is often misinterpreted when limited to macroeconomic comparisons such as GDP and carbon emissions, offering little actionable insight for business practice. While such national-level analyses indicate a general need for improvement, they may obscure the specific mechanisms through which companies contribute to environmental degradation. A more effective approach could be to assess decoupling at the firm level, where the structure and performance of business models can be directly examined (Böckin et al., 2022).

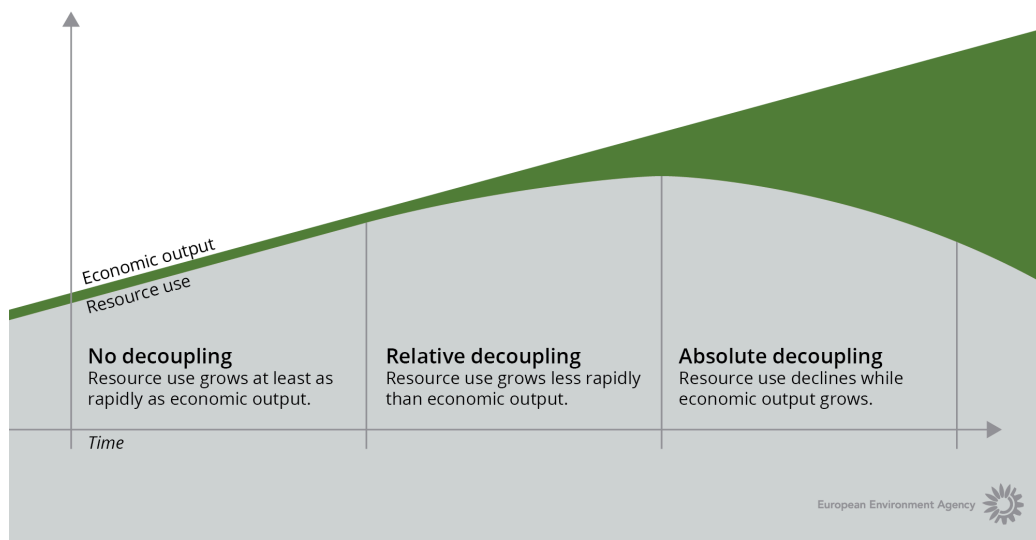


Figure 1. Decoupling demystified (EEA, 2020)

According to Albertini (2016), environmental performance refers to the measurable results of an organization’s environmental management in relation to its control over environmental aspects, objectives, and impacts. Environmental performance can be estimated based on the relationship between economic activity and environmental harm, meaning that lower environmental harm per unit of economic output indicates better performance (eeb, 2019).

In practice, environmental performance may be defined in different ways depending on context and goals. In one metric it can be an improvement, yet it might not hold true under an alternative perspective. For example, a business model may appear environmentally better in one measure but not in another context or at another scale (Böckin et al., 2022). Therefore it is important to specify the framework and metrics on which one is being used when making environmental performance claims.

2.2. Circular Economy, Business model and Remanufacturing

The circular economy (CE) is viewed as a condition for sustainability by many authors and organizations. CE is defined as a regenerative system minimizing input, waste, emission, and energy leakage (Geissdoerfer et al., 2017). Unlike the traditional linear economy model of "take, make, dispose," a circular economy emphasizes a restorative and regenerative approach, where waste is treated as a resource (Bocken et al., 2016; Geissdoerfer et al., 2017).

A widely used framework to understand circular material flows in CE is the concept of slowing, narrowing, and closing loops. *Slowing* refers to extending product life through design, maintenance, and reuse, thereby reducing the rate of resource flow. *Narrowing* involves using fewer resources per product, and *closing* means recovering materials at the end of a product's life for reuse or recycling. These strategies are integral to achieving material efficiency and reducing environmental impacts throughout the product lifecycle (Bocken et al., 2016).

To operationalize CE, various frameworks have been proposed, including different R frameworks, an example being 9R, ranging from refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover (Mishra, 2023). The order is ranked by their relative circularity. These strategies vary in their resource intensiveness and systemic impact (Potting et al., 2017). However, the diversity in CE definitions and metrics poses challenges for standardization. The lack of harmonized indicators and measurement methodologies creates ambiguity, complicating efforts to assess the actual circularity of business practices (Khan & Akhtar, 2020).

Despite these challenges, CE principles can be effectively embedded into business models to enhance sustainability (Lüdeke-Freund et al., 2019; Mishra, 2023). A circular business model shifts the traditional logic of value creation by integrating resource efficiency and lifecycle thinking into the core structure of how firms create, deliver, and capture value. Remanufacturing is a prime example of a business model that requires rethinking value creation (Lüdeke-Freund et al., 2019).

2.2.1. Remanufacturing Business Models

Remanufacturing involves restoring used products or components, generally referred to as cores, to a like-new condition through disassembly, cleaning, inspection, replacement of parts, and testing. As a strategy aligned with the 9R framework, remanufacturing is generally considered more sustainable than conventional production due to reduced material and

energy inputs (Sundin, 2004). However, the environmental benefits of remanufacturing are not guaranteed; they depend on factors such as the impact of reverse logistics and the energy consumed during the remanufacturing process (Lüdeke-Freund et al., 2019). While remanufacturing can lead to cost savings and waste reduction, challenges like network design and extended producer responsibility must be addressed to realize its full potential (Lüdeke-Freund et al., 2019; Mishra, 2023).

The feasibility and success of a remanufacturing strategy depend heavily on how it is integrated into a company's business model (Gray and Charter, 2007). A business model can be analyzed through three key dimensions: value proposition, value creation and delivery, and value capture (Lüdeke-Freund et al., 2019).

Value Proposition

In remanufacturing business models, the value proposition centers on delivering products that offer both economic and environmental benefits (Sundin and Bras, 2005). Remanufactured goods are typically offered at a lower price point than new equivalents, appealing to cost-sensitive consumers without significantly compromising perceived quality. At the same time, these products attract environmentally conscious customers due to the decrease in material extraction, energy consumption, and waste generation (King et al., 2006).

Value Creation and Delivery

The delivery of value in remanufacturing models involves unconventional logistics and specialized knowledge of product recovery. Unlike traditional production systems that rely on virgin inputs, remanufacturing firms depend on returned cores (Mishra, 2023), which can often only be effectively utilized by the original equipment manufacturer (OEM) due to proprietary design knowledge. This exclusivity can create competitive advantages for OEMs by leveraging components that are otherwise not valuable in secondary markets (Sundin, 2004).

Value Capture

Capturing value in remanufacturing is a bit more nuanced than conventional sales (Lüdeke-Freund et al., 2019). In a case where the customer is the supplier of cores, the value captured depends significantly on customer participation in take-back schemes and the incentive structures (e.g., discounts or credits) that facilitate core returns. This model requires firms to balance economic incentives with logistical efficiency to maintain profitability and sustainability. A possible scenario of this dynamic could be a service center negotiating a discounted price for parts in exchange for a steady supply of equivalent cores (Gray and Charter, 2007).

In conclusion, remanufacturing has the potential to align economic and environmental objectives. However, companies must design business models that are not only technically and economically viable but also capable of encouraging customer participation and maintaining material flow loops essential for circularity.

2.3. LCA

LCA is defined as a tool to measure the environmental impacts of a system throughout its entire life cycle, starting from raw materials to final disposal (Baumann & Tillman, 2004). By conducting an LCA, an organization can follow the International Organization for Standardization (ISO), 14040:2006 standard, which consists of an LCA structure. This structure includes guidelines and principles, and it is how an organization may evaluate the environmental impacts of a product, process, or service across its entire life cycle (ISO, 2006a).

An organization can also follow the ISO 14044:2006, which provides requirements and guidelines on goal and scope definition, life cycle inventory, life cycle impact assessment, interpretation, reporting, and critical review (ISO,2006b). ISO standards provide a framework but allow uncertainty in assumptions and interpretation, meaning that conducting several LCA studies on the same product could have varying results. Therefore, it is important to comprehend the various choices and assumptions a LCA study has made (Curran, 2013), and why it is important to point out that ISO 14040:2006 and ISO 14044:2006 are only voluntary international standards and not enforced by law (ISO, n.d.).

LCA is an iterative process, which means that the steps may need revision if the outcome is not sufficient or if there are too many uncertainties. Not all relevant information can be quantified in an LCA, so both qualitative and quantitative information should be reported. Since LCIA models have limitations, even with available data, the models used in LCIA may be restricted in some respects, making them incapable of comprehending every aspect of relevance within a product's impact on the environment. In an LCA, it is not always necessary to pick the best choice between the cases, but rather, it serves to better the understanding of the effects it has on the environment and health for each case. For instance, to know where these impacts occur (locally, regionally, or globally) and to distinguish their magnitude relative to other alternatives, hence completely revealing the benefits and drawbacks of each choice (Curran, 2013).

2.4. BM-LCA

There is a research initiative at the Environmental System Analysis Group at Chalmers University of Technology, where they have established a new type of assessment method from the company perspective. Böckin et al. (2022) introduced the method BM-LCA in a case of rental vs sales of jackets. The case company was a Swedish apparel company, and

their rental business model was assessed and compared to their conventional sales business model. A rental model is a type of product service system, often referred to as a circular strategy. Since then, numerous BM-LCA studies have been published, none of which have studied a case of remanufacturing.

BM-LCA extends conventional LCA by coupling material and energy flows with financial flows at the business model level. BM-LCA introduces a coupling phase in which the functional unit is redefined in this case as a fixed amount of profit (π), to achieve a set amount of profit, the amount of sold products is calculated by the costs and revenues. The conventional functional unit of LCA and the redefined functional unit of BM-LCA can both be tied to the production amount of a product (Böckin et al., 2022), meaning that a conventional LCA can be easily converted into a BM-LCA by connecting the product system with the monetary flows of production sales.

2.5 Conclusion of background

This chapter has outlined the emergence of the circular economy and the ideas of breaking the link between environmental bads and economic goods. Circular strategies are deployed to find value creation without being dependent on finite resources. However, it is difficult to assess circular approaches, and many circular economy indicators remain vague due to the lack of standardization and definition. Even though remanufacturing is generally considered more sustainable than conventional practices, it is not inherently sustainable. The processes that are avoided are replaced by new processes; furthermore, the sales market may differentiate from conventional manufacturing. An LCA would assess the environmental impact of this change in processes, whereas a BM-LCA would also account for the changes in market and pricing.

Business Model LCA has been developed to assess circularity and environmental performance at the business model level. While remanufacturing is recognized as an important circular economy strategy with significant environmental potential, conventional product-focused LCAs do not fully capture its environmental performance from a business model perspective.

Before this study, BM-LCA has not been conducted on a remanufacturing business model, meaning that there is a potential knowledge gap within BM-LCA research. To address this gap, the next chapter describes the methodological approach used in this study, how BM-LCA is relevant and applied to evaluate the environmental performance of remanufacturing compared to a traditional business model.

3. Method

This section outlined the research methodology used to compare the environmental performance of remanufacturing and traditional business models for turbochargers. The methodology followed a quantitative research design, combining environmental and financial data using the LCA and BM-LCA framework. Environmental data such as carbon emission, energy use, and waste generation were combined with financial data such as production costs, revenues, and economic viability. In this way, it was possible to analyze the environmental performance and economic feasibility of each business model. Figure 2 presents the sequential structure of the methodological approach followed in this study. Each step was detailed in the following subsections.

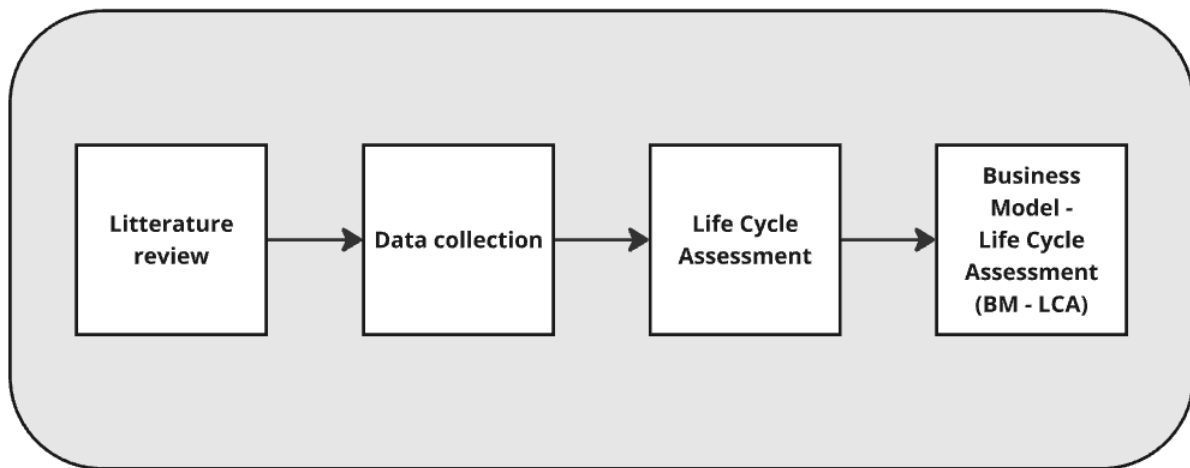


Figure 2 - Methodology overview.

3.1. Literature review

A literature review was conducted to establish a theoretical and methodological foundation for the study. The review focused on concepts related to sustainability transitions, circular economy, remanufacturing, sustainable business models, LCA, and BM-LCA. The purpose was to understand how environmental impacts can be evaluated at both the product and business model level, and to identify knowledge gaps addressed by this study.

Sources were collected from academic databases such as Google Scholar, Chalmers Library, and ScienceDirect, as well as from corporate sustainability reports. Key search terms included "LCA", "BM-LCA", and "Sustainable business models". The literature review helped identify best practices, current methodological challenges, and contextual relevance for applying BM-LCA in a remanufacturing case.

3.2. Case Description

The section covered the description of the case study, such as the company, the product, and the business models studied.

3.2.1. Company overview - BorgWarner

BorgWarner is a global supplier and developer of automotive components and systems. The company designs, manufactures, and markets components for passenger cars, SUVs, and light trucks. They are mainly known for supplying drivetrain components such as transmissions, all-wheel drive systems, and torque management systems. Besides drivetrain components, the company also manufactures chains, air and fluid systems, and turbochargers. BorgWarner has adapted into an innovative leader to meet changes within the automotive industry. The company has in recent years, pointed out its commitment toward sustainability and technological development, to meet worldwide demands for cleaner and more efficient transportation (Encyclopedia, 2019).

According to BorgWarner's sustainability goals, the company aims to be carbon neutral across operations, including Scope 1 and Scope 2, by 2035. From a 2021 baseline, the company aims to lower absolute Scope 1 and Scope 2 greenhouse gas emissions by 85 percent in 2030. BorgWarner is also working toward achieving an 85 percent recycling rate for generated waste by 2030. Regarding the rate of recycling, BorgWarner facilities have already achieved a rate of 92.8%, meaning the company is ahead of schedule to meet the goal. In 2023, 87% of the company's revenue came from EV-related and emission-reducing hybrid and combustion products. BorgWarner is also committed to social responsibility; they value diversity, equity, and inclusion in their company. The company has set targets, such as increasing the percentage of women in the global workforce to 35%, and raising the representation of racially or ethnically diverse employees in the U.S. workforce by 30% by 2026. It is also aiming for fair pay for all employees, thereby strengthening fairness within its staff (BorgWarner, 2024).

3.2.2. The product - Turbocharger

A turbocharger is a product that charges the intake of combustion engines and is used in most vehicles. The purpose is to enhance the filling of cylinders by pressurizing an additional volume of air into the combustion chamber. As increased input is provided, the fuel-air mix burns more efficiently, increasing the air density. This makes the engine more powerful and results in better overall performance (Wojciechowski et al., 2018).

Although the turbocharger studied contains 28 individual parts, there are six main components: compressor housing, compressor wheel, insert, bearing housing, shaft and wheel assembly, and turbine housing. The compressor housing draws air into the compressor wheel and then out to the engine with the high-pressure supplied air. The compressor wheel itself is

an impeller on the shaft, as it turns, it draws in and compresses ambient air to increase intake density. An insert sits between the bearing housing and compressor wheel to prevent leaks of oil or air. The bearing housing contains oil-lubricated thrust, supporting axial loads while also providing integrated lubrication and cooling passages (SKF, n.d.). Finally, the turbine housing captures the exhaust gas and delivers it to the turbine wheel, converting waste energy into rotational power that drives the compressor (Wojciechowski et al., 2018).

These main parts can be quite expensive and heavy; fortunately, they are not necessarily ruined during their use phase due to their durability, meaning that there is a chance that they can be restored to their original state. Allowing the remanufacturing strategy to be applied.

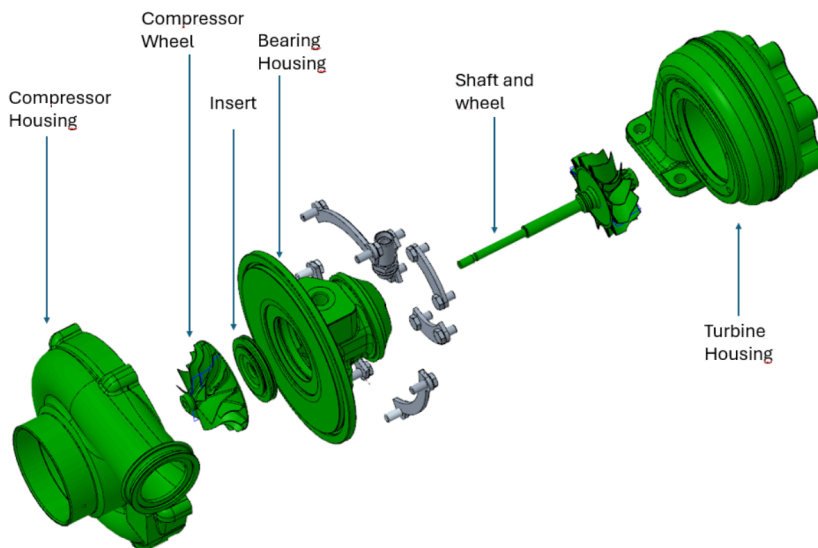


Figure 3 - Exploded view of a turbocharger.

3.2.3. Remanufacturing vs traditional

To contextualize the case study, the company's sole remanufacturing plant is co-located with one of its traditional manufacturing facilities for new turbochargers in Poland. Both cases are based on this location.

Traditional manufacturing consists mostly of finishing, balancing, and assembling foreign components. These components are manufactured by suppliers through casting, tilling, hot rolling, or other types of metal working. The material acquisition is assumed to be the market averages for acquiring raw materials.

In remanufacturing, the company retrieves whole cores, which are disassembled, and the reusable components go into a remanufacturing process (BorgWarner, 2018). The refurbished

components are used and the remaining components are replaced by newly produced ones, through the same suppliers as the traditional manufacturing. The use of refurbished and newly produced components varies based on the discard rates of old components. This business model reduces the overall demand for new components, meaning that the raw material extraction will be decreased. Furthermore, if fewer components are bought, less money is spent on material, and more resources can be put towards the refurbishing of cores and incentives for customers to participate.

3.3. Life cycle methodology

The LCA methodology has four connected stages (Curran, 2013). The first step is the definition of the goal and scope of the study, where the purpose of the study should be stated clearly. Also, selecting a functional unit, which describes the function of the product system, that provides a fair comparison between the cases. At this stage, the functional unit will be different from the functional unit used in BM-LCA. The second step is Life Cycle Inventory (LCI), where the aim is to collect data on energy and material inputs, as well as data on related emissions to the environment, making it into a complete product system of the product life cycle, simplified bill of materials, and other outputs/inputs are listed. Since the aim is to conduct a BM-LCA, the remaining LCA steps, such as LCIA and interpretation, will not be completed through the conventional LCA methodology.

3.4. Business model - Life cycle assessment (BM-LCA)

The following section describes the BM-LCA methodology and is based on the article authored by Böckin et al. (2022). The framework for BM-LCA is applied to systematically assess sustainability efforts across all stages of the case-specific product and business model.

Goal and Scope: Descriptive phase

The first step is to describe the two cases by assessing the business models and using them to adapt the already defined product systems from the LCA. Adapting the system includes redefining the system boundaries and doing an actor assessment so that the defined systems accurately represent the turbocharger business models. The impact categories are chosen by the relevant issues tied to the manufacturing of similar products so that problematic impacts of the cases won't go unseen.

The second step is to tie a relation between the business model and the product system. Since both cases are based on selling the produced product, the connection is made through the assumption that for every sale that is made, one unit of that product is produced, and that is true for both cases.

Goal and Scope: Coupling phase

The third step is to couple the environmental impact with the profitability of each case. Therefore, the functional unit is redefined as a set amount of profit π , so both business models can be compared independently of current scale and total profit.

The fourth step is to identify all of the business costs and revenues related to running each of the business models. There will be revenue for each transaction. In order to define profit, all types of costs within the system boundaries need to be accounted for. This includes direct costs, such as production, labour, and waste disposal; indirect costs, such as administrative overhead costs; and contingent costs, such as fines and penalties. For each case, n , set up an equation so that you have a conversion from the number of transactions to the resulting profit equal to the functional unit.

Equation 1 - Used to define the number of transactions to achieve a set amount of profit π .

$$\pi = f_{revenue, n} * t - f_{direct, n} * t - f_{indirect, n} * t - f_{contingent, n} * t$$

Life Cycle Inventory

The life cycle inventory (LCI) for the BM-LCA is created by adapting the LCI built through the LCA method. It is adjusted to the functional unit of the BM-LCA, and any missing flows that are within the system boundaries are added.

Life Cycle Impact Assessment (LCIA)

The LCI is used to quantify all flows so that impact categories can be evaluated and calculated through databases on environmental impact and mass flows derived from primary data. The results are to be in a measurement unit per functional unit, so that the flows can be compared accordingly. The data should be grouped in relevant midpoint categories so that the results can be easily understood, groups that can easily be interpreted and related to the product system increase readability. In addition to midpoint categories, the study aims to compare individual critical elements used in the product. In order to find the most important material extractions, another midpoint category is used as a basis of weighing the criticality of each use of material, by observing the contribution to that midpoint category. The larger contribution made by one element, the more relevant it is to compare the extraction of that element between cases. Both the midpoint categories and the comparison of critical material usage represent the environmental performance used to answer research question 1.

Interpretation, the sensitivity analysis

LCIA is followed by a sensitivity analysis, setting up different scenarios so that the study brings a good understanding of a broad array of changes represented by the scenarios, and their implications. The step aims to answer research question 2.

3.5. Recommendations

The results were interpreted so that relevant recommendations could be made. Based on the results, the priority for further improving environmental performance was determined. It was important that the results were set in the context of what it would mean for the company, the industry, and academia.

- If the company's turbocharger production were to expand, on-site or in different regions, any recommendation should be based on BM-LCA results, but also reflect realistic assumptions.
- If the reversed logistics are problematic, recommendations on how to improve should be given, if any could be made.
- The method can be reflected upon, describing the advantages and disadvantages of conducting BM-LCA can clarify when BM-LCA is the recommended method, especially with a conventional LCA as an option. This aims to answer research question 3.
- Recommendations on how to use the findings of the study as a decision-support tool were to be made so that the findings may influence any decisions appropriately, both academically and for the company.

3.6. Data Confidentiality and Presentation

Since a lot of the data used is sensitive and has the potential to harm the case company if misused, the presentation of data is managed with discretion. Absolute values are therefore avoided and are replaced by normalized results instead. Normalized results are appropriate for comparison as long as the contribution to those results is described. If the main driver for an impact category is generally considered problematic or not problematic in that category, the relevance of that category can still be determined without absolute values. The equations presented are the same as the ones used in the actual calculations, but for confidentiality reasons, the exact values cannot be disclosed. The specific materials used in the product are treated as confidential information; however, material specifications are only used in the calculation of critical material usage and in selecting simplified but appropriate material types. The ReCePi midpoint categories are based on a simplified version of each material, similarly to the names presented.

The presentation of data is designed to avoid being able to backtrack the results into potentially sensitive claims; however, the study does not skew the data to accomplish this, and any remaining potentially harmful claims are therefore protected by not giving any additional grounds for supporting these potential findings.

The case company has been allowed to oppose how the study presents any data, and the study cannot be published without the company's approval as long as the company's data is used. However, the company did not decide how the paper should be edited to accommodate their concerns.

4. Results of BM-LCA

The following chapter presents the results of conducting the BM-LCA for this study. Starting with a description of the goal and scope, detailing the descriptive and coupling phases. This is followed by the introduction of the life cycle inventory and data collection. The results of the Life Cycle Impact Assessment (LCIA) are then described and illustrated.

4.1. Goal and Scope: Descriptive phase

Both cases are mapped out and described in more detail in terms of how cost and revenue intersect with the physical flows of the product system. It gives an overview of the basis for the following integration of environmental and financial data within BM-LCA. As for the system boundary, the use phase of turbochargers will be excluded due to the assumed negligible impact caused by turbocharger maintenance.

In addition, this descriptive phase includes the selection of relevant environmental impact categories. By defining these methods, the study ensures that both cases are evaluated on fair terms and through relevant metrics.

4.1.1. Business As Usual

BAU consists of the company buying mostly finished components from a wide array of suppliers manufacturing components that make up the turbocharger, as illustrated in figure 4. 28 different components are bought and shipped to the same location at the turbocharger manufacturing plant, where final adjustments and assembly take place. In this case, the produced spare part turbocharger is then shipped to a specific truck maintenance center where the turbocharger is installed as a replacement. The composition of material used was received as primary data; however, they are simplified to fit the environmental data available in Ecoinvent. The supplier's manufacturing processes were also simplified for the same reason.

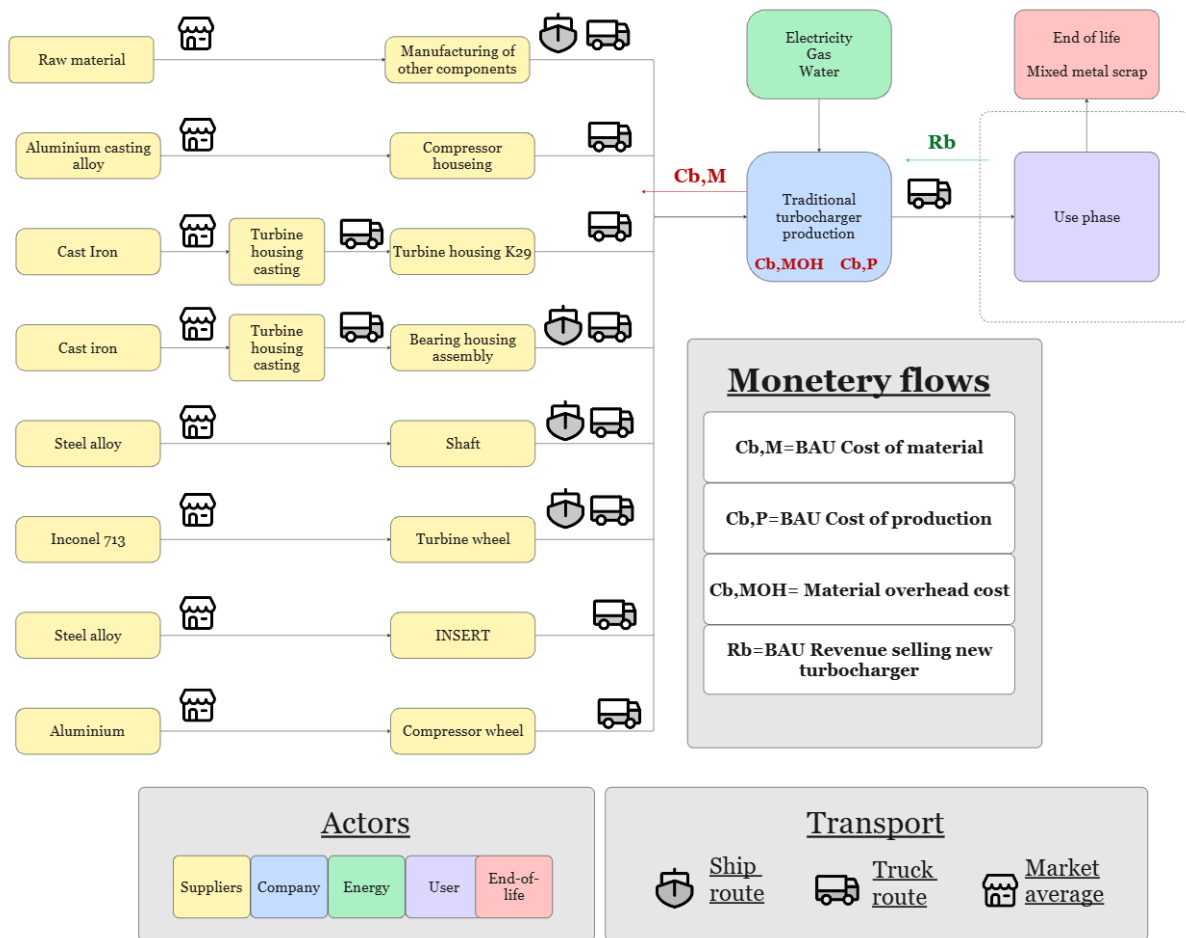


Figure 4 - Flowchart of the BAU processes.

4.1.2. REMAN

The process in REMAN has many similarities to BAU; the main difference is the processing of cores. The flowchart is illustrated in Figure 5. A core is collected in exchange for benefits such as credits, which is equivalent to a small cost. The core is then dismantled, sorted, and the components worth refurbishing are refurbished, the components that are never restored are grouped as *other components*, the components listed by name have a refurbish rate depending on how the core is damaged, as some components are more likely to be ruined during the use-phase than others. The rejected components of the core are discarded and replaced by newly produced components sourced from the same suppliers as BAU. The remanufactured products are assembled, then sold and shipped to the customer. The end-of-life is dependent on the customer since the products are no longer the property of the company.

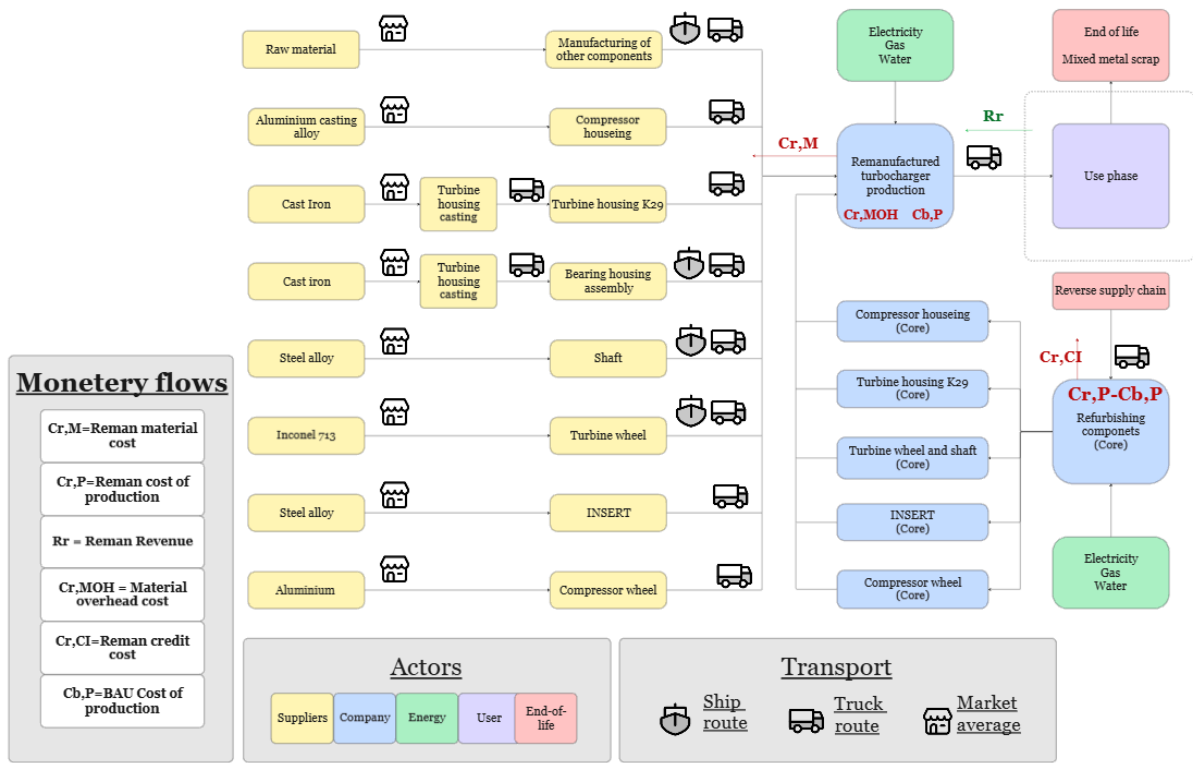


Figure 5 - Flowchart of the REMAN process for the turbocharger.

4.1.3. Impact categories

The environmental impact categorized in table 1 was applied throughout the study. It shows that the measurement of the environmental impacts is done through using the ReCiPe 2016 v1.1, Midpoint (H) and Crustal Scarcity Indicator (CSI) method. The impact category *total waste mass, mixed metal scrap*, was assumed to be 100 % of the EoL output and the material loss during the manufacturing of components. The impact categories deemed most important for this type of product, see table 2, are the categories in which results will be presented in the thesis. Limiting the impact categories to the ones deemed important improves the readability of the relevant results.

Table 1 - Overview of environmental impact categories, reference units, and selected methods. Even though not all were utilized, including all of them was done in case the chosen impacts changed during the study.

Impact category	Reference unit	Method
Acidification: terrestrial	kg SO ₂ -Eq	ReCiPe 2016 v1.1, Midpoint (H)
Climate change	kg CO ₂ -Eq	ReCiPe 2016 v1.1,

		Midpoint (H)
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Ecotoxicity: marine	kg 1,4-DCB-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Energy resources: non-renewable, fossil	kg oil-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Eutrophication: freshwater	kg P-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Eutrophication: marine	kg N-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Ionising radiation	kBq Co-60-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Land use	m ² *a crop-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Material resources: metals/minerals	kg Cu-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Ozone depletion	kg CFC-11-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Particulate matter formation	kg PM2.5-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Photochemical oxidant formation: human health	kg NO _x -Eq	ReCiPe 2016 v1.1, Midpoint (H)
Photochemical oxidant formation: terrestrial ecosystems	kg NO _x -Eq	ReCiPe 2016 v1.1, Midpoint (H)
Water use	m ³	ReCiPe 2016 v1.1, Midpoint (H)
Crustal depletion potentials	CSP (kg Si eq/ kg)	Crustal scarcity indicator (CSI)

Total waste mass, mixed metal scrap	kg	Estimate
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Table 2 - Detailed overview of chosen environmental impact categories.

Impact category	Reference unit	Method
Climate change	kg CO ₂ -Eq	ReCiPe 2016 v1.1, Midpoint (H)
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Material resources: metals/minerals	kg Cu-Eq	ReCiPe 2016 v1.1, Midpoint (H)
Particulate matter formation	kg PM _{2.5} -Eq	ReCiPe 2016 v1.1, Midpoint (H)
Crustal depletion potentials (CSP)	kg Si eq/ kg	Crustal scarcity indicator (CSI)
Total waste mass, mixed metal scrap	kg	Estimate

4.2 Goal and Scope: Coupling phase

The functional unit is defined as a set profit level (π), which is the basis for comparing the different business models. In Equation 2, this profit level is expressed as the difference between total revenues and total costs.

Equation 2 - Description of profit level

$$\pi = \sum Revenue - \sum Costs$$

To ensure a fair comparison, both business models are evaluated using the same target profit level. This means that the profit level for BAU, π_b , is set equal to the profit level for the REMAN model, π_r .

Equation 3 - Set profit level between business models

$$\pi_b = \pi_r = \pi$$

In order to couple the profit level to how many products the company needs to produce, the financial data for each sale is described in table 3 and 5; these variables are used to find how many products need to be sold to achieve the set profit level. The amount of sales required is equivalent to how many products the company would need to produce, coupling the financial flows with the product system's physical flows.

Table 3 - BAU financial flow and structure for turbochargers

Symbol	Description	Unit
t_b	Number of transactions (sales)	Amount
$C_{b,M}$	Total cost of material	€
$C_{b,FFG}$	Cost of material-Foreign finish.goods	€
$C_{b,RM}$	Cost of material- raw material	€
$C_{b,OMS}$	Cost of material- Other mat./services	€
$C_{b,MOH}$	Cost of material overhead	€
$C_{b,P}$	Total cost of production	€
$C_{b,S}$	Setup costs	€
$C_{b,U}$	Unit costs	€
C_b	Total cost per new turbocharger	€
R_b	Revenue per sold new turbocharger	€
π_b	Profit level	€

Table 4 defines the total cost in BAU; it consists of total material cost, $C_{b,M}$, derived from the cost of any material use or component bought; the material overhead cost, $C_{b,MOH}$, which represents the indirect expenses related to material acquisition; the total cost of production, $C_{b,P}$, which are categorized in unit and setup cost; the total cost per new turbocharger, C_b , which is the sum of all these costs.

Table 4 - BAU cost calculation overview for turbochargers.

Category	Equation	Unit
$C_{b,M}$	$C_{b,M} = C_{b,FFG} + C_{b,RM} + C_{b,OMS}$	€
$C_{b,MOH}$	$C_{b,MOH}$	€
$C_{b,P}$	$C_{b,P} = C_{b,U} + C_{b,S}$	€
C_b	$C_b = C_{b,M} + C_{b,MOH} + C_{b,P}$	€

With revenue and cost known for each sold product, the set profit level, π , can be used to describe how many transactions are needed to fulfill the functional unit. The number of transactions, t_b , is determined by dividing the profit level by the contribution margin ($R_b - C_b$).

Equation 4 - Formula describing the amount of BAU transactions needed depending on π , revenue, and costs, derived from equation 1.

$$t_b = \frac{\pi}{R_b - C_b} = \frac{\pi}{R_b - C_{b,M} - C_{b,MOH} - C_{b,P}}$$

Table 5 - REMAN financial flow and structure for turbochargers.

Symbol	Description	Unit
t_r	Number of transactions(sales)	Amount
$C_{r,M}$	Total cost of material	€
$C_{r,FFG}$	Cost of material-Foreign finish.goods	€
$C_{r,RM}$	Cost of material- raw material	€
$C_{r,OMS}$	Cost of material- Other mat./services	€
$C_{r,MOH}$	Cost of material overhead	€
$C_{r,P}$	Total cost of production	€

$C_{r,S}$	Setup costs	€
$C_{r,U}$	Unit costs	€
C_r	Total cost per remanufactured turbocharger	€
$C_{r,CI}$	Cost of core, credit handout	€
R_r	Revenue per sold remanufactured turbocharger, credit not included	€
π_r	Profit level	€

Table 6 defines the total cost in REMAN; it consists of total material cost, $C_{r,M}$, derived from the cost of any material use or component bought; the material overhead cost, $C_{r,MOH}$, which represents the indirect expenses related to material acquisition; the total cost of production, $C_{r,P}$, which are categorized in unit and setup cost; and the core credit cost, $C_{r,CI}$, which accounts for incentives provided to customers for returning used cores. The total cost per remanufactured turbocharger, C_r , is the sum of all these components.

Table 6 - REMAN cost calculation overview for turbochargers

Category	Equation	Unit
$C_{r,M}$	$C_{r,M} = C_{r,FFG} + C_{r,RM} + C_{r,OMS}$	€
$C_{r,MOH}$	$C_{r,MOH}$	€
$C_{r,P}$	$C_{r,P} = C_{r,S} + C_{r,U}$	€
$C_{r,CI}$	$C_{r,CI}$	€
C_r	$C_r = C_{r,M} + C_{r,MOH} + C_{r,P}$	€

Similar to BAU, the number of transactions needed to achieve the set profit level can be found. The number of transactions, t_r , is calculated by dividing the profit level by the contribution margin ($R_r - C_r - C_{r,CI}$).

Equation 5 - Formula describing the amount of REMAN transactions needed, depending on π , revenue, and costs, derived from equation 1.

$$t_r = \frac{\pi}{R_r - C_r - C_{r,CI}} = \frac{\pi}{R_r - C_{r,M} - C_{r,MOH} - C_{r,P} - C_{r,CI}}$$

4.3. Life Cycle Inventory

The following section describes the data from the business models' material, energy, and logistics. It consists of descriptions of the kind of data used to produce results, such as; bill of materials, describing each turbocharger component's mass and material content; list of critical raw material usage in BAU and REMAN; the consumption at the plant, excluding material use; how end-of-life was accounted for; and description of transportation routes.

4.3.1. Bill of materials and critical raw material use

As seen in Table 7, the turbocharger has several components, each of which is made up of different materials and weight. The table shows that both the produced turbo and the core weigh 15.6 kg; this is due to the core being shipped as a complete turbocharger to the company before it is dismantled and sorted.

Table 7 - An overview of the bill of materials and weight distribution for one turbocharger.

Turbocharger		
Component	Weight [kg]	Material
Bearing Housing	4.1	Cast iron
Turbine Wheel & Shaft	0.17	Inconel 713 & Steel alloy
INSERT	0.13	Steel alloy
Compressor Wheel	0.16	Aluminium
Compressor Housing	2.3	Aluminium
Turbine Housing	8.1	Cast iron
Other components	0.85	E.g., aluminium, steel, brass, rubber
Produced turbo	15.6	-
Core	15.6	-

Table 8 shows the inventory of critical raw materials used in newly produced components. The recycled-to-virgin ratio is assumed to be the same across both cases and all materials,

allowing for a comparison of virgin raw materials. REMAN turbochargers show a significant decrease in virgin material use per turbocharger, compared to BAU. The data is derived from the weight and specific material compositions of components.

Table 8 - Comparison of critical raw material usage in BAU vs REMAN turbochargers. Only accounting for the material used in newly produced components.

Critical raw material		
Element	BAU	REMAN
	Weight per produced turbo [kg]	Weight per produced turbo [kg]
Silicon metal	0.553	0.237
Magnesium	0.0106	0.0035
Cobalt	0.00877	0.00530
Phosphorus	0.0076	0.0033
Titanium	0.0057	0.0020
Tungsten	0.0029	0.0018
Tantalum	0.0017	0.0010
Vanadium	0.000076	0.000076
Borate	0.0000275	0.0000244
Bismuth	0.000000102	0.000000061

4.3.2. Consumption during production at the company plant

The primary data covers the consumption of energy, gas, and water from each of the cases, BAU and REMAN. Since the only significant difference is that remanufacturing has a refurbish step, the assumption was made that the difference in impact represents that refurbish step. The location of the plant is in Poland and is assumed to use energy from a medium voltage grid, for which the ecoinvent market for medium voltage is used. The gas consumption is assumed to be natural gas, which is converted from volume to energy content so that Ecoinvent data can be used.

4.3.3. End-of-Life (EoL)

While the end-of-life phase can contribute significantly to the overall impact of a product system, treating refurbishment as a production step makes it inappropriate to assume that the turbocharger will re-enter the remanufacturing system. Such an assumption would unfairly disadvantage traditional turbochargers, which may have an equal or even greater potential for refurbishment. Due to conflicting issues, the end of life is simplified and assumed to be treated as waste in both cases. Since the disposed turbocharger consists of many materials and the non-metal content is negligible, it can be considered mixed metal scrap.

4.3.4. Transport Routes & Modes

Data from Table 9 refers to the transport of BAU and REMAN turbochargers, from suppliers to the company, final product delivery, and the reverse supply chain. All routes and distance calculations were estimated using Google Maps and sea routes. EURO 6 was selected as the emissions standard for lorry transport due to it being the current standard, established by the European Union (ICCT, 2016). In contrast, for this study, raw material transport for the product is integrated using the Ecoinvent market average for the procurement of raw materials. Specifically related to ecoinvent, the transport activity for Truck is defined as transport, freight, lorry with a capacity of 16–32 metric tons, diesel-powered under EURO 6. The ship transport is defined as transport, freight, sea, container ship powered by heavy fuel oil, according to Ecoinvent.

Table 9 - An overview of Transport Routes, Distances, and Modes for BAU and REMAN Turbochargers.

Transport		BAU		REMAN		
Transport activity	Location	Distance Ship(km)	Distance Truck(km)	Distance Ship(km)	Distance Truck(km)	Source
Raw materials	-	Market average	Market average	Market average	Market average	Ecoinvent (market)
Components	Supplier - company	Mixed	Mixed	Mixed	Mixed	Company, google maps, searoutes
Product delivery	Company - Customer	0	970	0	970	Company, Google Maps
Reversed supply chain	Customer - Company	0	0	0	970	Company, Google Maps

4.4. Allocation

For the total consumption impact, e.g., energy, gas, and water, at BAU and REMAN production plant, the difference between the two is allocated to refurbishing, and the total consumption at BAU is assumed to represent the assembly step for both BAU and REMAN. The total impact of each case remains unchanged, but the allocation to the refurbishment step allows better representation of the additional steps added by remanufacturing.

EoL treatment is the same for both cases of turbochargers, meaning that no allocation was done concerning REMAN utilizing components that are otherwise considered waste. Furthermore, new turbochargers might be more suitable for remanufacturing than turbochargers that have been remanufactured before.

There is also no allocation due to product life expectancy, since the remanufactured product is expected to be of equal quality to the new one. Nonetheless, any decrease in quality would most likely be reflected in the selling price and therefore be indirectly accounted for in a BM-LCA.

The two cases have a large difference in revenue due to the company owning the REMAN aftermarket but not the BAU aftermarket for this specific product; the revenue allocated to the company's aftermarket is therefore not accounted for in either case.

4.5. Life cycle impact assessment (LCIA)

This section covers the results derived from conducting the BM-LCA. The results are based on data taken from Ecoinvent 3.11 through the use of the application OpenLCA. ReCiPe midpoint (h) was the method used to produce the measurement of each impact category, except for the measurement of Critical raw materials and the end-of-life waste flow. While the use of CRM is included in the ReCiPe impact category, material resources, the Crustal scarcity potential aims to highlight more controversial metals separately. The results are tied to the functional unit of a set profit level in a business model, meaning that a product-level perspective cannot be applied to compare the cases. Figure 6 shows the results for the ReCiPe impact categories and waste mass.

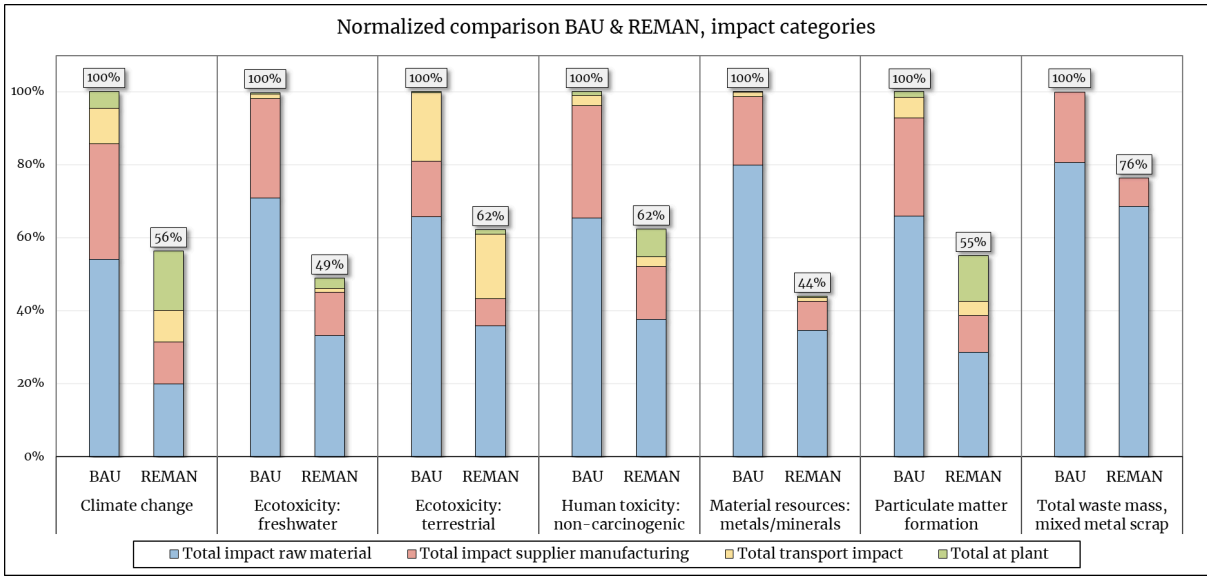


Figure 6 - Results of the total impact in each impact category, based on the functional unit, the chart is normalized to BAU in each impact category.

4.5.1. Crustal scarcity indicator

It is reasonable to assume that the use of critical materials is not negligible. In order to assess the critical material use, CSI was used, not as a midpoint indicator on the product, but on each element used in the product. Figure 7 illustrates a kind of ranking that serves as a basis for picking the most important materials for further comparison. While REMAN shows a 72% decrease in magnesium compared to BAU, the figure shows that it is largely insignificant since the CSP is 30000 times lower than titanium, meaning that it is not an important critical material in this study. The materials assessed are the ones present in the CSP list and that exist in the composition of materials.

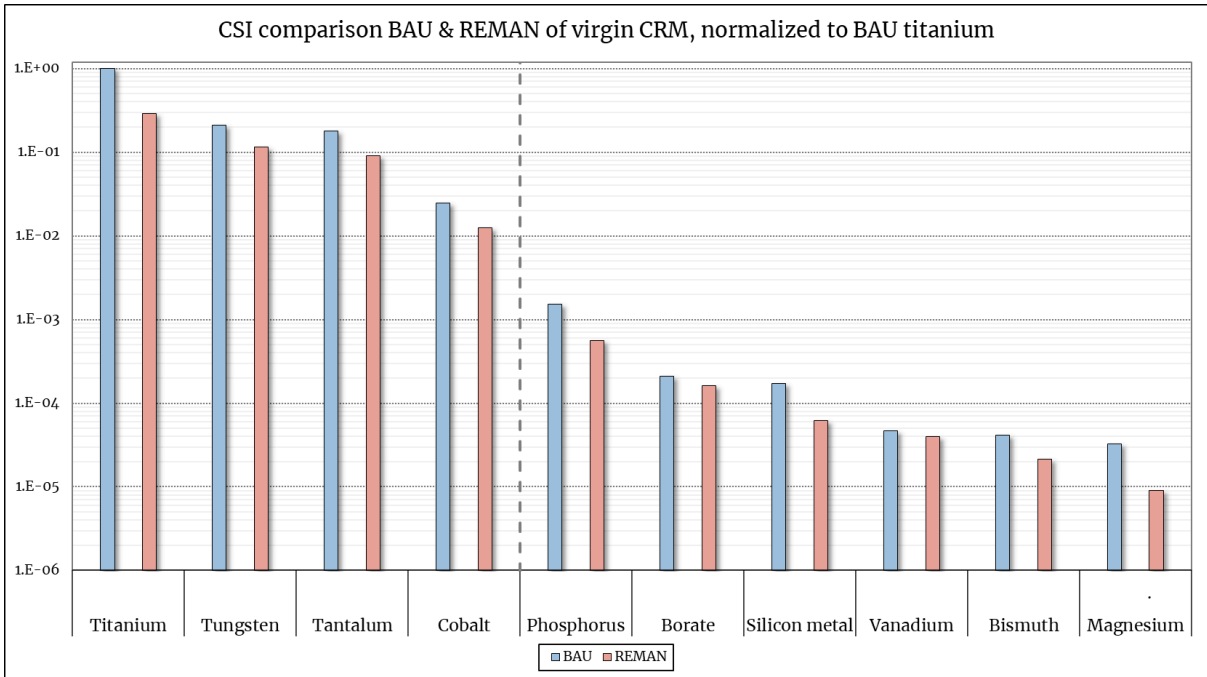


Figure 7 - CSI results presenting the CSP for CRM, presented in a 10-log scale and normalized to the highest score, titanium BAU. “1.E-02” for example, would mean 100 times lower CSI than titanium BAU.

The four biggest elements in figure 7 are assumed to be of interest for further comparison, being titanium, tungsten, tantalum, and cobalt. The usage of these is compared in figure 8. However, these four are not equal in importance, as the CSI still differs significantly. According to the CSI method, the most to least important element is titanium, followed by tungsten, tantalum, and cobalt.

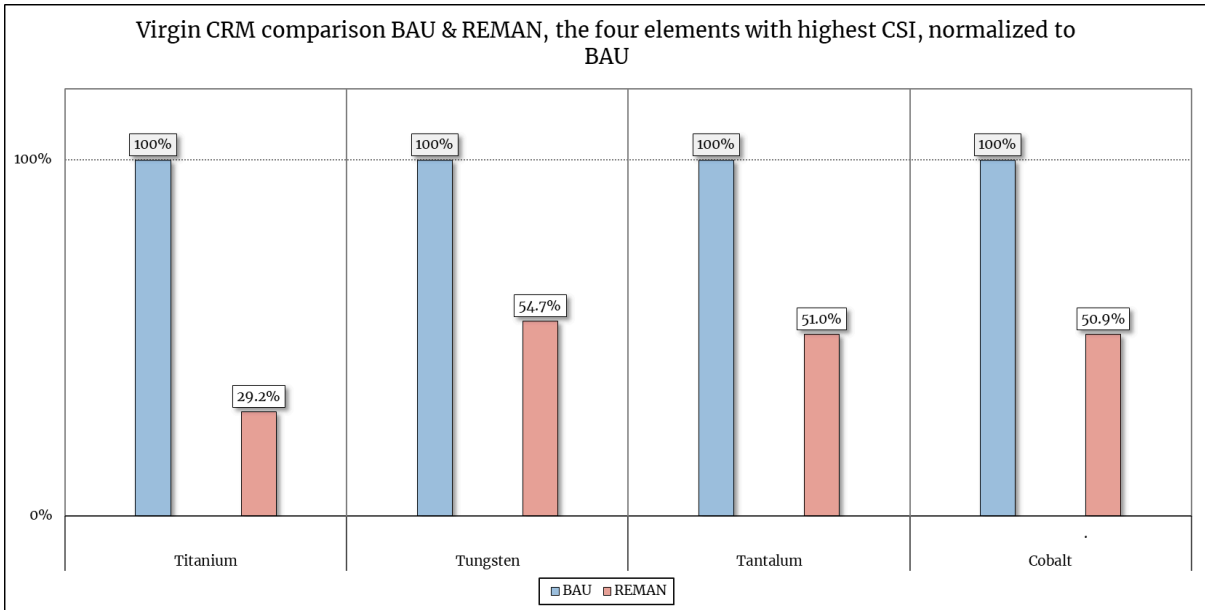


Figure 8 - The four most critical elements, according to CSI, shown in figure 7, are compared in how much virgin material is used in BAU vs REMAN, to fulfill the functional unit. Normalized to BAU for each element.

4.5.2. GWP distribution

Figure 6 shows a general measure of impact categories. However, the different flows in the flowchart are quite independent of each other, e.g., most components have separate suppliers. Furthermore, the distribution of impact changes drastically when the new large components are substituted with refurbished ones, meaning that new hotspots are to be expected when introducing remanufacturing.

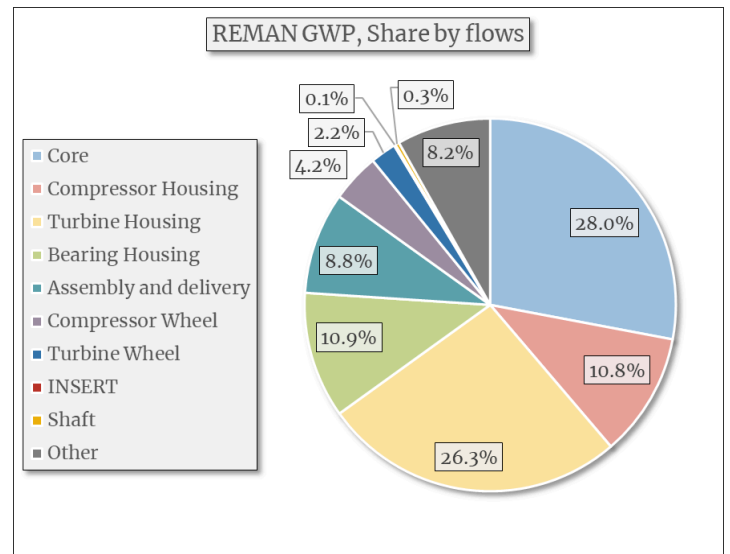
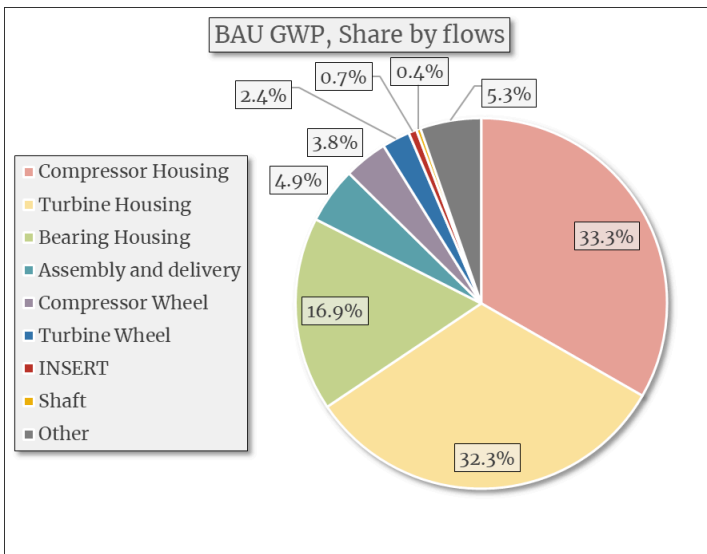


Figure 9a - Illustrates the distribution of impact between the branches depicted in the BAU flowchart, each flow connected to production of turbochargers is shown; however, Assembly and delivery include both the outgoing flow, product delivery, and the production activity at the company plant. The figure illustrates 100% of BAU GWP and is therefore not affected by any functional unit.

Figure 9b - Illustrates the distribution of impact between the branches depicted in the REMAN flowchart, each flow connected to the production of turbochargers is shown; however, Assembly and delivery include both the outgoing flow, product delivery, and the final assembly at the company plant. The core category represents the additional activities brought by remanufacturing, both the collection of cores and the processing into new-like components. The figure illustrates 100% of REMAN GWP and is therefore not affected by any functional unit.

Figure 9a shows that the main components are in fact the main sources to GWP, whilst assembly and delivery are responsible for a mere 4.9%. Showing the weight of sourcing the right component suppliers. However, Figure 9b shows that company activities stand for more than one-third of GWP contributions, which includes both refurbishing the core, assembly, and delivery. Meaning that the GWP distribution shifts more towards company activities, which is natural due to REMAN having more company activities. Even though sourcing the large components from high-standard suppliers is not as important for REMAN, it is nonetheless still significant. There is always a need for newly produced components, and if

changing suppliers is explored, knowing what part of the production drives the impact will serve as an important basis for choosing the right supplier. In figure 10, the five components with the largest GWP contribution are presented with the distribution of GWP across raw material, manufacturing, and transport.

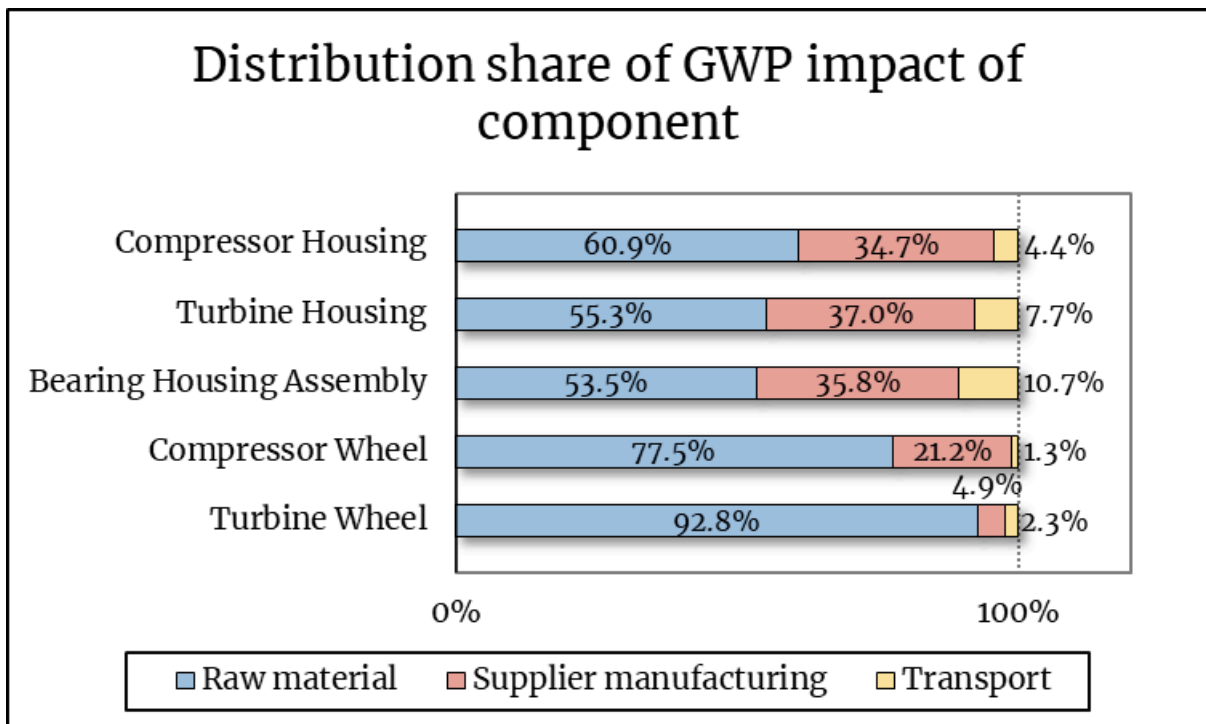


Figure 10 - Presents the distribution of GWP impact between raw materials, supplier manufacturing, and transport for each of the components with the largest contribution to the total GWP.

Sourcing a supplier closer to the company might not be beneficial if that supplier is less concerned with sourcing the raw material, or if the power grid is worse, making the manufacturing activities worse. The distribution of impact in figure 10 helps in measuring the impact of change. A general observation would tell us that the raw material might be the most dominant aspect, followed by manufacturing, and least dependent on transport.

4.5.3. Transport impact

Even though transport contributes with a lesser share of impact compared to other activities, since it might be difficult to simulate exact changes to logistics during change, having a breakdown of what contributes to the impact of transport could be used as a basis for more general patterns. Figure 11 is a breakdown showing the contribution to the total transport impact.

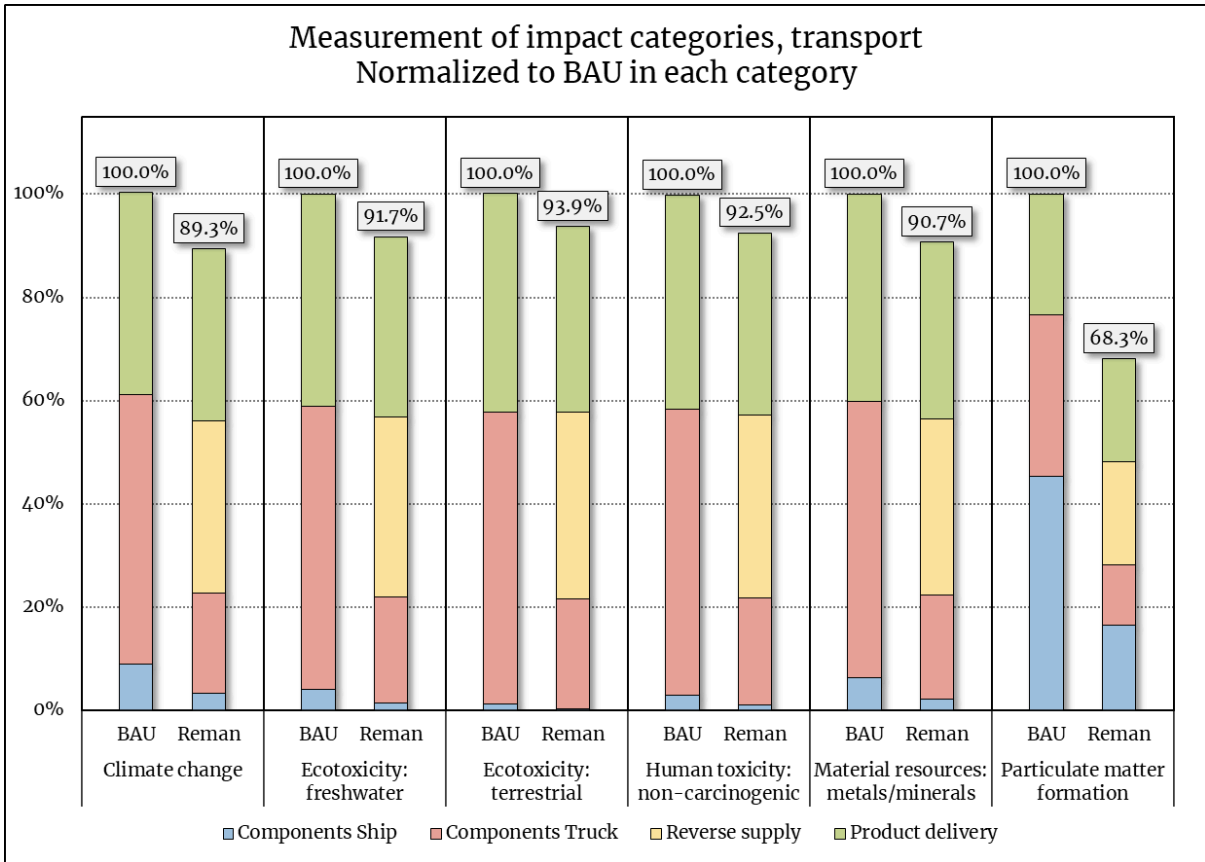


Figure 11 - Breakdown of the results of the total transport in selected ReCePi impact categories, normalized to BAU in each impact category. Transportation of raw materials is not included.

Figure 11 shows how the component transport is greatly reduced by utilizing components of cores; however, the transport of cores (reversed supply) almost makes up for that decrease, highlighting the consequences of shipping whole cores from customers further away. Shipping, however, does not seem to be a large contributor except for particulate matter, meaning that shipping doesn't necessarily need to be problematic unless the amount of particulate matter emitted by sea shipping is controversial on its own.

5. Sensitivity analysis

This section will cover the interpretation, the final step of the BM-LCA. The goal of the BM-LCA is to produce insight about the business model, so that the insight can be applied when making decisions about future development. Making scenarios of changing conditions can therefore be an important part of the assessment. For one, the company's activity location is interesting if the company is considering expanding its operations. If they were to change location, the costs of running the business would likely change. Furthermore, costs are also changing over time, independent of location. Scenarios of altering production cost and material cost are therefore of interest. Here, the sensitivity analysis will look into the impacts of the energy grid used by the production plant at alternative locations. It will also look into the implications of change in cost, both production cost and material cost.

5.1. Company location, Company energy grid

Currently, the company's turbocharger production plant is located in Poland. Alternative locations deemed of interest were Germany, Sweden, the USA, and China. Germany is relevant since it is a neighboring country; Sweden, due to its extensive use of renewable energy; the USA, because the company is American; and China, since it is a common location for manufacturing.

Making scenarios of different locations, the change in routes is assumed to have a negligible impact, making the only variable the power grid used by company activities. The impact of power usage is sourced from the Ecoinvent market for medium voltage in each country. However, the company location does not explicitly mean that the local energy grid is used; the alternative to install solar panels, equivalent to the annual energy use, are therefore also included.

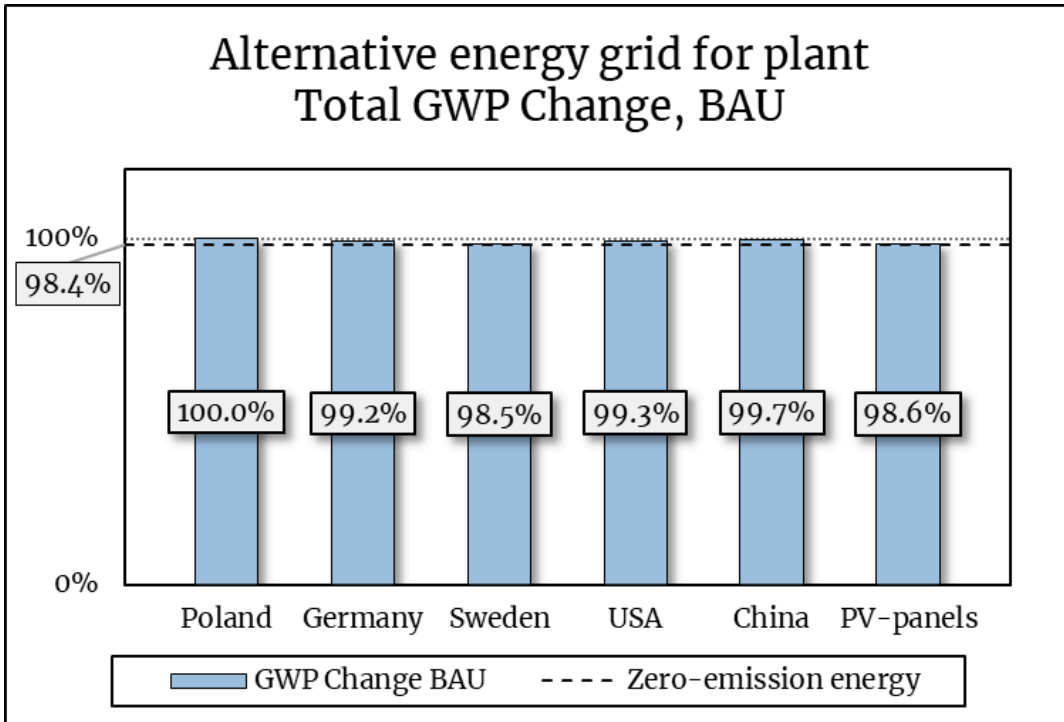


Figure 12 - illustrates the total GWP impact by alternative company plant locations of traditional manufacturing.

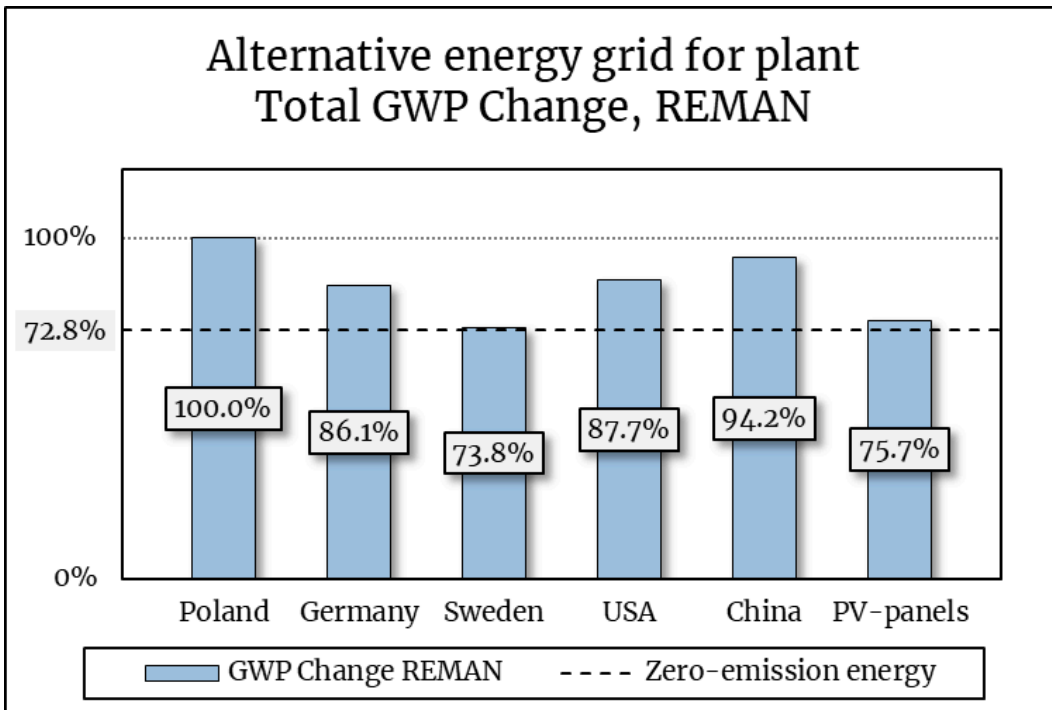


Figure 13 - illustrates the total GWP impact of alternative remanufacturing plant locations, but only considering changes in the energy grid.

As seen in figure 12 and 13, REMAN is a lot more sensitive to changes in the energy grid than BAU. This can be explained by two main aspects. The first aspect is the amount of impact caused elsewhere, since REMAN causes less impact through new components, a larger share of impact is within company activities, since these impacts have not decreased proportionally. The second aspect is the added company activities, which are quite energy-intensive. The key takeaway is that this graph does not measure what is better between the cases, since one aspect reflects improvement, the other reflects increased impacts, but it does reflect the potential for improvement.

The favoured scenario is Sweden; however, having to set up in Sweden won't come without significant drawbacks, such as significantly increased production costs. In that aspect, the option to install PV panels is most likely more favourable. PV panels not only provide a renewable energy source, but also have one of the highest GWP decreases among the options.

The company has taken initiatives to improve the sustainability of the grid, as they pay green tariffs on their energy consumption. This means that the energy bought is guaranteed to be from renewable sources. However, this is a market mechanism and does not necessarily reflect the proportional additional capacity of renewable energy production.

5.2. Change in cost conditions

This section explores scenarios where the production cost and/or material cost are changed, assuming that the selling price remains fixed. Such scenarios are to be expected if the company expands to new locations where manufacturing conditions are different or where costs develop over time, and the selling price is yet to follow. Table 10 shows the change in GWP impact for fulfilling the functional unit under changing conditions. An increase in GWP would be caused by less profit per sale and therefore needing to produce more to achieve the profit level set by the functional unit.

Table 10 - The change of total GWP when financial conditions are changing, where 100% is the baseline GWP.

BAU		Production cost				
		+20%	+10%	Current	-10%	-20%
Material cost	+10%	211.8%	182.9%	160.9%	143.7%	129.8%
	+5%	151.2%	135.8%	123.3%	113.0%	104.2%
	Current	117.5%	108.1%	100.0%	93.1%	87.0%
	-5%	96.1%	89.7%	84.1%	79.1%	74.7%
	-10%	81.3%	76.7%	72.5%	68.8%	65.5%
REMAN		Production cost				
		+20%	+10%	Current	-10%	-20%
Material cost	+10%	181.9%	148.4%	125.4%	108.5%	95.6%
	+5%	153.6%	129.0%	111.3%	97.8%	87.2%
	Current	132.9%	114.1%	100.0%	89.0%	80.1%
	-5%	117.2%	102.3%	90.8%	81.6%	74.1%
	-10%	104.8%	92.7%	83.2%	75.4%	69.0%

While BAU is generally more sensitive to changes in cost, it is mostly due to the material cost being quite a lot larger compared to REMAN, which is instead more labour-intensive. If the production were to change location, production cost would be more likely to change due to operations having to adapt to new laws and regulations, such as the cost of labour, while material cost would be less affected. If material cost were to change, it would probably be on a larger geographical scale, and it would be reasonable to assume that the selling price would be changed accordingly.

Combining section 5.1. and 5.2., it further supports the claim that increased cost is a significant drawback of moving to a country such as Sweden, since a 20% increase in production cost would almost completely remove the benefits of using the Swedish grid in the case of REMAN. Furthermore, the production cost would most likely increase by a lot more than 20% compared to manufacturing in Poland and in Sweden, which can be supported by the difference in labour cost (Eurostat, 2025).

6. Synthesis and Interpretation

In this section, the research questions are discussed through the research findings of the study and their interpretation.

6.1. Research question 1: Environmental performance

How does the environmental performance of BorgWarner's remanufactured turbocharger business model compare to the traditional linear model, according to the BM-LCA?

The environmental performance of REMAN is consistently better than BAU. With REMAN GWP only being 56% of BAU, meaning a GWP decrease of 44%, is solid evidence of remanufacturing being a more sustainable option. As for waste, while the results don't show a significant reduction, waste is nonetheless avoided when it is used as a core, which could arguably be one of the greatest features. Furthermore, there is potential for better recycling, since the core is dismantled to scavenge usable parts, it is implied that the parts that are replaced are dismantled as well, allowing better sorting of waste. Another key aspect is the direct reduction in demand for virgin raw materials. Although refurbishing is energy-intensive, it significantly reduces the extraction of rare earth elements, since the most advanced components, which typically contain the highest concentrations of such materials, are the ones being refurbished.

6.2. Research question 2: Sensitivity to scale and conditions

How sensitive is the environmental performance to aspects relating to changes, such as labour, reverse logistics, and technology?

REMAN is overall more sensitive to the practices of company activities, due to having more processes and higher energy consumption within the scope of the company. This implies that REMAN has more potential for improvement initiated by the company. This may also limit the scaling of REMAN as it is more dependent on the capacity of the company and the reversed logistics, all while BAU may be more dependent on the capacity of their mass-producing suppliers, which presumably makes it easier to accomplish any upscaling.

REMAN is more sensitive to changes in production cost, and that is presumably the most affected cost when it comes to expanding production to other countries. However, technology is always developed to decrease company production costs, and since BAU consists of fewer machining activities by the company compared to REMAN, it would be reasonable that investments in technology development would benefit the production cost of REMAN more so than BAU.

6.3. Research question 3: BM-LCA vs traditional LCA

In what way did the BM-LCA exceed a traditional LCA?

This case is pretty straightforward; the activities that we defined within the remanufacturing business model are not so different from BAU. A traditional LCA would most likely cover all activities that this study included, except maybe delivery of cores, it seems obvious that the whole core should be accounted for when cores are collected and shipped, but it would be ignorant to not view the possibility to only account for the refurbished components since that is the metric given by the bill of materials. If the refurbished components hadn't been waived from that bill of material, this study would have made that choice as well. Nonetheless, the business model perspective did, at most, only slightly improve the product systems' presentation of reality. This is otherwise a great advantage to strategies such as renting, where additional transport and dependency on user behavior can change the characteristics of a business model.

Another advantage of BM-LCA is the ability to debunk cheap products pushing for extensive consumption, such as low-margin clothing, being profitable because of the possibility of selling a lot more of them. In this case, however, both the economic performance and quality of the REMAN product are on par with BAU, meaning that greenwashing can't be argued for in this context, which would have otherwise shown in the result of doing the BM-LCA.

But is the business perspective the most reasonable approach? The amount of turbochargers sold, independent of the company, in reality does not depend on how many need to be sold to reach a set profit level, but instead on the number of turbos that need to be replaced in commercial transport trucks. If the market for the turbochargers studied in this paper were to increase, it would be due to an increase of trucks using this turbocharger. It is reasonable to assume that turbo maintenance is not one of the deciding costs of transporting by truck, and that an increase in trucks is more dependent on the increased demand for truck transport rather than the turbo pricing. Meaning that BM-LCA removes the product and societal demand for that type of function from the equation, implying it is more about a general business creating value and causing environmental strain in doing so. BM-LCA is tied to decoupling, but not necessarily in the same way as comparisons of GDP and greenhouse gas emission trends are viewed, since company profit doesn't necessarily reflect GDP contribution. Whether BM-LCA or traditional LCA is more relevant may depend on how the context of the study is defined and for what purpose it is conducted.

7. Discussion

This chapter discusses the credibility of the results and provides recommendations for improvements and future research.

7.1. Credibility of results

This study incorporates a combination of primary data, secondary data, and informed assumptions. As a result, while every effort has been made to ensure the reliability of the findings, they may not fully reflect real-world conditions. However, this potential inaccuracy should not, in itself, be grounds for discrediting the outcomes. All assumptions were applied with neutrality and were not made to favor any particular outcome or scenario. Moreover, the study was conducted with the critical awareness that its results could potentially reveal arguments indicative of greenwashing. Had such findings emerged and affected the results, it would have been explicitly addressed.

There are several limitations that should be considered when interpreting the results. First, the analysis is confined to a single product and specific case context, which limits the generalizability of the findings to other products, companies, or sectors. Second, while efforts were made to include all relevant flows, data limitations may have influenced the completeness of the model. Third, due to the nature of the data, some estimations and assumptions were necessary, which implies a degree of uncertainty.

The BM-LCA is set to measure from a set amount of profit, which may create unfair aspects in the comparison. In this case, REMAN had a higher count of value-creating company activities, since a turbocharger is usually mainly just assembled from foreign components. REMAN may not gain revenue from these added activities, but the company saves as they decrease the need for new components. If the company produced value by producing their components, there would be a shift in the results since REMAN would miss out on these value-producing activities, if those components are the ones also being refurbished. This phenomenon could be an argument for unfair comparison, but also an argument for REMAN being a better business model.

The suggested improvements are further discussed in section 7.3; however, all of the results show that REMAN outperforms BAU from the perspective that BM-LCA was made to compare business models. Most likely, any slight variations in assumptions and limitations couldn't contradict this claim.

7.2. Practical implications

The study may serve as a basis for an expansion of the businesses studied, even though environmental performance is second to economic performance in priority, more and more,

regulation integrates the two by making it difficult to pollute. These results show how sourcing sustainable energy becomes important for REMAN, so if the company chooses to expand across borders, there is reason to look beyond the routines necessary for expanding traditional manufacturing. There is solid support for REMAN staying in Poland due to low production costs; nonetheless, the environmental performance suffers from sourcing energy from the Polish grid. The company has made efforts to improve this through green tariffs on their energy consumption; however, it may be further improved to ensure that the green tariffs reflect proportional additional renewable energy capacity. Another option would be to install their own energy source, such as PV panels, which might not be as costly as moving to another country, such as Sweden.

This work can also be used to expand the knowledge of conducting a BM-LCA. This is the first instance of a BM-LCA study on a remanufacturing model, and it may be used as a basis for others like it in the future. Researchers and practitioners of life cycle assessments may use this as a guide or utilize any takeaways found in this study.

7.3. Methodological reflections and future research

This section covers what improvements or possible additions that would have been interesting to include if the time constraint was not a deciding factor, thus also what can be implemented in future studies. It will also cover the realized restrictions of the method BM-LCA, as well as how it can be further developed.

7.3.1. Possible improvements in future similar projects

For future studies, some proposed improvements are:

- Broader primary data collection, such as requesting data from suppliers, would allow a more accurate calculation of raw materials and suppliers' processes.
- Consideration of products going through multiple life cycles or the probability of turbochargers, new or REMAN, being collected as a core, could nuance the system to better represent the real scenario. This would mainly allow a more accurate flow of waste.
- It might be possible to describe the array of core quality, making the BM-LCA applicable to individual REMAN purchases of varying core qualities.
- The sensitivity analysis could combine the location and cost conditions (sections 5.1 and 5.2) by studying the production conditions of each country, showing a more realistic change in results when expanding to other countries.

- One improvement could be by modeling market scenarios and policy instruments on external drivers, for example, carbon pricing, increased tax on finite energy, or EPR laws. This could evaluate how sensitive the business models are under additional possible scenarios of the future.

7.3.2. Improvements and future research for BM-LCA

Expanding the business model perspective to a whole supply chain network perspective could be of interest. This could give a more society-related business perspective, as of now, there are other profits made by the suppliers, of which no impacts are allocated, so the total revenue gained across actors from the measured environmental strain is still unknown.

A business is more than just profit; the number of jobs and development of technology are a key part of societal welfare, and there might be more ways of defining the functional unit. More nuanced guidance on defining a business model could lead to other insightful results.

There are standardized ways of conducting both environmental and economic performance, such as EPD and financial reporting standards. Perhaps combinations of these could be developed so that they may be integrated into company practice, aiding in maintaining competitiveness during sustainable development.

To ease the adoption of BM-LCA, existing or new LCA softwares could be further developed, so it would fit the methodology of conducting a BM-LCA. Developing software for BM-LCA would help companies run their products and see where the hotspots are, and find improvements that can be made. Academic researchers can contribute by developing pilot models/projects and demonstrating them with case studies. One case study could be this project. The developer could demonstrate how the tool works and the kind of insights it can deliver.

8. Conclusion

In conclusion, BM-LCA was successfully applied to compare traditional and remanufacturing business models, integrating environmental and economic performance. The cases did not have any prior environmental assessment, so an LCA was performed and tied to economic performance as described by the method BM-LCA. The results consistently showed that the REMAN business model environmental performance is significantly better than BAU. Furthermore, REMAN showed that a larger part of the impact lay within the scope of the company, meaning that further decreases in impact are easier leveraged if the company wishes to continue developing its sustainability. Even though sourcing sustainable energy is critical for REMAN, the economic feasibility of changing production location is determined problematic, highlighting the options available locally, such as investing in additional renewable capacity or installing PV panels.

BM-LCA proved to be a valuable tool for finding insight related to decoupling. If companies were to integrate BM-LCA into their corporate sustainable aspirations, it would enable companies to learn more about what it means to run sustainable business models.

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