Annals of Operations Research
https://doi.org/10.1007/s10479-024-06014-4

ORIGINAL RESEARCH

Green PLM: business goals-oriented algorithm assessing the greenness of a product in the new product development phase for the automotive industry

Maria Rosienkiewicz[1,2] · Joanna Helman[1,2] · Mariusz Cholewa[1,2] · Mateusz Molasy[1,2] · Sylwester Oleszek[3] · Giovanni Berselli[4,5]

Received: 24 November 2023 / Accepted: 16 April 2024

Abstract

Sustainability-oriented new product development process is becoming of key importance in many sectors of the industry. Especially in the automotive industry, it plays a major role as this sector is historically associated with resource-intensive production and fossil fuel consumption, and thus has to implement solutions that will contribute to restraint of climate change. Manufacturing companies are currently faced with the challenge of adapting their business models to changing market expectations and requirements resulting from the sustainable development path. Moreover, the development of the new digital factories and pressure from the legislators require adjustment of existing Product Lifecycle Management systems. To enhance the concept of the Green Product Lifecycle Management which is still under development, in this work we propose a new three-step methodology composed of three main steps: (1) assessing indicators' importance for sustainable business goals and business models, (2) assessing indicators and their importance in the automotive industry, (3) assessing "greenness" of the product. This complex approach is innovative as it is based on the business-oriented perspective. Selecting suitable business goals and corresponding business models leads to the selection of the appropriate subset of green indicators. Several more aspects are taken into account in this holistic analysis: the indicator's features, relevance for the company, importance to sustainable business goals, importance in terms of subsectors of the automotive industry as well as environmental, economic, and social impact. This approach enables the company to compute the value of the greenness of the product in reference to the key green indicators.

✉ Maria Rosienkiewicz
maria.rosienkiewicz@pwr.edu.pl

1 Department of Laser Technologies, Automation and Production Management, Wroclaw University of Science and Technology, Lukasiewicza 5, 50-370 Wroclaw, Poland

2 Instytut Transferu Technologii Sp. z o.o, Na Grobli 15, 50-421 Wrocław, Poland

3 Transition Technologies PSC S.A, Piotrkowska 276, 90-361 Lodz, Poland

4 Department of Mechanical Engineering, Energetics, Management and Transportation, University of Genoa, Via all'Opera Pia 15/A, 16145 Genoa, Italy

5 ADVR, Department of Advanced Robotics, Istituto Italiano di Tecnologia, Via S. Quirico 19d, 16163 Genoa, Italy

Published online: 13 May 2024

Keywords Sustainability · Product lifecycle management · Business goals · Digital manufacturing · Automotive industry · Circular economy

1 Introduction

Sustainability-oriented new product development (NPD) process is becoming of key importance in many sectors of the industry. Especially in the automotive industry, it plays a major role as this sector is historically associated with resource-intensive production and fossil fuel consumption, and thus has to implement solutions that will contribute to restraint of climate change. Embracing sustainability in the new product development process is in fact a strategic necessity for the automotive industry's long-term viability. Practices based on green economy, circular economy, and sustainability not only lead to reducing the net greenhouse gas emissions but also enhancing overall corporate responsibility. When designing a new product, a company is faced with the choice of hundreds, if not thousands, of possible variants ranging from the use of eco-friendly materials to the integration of energy-efficient manufacturing technologies. Selection of the optimal variant of the final product is extremely tough nowadays—it is often a compromise between manufacturing cost, time, and environmental footprint. Therefore, from the scientific point of view, it is very important to support industrial companies with solutions enabling the proper choice in this context. What is more, sustainability-oriented new product development process is in line with the growing consumer demand for environmentally conscious choices, thus fostering brand loyalty and market competitiveness. As the world struggles with the urgent need to transition towards greener economies, the automotive industry's commitment to sustainability not only mitigates environmental, economic, and social impacts but also positions it as a proactive contributor to global efforts in achieving a more sustainable future. Without a doubt, companies operating in the automotive sector are and will be—both directly and indirectly—forced to change their manufacturing processes in order to meet regulations concerning environmental protection. In Europe, a number of documents indicate a direction in which manufacturing companies should be oriented—e.g.:

(1) *European green deal* which is trying "to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels" ("The European Green Deal" 2021);
(2) *Fit for 55* package which "is a set of proposals to revise and update EU legislation and to put in place new initiatives with the aim of ensuring that EU policies are in line with the climate goals agreed by the Council and the European Parliament" ("Fit for 55" 2023);
(3) *Circular economy action plan* which provides "provides a future-oriented agenda for achieving a cleaner and more competitive Europe in co-creation with economic actors, consumers, citizens and civil society organisations. It aims at accelerating the transformational change required by the European Green Deal, while building on circular economy actions" (Commission and Communication 2020);
(4) *Ecodesign directive* that successfully regulates energy efficiency and some circularity features of energy-related products (*Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast) (Text with EEA relevance)* 2009);
(5) *EU ecolabel* "helps consumers, retailers and business make truly sustainable choices. The EU Ecolabel logo has become a byword for quality while meeting the highest

environmental standards. It means products (goods and services) displaying the iconic "EU flower" symbol meet all the criteria and have earned the right to join the growing EU Ecolabel Community" (*Regulation (EC) No 66/2010 of the European Parliament and of the Council of 25 November 2009 on the EU Ecolabel (Text with EEA relevance)* 2009);

(6) *EU green public procurement (GPP)* is defined as "a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their lifecycle when compared to goods, services and works with the same primary function that would otherwise be procured"("Green Public Procurement" n.d.).

(7) *Carbon border adjustment mechanism (CBAM)* regulation it is "one of the key elements of the European Union's 'Fit for 55' package.(…) CBAM targets imports of carbon-intensive products, in full compliance with international trade rules, to prevent offsetting the EU's greenhouse gas emissions reduction efforts through imports of products manufactured in non-EU countries, where climate change policies are less ambitious than in the European Union. It will also help prevent the relocation of the production or the import of carbon-intensive products. The products of the following sectors will be covered by CBAM: cement, aluminium, fertilisers, electric energy production, iron and steel"("Council agrees on the Carbon Border Adjustment Mechanism (CBAM)" n.d.).

Bearing in mind the above-listed issues, it can be stated that the development of solutions enhancing companies from the automotive industry in the new product development process is of high importance. Therefore, the research presented in this paper focus on this particular topic. On the contrary to well-known methods used widely in the industry (like e.g. Lifecycle Assesment LCA) the authors of this paper propose a new approach in assessing greeness of a product—it is based on a business goals-oriented algorithm applied to the new product development phase for the automotive industry. The presented paper is divided into 5 main chapters. At first literature review is presented and discussed. Literature analysis covers topics related to (1) sustainability-oriented business models, (2) Green Product Lifecycle Management (PLM) and (3) automotive industry. Based on obtained results, the aim of research is defined. Subsequently, a three-step research methodology is described and explained. Finally, results and conclusions are presented. The research—based on which the paper was created—was carried out within the GreenPLM project commissioned by Transition Technologies PSC S.A. This paper is a follow-up of a paper entitled "Towards GreenPLM—Key Sustainable Indicators Selection and Assessment Method Development" (Helman et al., 2023). In the mentioned paper the primary scientific goal was to offer a methodical way to choose and assess sustainability indicators for use in the various stages of the automotive lifecycle management. By determining which sustainability indicators are pertinent to each stage of the product lifecycle, the application's principal objective is to assist the industry in its pursuit of more environmentally friendly development. As a result, the important green indicators for the automotive sector in line with the GreenPLM concept are highlighted, together with their classification into the early stages of the car's lifecycle and prospective data sources. The paper written by Helman et al. introduces the idea of GreenPLM and the potential uses for it in the future (Helman et al., 2023). In the present paper, further analysis is carried out, which focuses on the development of a new—based on sustainability- oriented business goals—approach enabling assessing greenness of a product in the automotive industry.

2 Literature analysis

2.1 Sustainability-oriented business models

Nowadays, a highly developed economy and strong market competitiveness force companies not only to continuously increase the effectiveness in every area, but also—like never before—to take into consideration environmental aspects (Kochańska, 2024). Manufacturing companies are currently faced with the challenge of adapting their business models to changing market expectations and requirements resulting from the sustainable development path. Business model can be defined as "a conceptual tool containing a set of objects, concepts and their relationships with the objective to express the business logic of a specific firm" (Osterwalder et al., 2005). It helps to understand how a company does a business and it can be used for analysis, comparison and performance assessment, management, communication, and innovation (Bocken et al., 2014). It answers a series of questions essential to any business, i.e. who are the customers, what do they value, how that value can be delivered to the customer at an appropriate cost and how the business deploys its assets. Business model includes a description of the key assets and are concerned with how the firm defines its competitive strategy through the design of the product or service it offers to its market, how it charges for it, what it costs to produce, how it differentiates itself from other firms by the value proposition, and how the firm integrates its own value chain with those of other firm's in a value network (Rasmussen, 2007). Business models cover two main spheres: the first sphere is operations and related resources, the second sphere is about created and captured value (Rudnicka, 2016). The central point of every business model is value proposition ("BS8001:, 2017 BSI Knowledge" 2017). As presented in the Introduction, changing business models into those supporting green economy, circular economy and sustainability is no longer a need, but rather necessity. Business models (innovations) for sustainability can be defined as "innovations that create significant positive and/or significantly reduced negative impacts for the environment and/or society, through changes in the way the organization and its value-network create, deliver value and capture value (i.e. create economic value) or change their value propositions" (Bocken et al., 2014). Also, the transition to a circular economy requires significant changes in the way organizations operate. The transition to the circular economy often entails holistic adaptations in firms' business models or even the creation of new ones. The implementation of circular economy principles often requires new visions and strategies and a fundamental redesign of product concepts, service offerings, and channels towards long-life solutions. CE principles also affect how companies can make money, with the ownership structure perhaps shifting, boosting demand for services along the product lifecycle (Ferasso et al., 2020). Early developments of sustainable business models link the concept of sustainability with innovation. Namely, the sustained success of an organization depends on innovation. Rules determining the functioning of a sustainable business model need to be based on creating technological innovations that can create new markets after being commercialized (Boons & Lüdeke-Freund, 2013). Schaltegger et al. define a business model for sustainability as one which helps in describing, analyzing, managing, and communicating as follows (Schaltegger et al., 2016):

1. a company's sustainable value proposition to its customers, and all other stakeholders,
2. how it creates and delivers this value,
3. how it captures economic value while maintaining or regenerating natural, social, and economic capital beyond its organizational boundaries.

Wells states that "a sustainable product cannot be produced by an unsustainable industry" (Wells, 2013). The author considers defining a sustainable automotive industry that is "one that creates life-enhancing employment for communities over a long period of time. It has zero net consumption of physical resources in production. It is consistently profitable while being able to withstand short-term fluctuations in economic circumstances. And it produces products that themselves do not pollute or otherwise degrade the environment, are fit for purpose, and are designed for longevity" (Wells, 2013). This definition suggests that, over time, manufacturing as such (of new, complete products) is only a small part of the business model, that concepts such as product-service systems are more appropriate. It is recognised that profitability is absolutely vital for sustainability. However, profitability is a necessary but insufficient condition for sustainability: the environmental and social dimensions must also be included.

Jonker and O'Riordan define four criteria that a sustainable business model must meet. They are: sharing knowledge, making connections (sustainability is between companies), awareness and multiple value creation (Jonker & O'Riordan, 2016). As the traditional business model elements are insufficient for showing the full relationships and values into the direction of sustainable development in business context, Rudnicka presented elements of business models including sustainability issues in (Rudnicka, 2016). Bocken et al. identified eight sustainable business model archetypes on the basis of analysis of practice and literature business model examples. The archetypes are classified in higher order groupings that describe main types of business models innovations: technological, social, and organizational oriented innovations. They are as follows (Bocken et al., 2014):

1. maximizing material and energy efficiency,
2. creating value from 'waste',
3. substitute with renewables and natural processes,
4. delivering functionality rather than ownership,
5. adopting a stewardship role,
6. encouraging sufficiency,
7. re-purposing the business for society/environment,
8. developing scale-up solutions.

Clinton and Whisnart presented 20 business model innovations for sustainability. They have been categorized into 5 categories, however authors admit that some business models fit into multiple categories. They are as follows (Clinton & Whisnant, 2019):

- category of environmental impact
  1. Closed Loop Production,
  2. Physical to Virtual,
  3. Produce on Demand,
  4. Rematerialization,
- category of social impact
  5. Buy One, Give One,
  6. Cooperative Ownership,
  7. Inclusive Sourcing,
- category of financial impact
  8. Crowdfunding,
  9. Differential Pricing,

10. Freemium,
11. Innovative product financing,
12. Pay for Success,

- category of social innovation focused on “the base of the pyramid”

13. Building a Marketplace,
14. Microfinance,
15. Micro-Franchise,
16. Subscription Model,

- category of diverse impact

17. Alternative Marketplaces,
18. Behavior Change,
19. Product as a Service,
20. Shared Resource.

The value proposition seems central to any business model, because it defines the products/services that create value for the organization’s existing and/or new customer base. It also relates to the viability of the business model, because it identifies how the organization makes money. For organizations transitioning to more circular and sustainable operations, the value proposition might not be solely financial in nature and instead reflect delivery of wider social and/or environmental benefits (“BS8001:, 2017 BSI Knowledge” 2017). Referring to the circular economy, Mentink (2014) identified the changes of business model components needed for developing a more circular service model. They are as follows:

- “value propositions (what?)—products should become fully reused or recycled, which requires reverse logistics systems, or firms should turn towards product-service system (PSS) and sell performance related to serviced products,
- activities, processes, resources and capabilities (how?)—products have to be made in specific processes, with recycled materials and specific resources, which may require not only specific capabilities but also creating reverse logistics systems and maintaining relationships with other companies and customers to assure closing of material loops,
- revenue models (why?)—selling product-based services charged according to their use,
- customers or customer interfaces (who?)—selling circular products or services may require prior changes of customer habits or, if this is not possible, even changes of customers” (Lewandowski, 2016).
- Laubscher and Marinelli (Laubscher & Marinelli, 2014) identified six key areas for integration of the circular economy principles with the business model. They are as follows: sales mode, product design/material composition, IT/data management, supply loops, strategic sourcing for own operations, HR/incentives (Lewandowski, 2016).

In order to provide a framework for and guidance on implementing the principles of the circular economy within organizations, the British norm BS 8001:2017 has been developed (“BS8001:, 2017 BSI Knowledge” 2017). The guidance is intended to apply to any organization, regardless of location, size, sector and type. In the norm six general business model groupings have been introduced that have the potential to be compatible with a circular economic system. They are as follows and they include following specific business models (“BS8001:, 2017 BSI Knowledge” 2017):

1. On-demand

    - business model “produce on demand/made to order”,

2. Dematerialization
    - business model "digitalization",
3. Product lifecycle extension/reuse
    - business model "product life-extension",
    - business model "facilitated reuse",
    - business model "product modular design",
    - business model "refurbish, repair, remanufacture and recondition".
4. Recovery of secondary raw materials/by-products
    - business model "recovery of secondary materials/by-products (including recycling)",
    - business model "incentivized return/extended producer responsibility".
5. product as a service/product–service system (PSS)
    - business model "lease agreement",
    - business model "performance based (pay for success)",
6. sharing economy and collaborative consumption
    - business model "sharing economy",
    - business model "sharing platforms/resources (collaborative consumption)".

It has been assumed that these business models are not mutually exclusive. In order to realize its value proposition an organization might need to adopt a business model which includes elements of each of them. Moreover, complex organizations might concurrently have different business models operating across their divisions/units and for different product/markets ("BS8001:, 2017 BSI Knowledge" 2017).Popular circular economy business models collected by Lewandowski are as follows (Lewandowski, 2016):

- classification criteria: renegade
    1. Energy recover—the conversion of non-recyclable waste materials into useable heat, electricity, or fuel,
    2. Circular supplies—using renewable energy,
    3. Efficient buildings—locating business activities in efficient buildings,
    4. Sustainable product locations—locating business in eco-industrial parks,
    5. Chemical leasing—the producer mainly sells the functions performed by the chemical, so the environmental impacts and use of hazardous chemical are reduced,
- classification criteria: share
    6. Maintenance and Repair—product lifecycle is extended through maintenance and repair,
    7. Collaborative Consumption, Sharing Platforms, PSS[1]: Product renting, sharing or pooling—enable sharing use, access, or ownership of product between members of the public or between businesses,
    8. PSS: Product lease—exclusive use of a product without being the owner,
    9. PSS: Availability based—the product or service is available for the customer for a specific period of time,
    10. PSS: Performance based—the revenue is generated according to delivered solution, effect or demand-fulfillment,

[1] PSS: product-service systems.

11. Incentivized return and reuse or Next Life Sales—customers return used products for an agreed value. Collected products are resold or refurbished and sold,
12. Upgrading—replacing modules or components with better quality ones,
13. Product Attachment and Trust—creating products that will be loved, liked or trusted longer,
14. Bring your own device—users bring their own devices to get the access to services,
15. Hybrid model—a durable product contains short-lived consumables,
16. Gap-exploiter model—exploits "lifetime value gaps" or leftover value in product systems. (e.g., shoes lasting longer than their soles),

- classification criteria: optimize

17. Asset management—internal collection, reuse, refurbishing and resale of used products,
18. Produce on demand—producing when demand is present and products were ordered,
19. Waste reduction, Good housekeeping, Lean thinking, Fit thinking—waste reduction in the production process and before,
20. PSS: Activity management/outsourcing—more efficient use of capital goods, materials, human resources through outsourcing,

- classification criteria: loop

21 Remanufacture, Product Transformation—restoring a product or its components to "as new" quality,
22. Recycling, Recycling 2.0, Resource Recovery—recovering resources out of disposed products or by-products,
23. Upcycling—materials are reused and their value is upgraded,
24. Circular Supplies—using supplies from material loops, bio based- or fully recyclable,

- classification criteria: virtualize

25. Dematerialized services—shifting physical products, services or processes to virtual,

- classification criteria: exchange

26. New technology—new technology of production.

On the basis of analysis of fore mentioned business models Lewandowski (2016) proposes a circular business model canvas, that is extended and adjusted to the circular economy version of the business model canvas developed by Osterwalder and Pigneur (2010). The building blocks allow for designing of a business model according to the principles of circular economy, and consists of value propositions, customer segments, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, cost structure, take-back system, adoption factors (Lewandowski, 2016). Another nineteen circular business models grouped into 6 groups have been proposed by IMSA, an independent think tank and consultancy & research firm committed to the environment, sustainability and innovation, headquartered in Amsterdam. They can be found in ("Circular Future—Public Affairs and consultancy about Circular Economy" 2022). Four main business models that circulate products and materials in the economy, and have the potential to decouple revenue streams from production and resource use, have been presented by Ellen MacArthur Foundation. They are: "Resale" business model, "Rental" business model, "Repair" business model, "Remaking" business model (Ellen MacArthur Foundation, 2021). The business model approach seems useful for analyzing and improving sustainability, because business models can be viewed as activity systems that cover internal and external activities in which companies are engaged. When activities represent sustainable issues, they are best represented by the practical descriptions, communication, and expression of activities of companies (Ritala et al., 2018). Analysis of Green Supply Chain Management operations used by Ford, BMW, Toyota, and BYD has been performed by Sanghavi et. al and is presented in (Sanghavi et al., 2015).

Literature review focused on sustainability-oriented business models shows that a lot of studies have been dedicated to this topic. Numerous classifications have been developed and described. Companies, depending on their business goals, can suitably choose a proper business model to start their transition process towards sustainability and green economy.

2.2 Green product lifecycle management

Product Lifecycle Management is facing a major change. New phenomena are emerging in new product development—including crowdsourcing, crowdfunding, and gamification (Molasy et al., 2023). Development of the new digital factories and pressure from the legislators require adjustment of existing PLM systems. They need to support the companies in terms of collaborative processes and workflows to enhance sustainable information sharing.

According to Belkadi et al., the key challenge in this context is not only the definition of information flow between all involved entities in the sustainability process but also the mapping of information between different production lifecycle phases (Belkadi et al., 2015). In the investigated area a number of definitions have been developed to better precise the emerging area, including sustainable products (Bangsa & Schlegelmilch, 2020), Closed Loop Lifecycle Management (CL2M), Green Information Systems, Sustainable PLM, and Intelligent Products (Främling et al., 2013). In terms of sustainable products a number of indicators can be considered in order to provide the customers with the appropriate assurance and information about their sustainability performance (Bangsa & Schlegelmilch, 2020). According to Främling et al. Sustainable PLM can be defined as a type of Closed Loop Lifecycle Management (CL2M). The key feature is the possibility to connect Intelligent Products with each other and at the same time with other information systems. The systems that are called Green Information Systems (Green IS) aim at reducing environmental impacts (Främling et al., 2013). Their focus is to reduce"the production of CO_2 and other greenhouse gases through new combinations of people, processes, and technologies that enable the processing of digitized information" (Främling et al., 2013). Främling et al. underline that the main purpose of CL2M is to constantly improve design, manufacturing, use and end-of-life handling of products, in order to obtain "improved quality, less breakdowns, reduced need for spare parts and ensuring an operation that is continuously maintained at the most energy- and resource-efficient level" (Främling et al., 2013). According to Främling et al. Sustainable PLM should be understood as CL2M for the purpose of improving environmental sustainability during all phases of the lifecycle. A key issue in terms of Sustainable PLM or so called Green PLM is related to measurement of environmental sustainability and ways to improve it. Therefore, it is crucial to measure, gather, and analyse data and corresponding indicators which can be a firm basis and a trigger for companies in their shift towards green production. A helpful approach in this process is LCA, which stands for Lifecycle Assessment or Lifecycle Analysis defined a methodological framework for estimating and assessing the environmental impacts attributable to the lifecycle of a product (Främling et al., 2013). According to Främling et al., it is hard to extend and/or adapt existing ERP systems to the requirements of Sustainable PLM. Främling et al. state that "it is likely that an easier, safer, and more scalable approach is to develop and increase the use of Intelligent Product-based information systems separately and communicate with stock-based information systems using their own external interfaces. The multi-organizational, multi-manufacturer, etc., reality and requirements of Sustainable PLM can only be met in a scalable way if ad hoc, loosely coupled interoperability between devices and other information systems is technically easy and economically feasible enough. Failing to recognize the importance of loosely coupled integration can delay the speed of evolution and adoption of Sustainable PLM" (Främling et al., 2013). According to Vila et al. (2015) a Green PLM strategy should be composed of mission, vision and objective. They propose an approach to product lifecycle with green competencies as well as Green Product Lifecycle Framework. Green Product Lifecycle Framework should be composed of 3 main phases (Vila et al., 2015):

1. Design-Development phase, focused on Eco Design and Green Development, composed of: Strategic Planning, Conceptual Design, Embodiment Design, Detail Design, Manufacturing Plan;
2. Manufacturing phase focused on Green Manufacturing and Sustainable Production, composed of: Storage Package, Assembly, Production, Production Control, Resource Management;
3. Service phase, focused on Sustainable Logistics, Product Special Response and Responsible Use and Maintenance, composed of: Logistics, Sales, Delivery, Client Service, Reduce/Reuse/Retire/Recycle;

For each of the 3 above-mentioned phases, Vila et al. propose an approach based on dedicated methods, tools and knowledge, as follows (Vila et al., 2015):

1. Design-Development phase:
   - *Methods*: Design for environment (Eco Design), Eco-standards application
   - *Tools*: Eco CAD/CAE/CAM tools, Lifecycle management tools (PLM)
   - *Knowledge*: Product lifecycle assessment, Materials and process selection
2. Manufacturing phase:
   - *Methods*: Design for sustainable manufacturing, Green Supply chain management
   - *Tools*: Green manufacturing, Intelligent/smart sensors/controls, Green energies
   - *Knowledge*: New materials, New manufacturing technologies
3. Service phase:
   - *Methods*: Design for Sustainable Maintenance, Sustainable service system
   - *Tools*: Product Usefulness Time Control, Sustainable Use Scorecard
   - *Knowledge*: Energy consumption (CO2 impact), Maintenance and care.

Marcon et al. propose another framework for a green product. They divided green product attributes' groups into 3 main product lifecycle phases, namely—(1) Production, (2) Use and (3) End-of-life (Marcon et al., 2022). Recently, the Brazilian automotive industry has been pressured by stricter environmental laws and regulations focusing on adopting more green production processes, whereas consumers have increased demand for green products. In this context, De Medeiros et al. investigated behavioural motivation for green product consumption. They focused their research on the decision-making process regarding the purchase of cars and furniture (de Medeiros et al., 2016). According to the obtained results de Medeiros et al. prove that "if the prices of products with and without ecological appeal were the same, 95% of the respondents would prefer to buy the green product". This key finding from this research provides the manufacturers with very important information.

2.3 Automotive industry insight

The automotive industry comprises of a wide range of companies and organizations involved in the design, development, manufacturing, marketing, and selling of motor vehicles. It can be divided into sectors in many different aspects. For the purpose of this research the four classifications were taken into account—namely: (1) Global Industry Classification Standard, (2) Industry classification taxonomy, (3) Refinitiv Business Classification and (4) Automotive supply chain actors.

The Global Industry Classification Standard, developed by S&P Dow Jones Indices, was designed in response to the global financial community's need for accurate, complete and standard industry definitions ("Global Industry Classification Standard" 2018). The GICS structure consists of 11 Sectors, 24 Industry groups, 69 Industries and 158 sub-industries. Under the sector of Consumer Discretionary, the Automobiles & Components industry group can be found. It is divided into two industries with two sub-industries (each) are indicated. They are as follows:

- Auto Components
  - Auto Parts and Equipment
  - Tires and Rubber
- Automobiles
  - Automobile Manufacturers
  - Motorcycle Manufacturers

Industry classification taxonomy developed for the Industrial Classification Benchmark (ICB) is a widely used standard of detailed and comprehensive structure for sector and industry analysis, facilitating the comparison of companies across four levels of classification and national boundaries. Its taxonomy covers a robust system of 11 Industries with 20 Supersectors and 45 Sectors detailed into 173 Subsectors ("Industry Classification Benchmark" 2022). Under the industry of Consumer Discretionary, the supersector of Automobiles and Part can be found. It is divided into 4 subsectors ("Industry Classification Benchmark" 2022):

- Auto Services—Companies that provide assistance to individual vehicle owners.
- Tires—Manufacturers, distributors and retreaders of automobile, truck and motorcycle tires
- Automobiles—Makers of passenger vehicles, including cars, sport utility vehicles (SUVs) and light trucks. Excludes makers of heavy trucks and makers of recreational vehicles (RVs and ATVs).
- Auto Parts—Manufacturers and distributors of new and replacement parts for motorcycles and automobiles, such as engines, carburettors and batteries. Excludes producers of tires, which are classified under Tires Subsector.

A similar division is presented by Refinitiv Business Classification (previously called Reuters Business Sector Scheme as well as Thomson Reuters Business Classification, developed by the Reuters Group. It is a market-based classification scheme, similar to the GICS and ICB systems. The automotive industry is represented by Consumer Cyclicals economic sectors in Automobiles & Auto Parts business sector. The industry group of Automobiles & Auto Parts covers 3 types of industries that are divided into the following activities ("TRBC Sector Classification" n.d.):

- Auto and Truck Manufacturers

  - Auto and Truck Manufacturers
  - Motorcycles and Scooters
  - Automobiles and Multi Utility Vehicles
  - Light Trucks
  - Electric (Alternative) Vehicles
  - Luxury Vehicles
  - Auto & Truck Wholesale

- Auto, Truck & Motorcycle Parts

  - Auto, Truck & Motorcycle Parts
  - Automotive Body Parts
  - Engine & Powertrain Systems
  - Automotive Batteries
  - Automotive Systems
  - Automotive Accessories
  - Motorcycle Parts & Accessories
  - Auto & Truck Parts Wholesale

- Tires & Rubber Products

  - Tires & Rubber Products
  - Tire & Tube Manufacturers
  - Tire Retreading
  - Industrial Rubber Products
  - Rubber Plantations
  - Tires & Rubber Products Wholesale

The other type of the classification of the automotive industry is its division into supply chain actors, where at least 4 levels can be distinguished ("Driving Innovation for Automotive Manufacturing Tier 1 Suppliers" n.d.):

1. Tier 3—suppliers of raw and semi-raw materials,
2. Tier 2—non-automotive grade parts,
3. Tier 1—automotive parts and systems,
4. OEM—Original Equipment Manufacturer.

Above-presented classifications prove that the automotive industry is complex and is divided into many subsectors. Its influence from the global perspective is huge. Thus, the car sector is regarded as one of the primary causes of the environmental problem on the planet. Additionally, it has been demonstrated that the social and environmental aspects are negatively impacted by existing methods in the automotive industry. On the other hand, any nation's economic development depends heavily on the automotive industry. As a result, the sector needs to drastically alter its current operational procedures (Helman et al., 2023). Currently, according to Golinska-Dawson (2019) the Automotive Parts Remanufacturers Association (APRA) "identifies over 50 different components which are currently remanufactured". Although the material flow in remanufacturing process can be assessed as much more complex than in the primary manufacturing process (Golinska-Dawson & Pawlewski, 2015), Kosacka-Olejnik et al. (2020) emphasise that remanufacturing is set to become an increasingly important player in the future manufacturing industry with an EU market potential of €90 billion by 2030 according to the European Remanufacturing Network. Certain publications mention that sustainability-oriented goals are still not seen as being as significant in the manufacturing sector as traditional productivity targets, yet this is slowly changing

(Kochańska & Burduk, 2023). Sliż and Wycinka underline that in order to decrease the negative influence on the economy and environment, attempts are made to design vehicles in a way which reduces both CO_2 emissions, and fuel consumption as well as replaces internal combustion engines with electric units (Sliż & Wycinka, 2021). To reduce negative environmental impact, engine emission standards are getting stricter – i.a. ambitious goals to reduce the concentrations of hazardous compounds in the exhaust gases were supplemented by strict requirements for the reduction of the concentration and volume of solid particles (Žvirblis et al., 2023). It is crucial to develop methods that allow to perform the same processes but with the more ecologically-oriented solutions—i.e. by the reduction of pollutant emissions (Łapczyńska, 2023) or by optimizing transportation processes, as they are one of the most important sources of waste, no matter how necessary transport is. (Kochańska et al. Early Access). All the mentioned requirements and trends cause the automotive industry to make the new product development process greener. Therefore, in the automotive sector, sustainability metrics, particularly those pertaining to the environmental aspect, have gained substantial attention.

2.4 Significance and aim

The literature review presented in the previous chapters leads to certain important conclusions. First of all, many business models for sustainability have been developed so far. Companies, depending on their business goals, can suitably choose a proper business model to start their transition process towards sustainability and a green economy. Moreover, the transition towards digital manufacturing and legislative pressure cause a need to modify the current PLM systems. They must assist the businesses with their collaborative workflows and processes in order to improve sustainability- and green-oriented processes. The concept of the Green Product Lifecycle Management is still under development. It can also be noted that the new product development (NPD) phase is crucial from the perspective of further environmental impact. In general, there are certain methods—the majority of them based on Lifecycle Assessment (LCA) approach, yet a dedicated solution based on sustainability-oriented business models is missing. Last, but not least, it should be emphasized that especially the automotive industry—due to its huge impact on the environment—requires a radical shift in the way it performs usual business practices Based on these conclusions, the main aim of the paper was derived. Bearing in mind a number of existing sustainability-oriented business models, and a need of development PLM systems towards greenness (especially in the NPD process) and major shift within the automotive industry, the main aim of this paper is to develop a new approach to assessing greenness of a product which would be based on a business goals-oriented algorithm and applied to the new product development phase for the automotive industry. This algorithm will be applied to the 20 indicators identified within the first stage of the research described in the paper "Towards GreenPLM—Key Sustainable Indicators Selection and Assessment Method Development" (Helman et al., 2023).

3 Research methodology

In order to reach the above-mentioned aim, the three-step research methodology was proposed. It is composed of 3 main steps:

Step 1: assessing indicators' importance for sustainable business goals and business models.
Step 2: assessing indicators and their importance in the automotive industry.

Fig. 1 Step 1: Methodology of assessing indicators' importance for sustainable business goals and business models; own elaboration

Step 3: assessing "greenness" of the product.

To assess the 20 indicators (selected in (Helman et al., 2023)) in terms of their importance for sustainable business goals and business models, the step 1 of the research methodology—presented in Fig. 1—has been developed. In the first stage, business goals need to be analyzed with respect to sustainability issues. Parallelly, business models focused on sustainability aspects should be analyzed. Next, to each of the defined business goals, corresponding business models must be identified, and their impacts on sustainability should be indicated (selecting from: environmental, economic and/or social). The final step of the methodology is to assign indicators that can be used to achieve defined business goals and corresponding business models.

Once the 20 indicators will be assessed in terms of their importance for sustainable business goals and business models according to the step 1, the methodology for assessing indicators and their importance in the automotive industry will be applied (step 2). The scheme of the proposed methodology is presented in the figure below. At first five overarching assessment criteria are defined, namely:

1. Indicator's features,
2. Relevance for the company,
3. Importance to sustainable business goals,
4. Importance in terms of subsectors,
5. Environmental, Economic, Social impact.

Some of the overarching criteria have been detailed to more precisely assess the indicators:

1. Indicator's features:

a. availability of data,
b. durability (low variability over time),
c. need of monitor—cost of collecting,
d. preciseness/quality/confidence level,
e. ease of indicator-related data processing,
f. standardized indicator,

2. Relevance for the company,
3. Importance to sustainable business goals,
4. Importance in terms of subsectors:

a. Auto Services,
b. Tires,
c. Automobiles,
d. Auto Parts,

5. Environmental, Economic, Social impact:
Environmental impact:

Raw material extraction,
Emissions,
Modification of natural area,
Noise,

Economic impact:

Material cost of product,
Maintenance cost of product,
Manufacturing cost of product,
End-of-life cost of product,

Social impact:

Health and safety,
Socio-economic repercussion,
Governance by customers,
Human rights.

According to the step 2 of the research methodology presented in Fig. 2, each assessment criterion has to be analyzed and rated. The ratings for particular criteria are presented in the figure above. Once the points are assigned, an overall criterion assessment has to computed—for each overarching criterion separately. Subsequently, all calculated values have to be normalized to enable mutual comparison and further analysis. Thus mean of the overall normalized assessment for all five criteria can be estimated. Finally, the indicators can be sorted from the most relevant to the least relevant and the key sustainability-oriented indicators for Green PLM can be identified.

Once the key indicators are selected according to the step 2 of the methodology of assessing indicators and their importance in the automotive industry, they can be further analyzed in order to indicate how to use them in terms of the "greenness" of the product. The algorithm presented in Fig. 3 can serve as a tool helping a company to assess to what extent their product can be defined as "green".

A scheme presenting the step 3 of the research methodology, which is an algorithm assessing the "greenness" of a product, is in the figure below. It is composed of 10 steps.

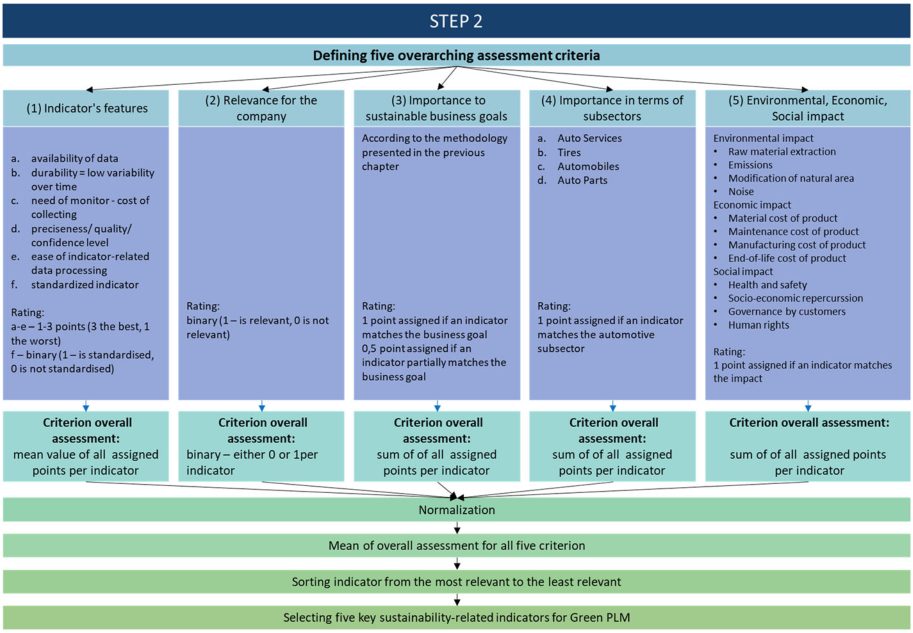

Fig. 2 Step 2: Methodology for assessing importance of indicators for the Green PLM project

In order to initiate the algorithm assessing the "greenness" of a product, a company has to first determine its business goals. Next, based on that, relevant indicators should be selected. In the following step, values of the indicators should be defined and (if needed) results aggregated. Next, the corresponding values of the final product and the critical value of the indicators in terms of the greenness of the product need to be defined. Subsequently, results for all analyzed indicators should be calculated. If the results meet the criterion 1 point for each indicator is assigned. Within another step, the weight of each of the criteria has to be defined and then summed up (value X). Next, for each indicator, the point value has to be multiplied by the criterion's weight and then summed up (value Y). Finally, Y by X should be divided. The obtained value defines the level of greenness of the product in percentage terms.

4 Results

4.1 Step 1: assessing indicators' importance for sustainable business goals

In the following chapters, the results obtained from the described three-step research methodology will be presented. At first, the procedure of assessing green indicators' importance for sustainable business goals will be applied.

According to the step 1 of the research methodology, business goals and business goals have to be identified at first. The review of numerous sustainability-oriented business models is presented in chapter 2.1, enabled to define the final list of the business models used in the

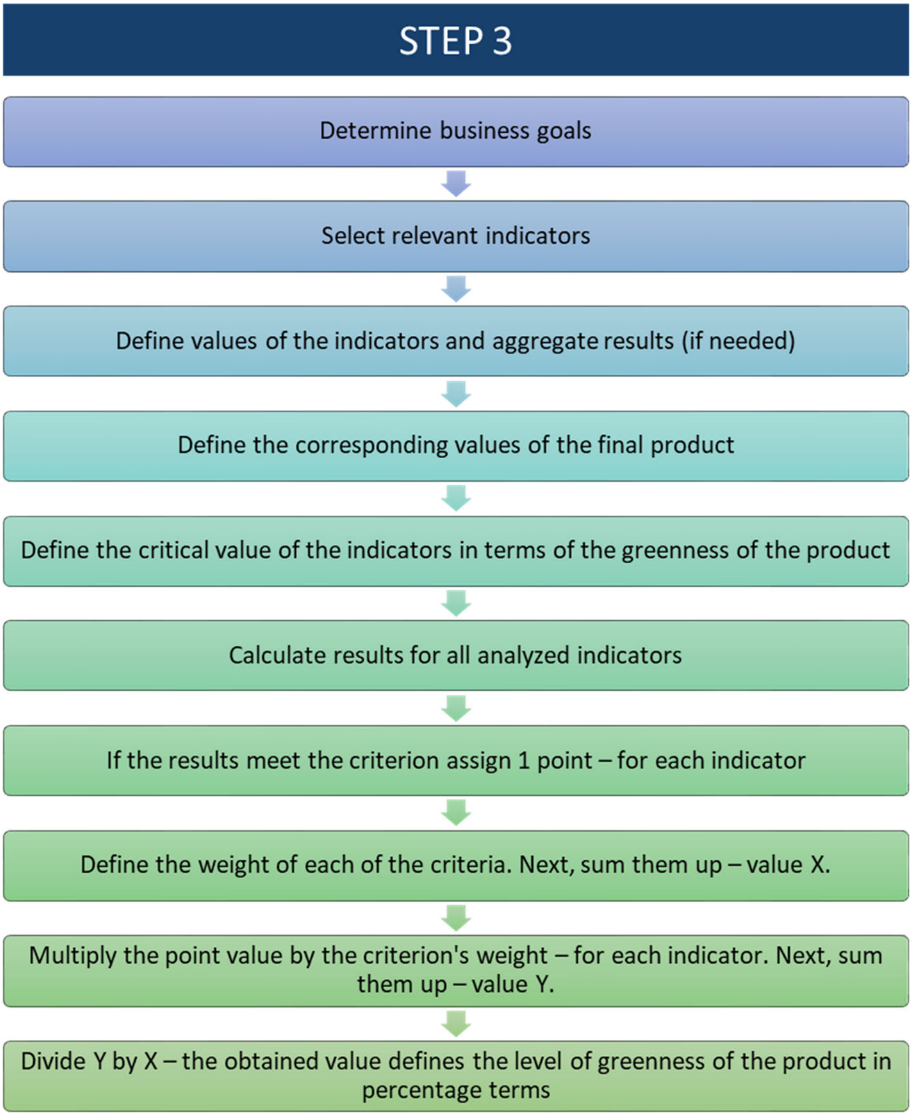

Fig. 3 Step 3: Algorithm assessing the "greenness" of a product

further analysis. The most suitable business models that are reflecting sustainable business goals were identified by:

- British norm BS 8001:2025 ("BS8001:, 2017 BSI Knowledge" 2017),
- Lewandowski (2016),
- IMSA ("Circular Future—Public Affairs and consultancy about Circular Economy" 2022),
- Clinton & Whisnart (2019),
- Ellen MacArthur Foundation (2021).

They are as follows:

- Produce on demand/made to order,
- Produce on demand,
- Remanufacture, Product Transformation,
- Recycling, Recycling 2.0, Resource Recovery,
- Closed loop production,
- Upcycle/upcycling,
- Digitalization,
- Dematerialized services,
- Physical to virtual,
- Product life-extension,
- Rental,
- Product as a service,
- Circular supplies,
- Repair,
- Facilitated reuse,
- Product modular design,
- Upgrading,
- Next life sales,
- Resale,
- Refurbish and resell,
- Refurbish, repair, remanufacture and recondition,
- Recovery of secondary materials/by-products (including recycling),
- Recycling (waste handling and repurpose),
- Remaking,
- Incentivized return/extended producer responsibility,
- Take back management,
- Asset management,
- Incentivized return and reuse or next life sales,
- Lease agreement,
- Innovative product financing,
- Pss: product lease,
- Sharing Economy,
- Collaborative Consumption, sharing platforms, pss: product renting, sharing or pooling,
- Collaborative production,
- Shared resource,
- Sharing platforms/resources (collaborative consumption),
- Sharing platforms,
- Pay per use,
- Rematerialization,
- Buy one, give one,
- Inclusive sourcing,
- Maintenance and repair,
- Freemium,
- Behavior change,
- Energy recover,
- Waste reduction, good housekeeping, lean thinking, fit thinking,
- Chemical leasing.

The business goals focused on implementing the principles of green economy are defined as follows:

- to minimize raw material and/or energy demand,
- to avoid overstocking,
- to replace physical infrastructure and assets with digital/virtual services,
- to design new products to be durable for a long lifetime (durability),
- to reuse parts/components with or without repair/upgrade,
- to encourage cost effective product repairs and reduce need for replacement of integrated components, thereby reducing resource consumption,
- to put the product back into the market to earn a second or subsequent income,
- to create products from secondary raw materials/by products and recycling,
- to recover used/unwanted products and sell it again,
- to increase overall profitability during the lease period,
- to strengthen community relationships,
- to reduce costs over directly sourcing the products/services,
- to increase utilization rate of products and services,
- to create an entirely new product from the source material (waste),
- to attract consumers to the cause (to donate a portion of the profits to those in need),
- to create more 'ethical' products by setting supplier standards or conducting audits (toward sustainable sourcing),
- to extend product lifecycle,
- to increase "stickiness" with the customer, making them less likely to buy from another good/service provider,
- to convert non-recyclable waste materials into useable heat, electricity, or fuel,
- to reduce waste in the production process and before,
- to cooperate in the production value chain leading to closing material loops,
- to reduce environmental impacts and use of hazardous chemical.

Below, for the three selected business goals, the examples of the explanatory results are presented.

Business goal: to minimize raw material and/or energy demand (Table 1).

Corresponding indicators:

- lightweight material
- sustainable material
- number of renewable parts
- number of reused parts assembled
- energy usage
- water usage
- amount of waste
- product size (partly)
- product weight (partly)
- amount of scrap (partly)

Business goal: to reuse parts/components with or without repair/upgrade (Table 2).

Corresponding indicators:

- number of renewable parts
- number of reused parts assembled
- energy usage water usage
- waste recycled/reused

Table 1 Business goal: to minimize raw material and/or energy demand

Business model	Impact	Typology
Produce on demand/made to order	Environmental, Economic	British norm BS 8001:2017
Produce on demand	Environmental, Economic	Lewandowski
Remanufacture, Product Transformation	Environmental, Economic	Lewandowski
Recycling, Recycling 2.0, Resource Recovery	Environmental, Economic	Lewandowski
Closed Loop Production	Environmental, Economic	Clinton and Whisnart
Upcycle	Environmental, Economic	IMSA
Produce on Demand	Environmental, Economic	Clinton and Whisnart

Table 2 Business goal: to reuse parts/components with or without repair/upgrade

Business model	Impact	Typology
Product as a Service	Environmental, Economic, Social	Clinton and Whisnart
Recycling, Recycling 2.0, Resource Recovery	Environmental	Lewandowski
Circular supplies	Environmental, Economic	Lewandowski
Repair	Environmental, Economic	Ellen MacArthur Foundation
Upcycling	Environmental, Economic	Lewandowski
Upcycling	Environmental, Economic	IMSA
facilitated reuse	Environmental	British norm BS 8001:2019

Business goal: to extend product lifecycle (Table 3).
Corresponding indicators:

- number of renewable parts
- number of reused parts assembled (partly)

Analogous analysis was performed for all the identified business goals. In the next step all indicators were analyzed under the aspect of their suitability to reach sustainable business goals. Indicators were assigned as corresponding (blue color in Table 4) or partly corresponding (light blue color in Table 4) to defined business goals (Table 4).

Table 3 Business goal: to extend product lifecycle

Business model	Impact	Typology
Product as a Service	Environmental, Economic, Social	Clinton and Whisnart
Rental	Environmental, Economic, Social	Ellen MacArthur Foundation
Maintenance and Repair	Environmental, Economic, Social	Lewandowski
Repair	Environmental, Economic, Social	IMSA
Freemium	Environmental, Economic, Social	Clinton and Whisnart

4.2 Step 2: Assessment of indicators and their importance in the automotive industry—presentation of results

According to the step 2 of the research methodology, the assessment of the 20 indicators has been performed by the Authors of this paper. Each of the five overarching assessment criteria (Indicator's features, Relevance for the company, Importance to sustainable business goals, Importance in terms of subsectors, Environmental, Economic, and Social impact) were assessed and presented in a separate table (namely Tables 5, 6, 7, 8, 9).

Based on the above-presented analysis, the last steps of step 2 of the research methodology were applied. The obtained results summarize the assessment in the five overarching criteria:

- Criterion 1: Indicator's features—mean value of all assigned points per indicator,
- Criterion 2: Relevance for the company—binary value per indicator,
- Criterion 3: Importance to sustainable business goals—sum of all assigned points per indicator,
- Criterion 4: Importance in terms of subsectors—sum of all assigned points per indicator,
- Criterion 5: Environmental, Economic, Social impact—sum of all assigned points per indicator.

They were normalized and the mean value was calculated for each indicator (I.1–I.20). The results can be found in Table 10.

Based on the above-presented computations, the key indicators for Green PLM were ranked in terms of their importance for the automotive industry from the sustainability-oriented perspective (see Fig. 4).

Implementation of the two steps of the three-step methodology enabled selection of the key indicators in terms of their importance in the automotive industry and at the same time the indicators that can be used as key sustainability-related indicators for Green PLM development. The five key indicators are:

1. number of reused parts assembled,
2. sustainable material,
3. number of renewable parts,
4. hazardous material,
5. non-polluting material.

They have been indicated as the most important and versatile due to the reason that they simultaneously:

Table 4 Sustainability-oriented business goals linked to green PLM indicators

Sustainability-oriented business goals	Green indicators									
	I.1 Non-polluting material	I.2 Hazardous material	I.3 Lightweight material	I.4 Sustainable material	I.5 Material carbon footprint	I.6 Material water footprint	I.7 Number of renewable parts	I.8 Number of reused parts assembled	I.9 Reduced water consumption of product	I.10 Product size
Impact sum	2	2	1	5	2	2	7	7.5	1	*0.5*
To minimize raw material and/or energy demand			**1**	**1**			**1**	**1**		*0.5*
To avoid over-stocking										
To replace physical infrastructure and assets with digital/virtual services										
To design new products to be durable for a long lifetime (durability)				**1**					*0.5*	

Table 4 (continued)

Sustainability-oriented business goals	Green indicators									
	I.1 Non-polluting material	I.2 Hazardous material	I.3 Lightweight material	I.4 Sustainable material	I.5 Material carbon footprint	I.6 Material water footprint	I.7 Number of renewable parts	I.8 Number of reused parts assembled	I.9 Reduced water consumption of product	I.10 Product size
To reuse parts/components with or without repair/upgrade							**1**	**1**		
To encourage cost-effective product repairs and reduce need for replacement of integrated components, thereby reducing resource consumption							**1**	**1**		
To put the product back into the market to earn a second or subsequent income							**1**	**1**		
To create products from secondary raw materials/by-products and recycling				**1**			**1**	**1**		

Table 4 (continued)

Sustainability-oriented business goals	Green indicators									
	I.1 Non-polluting material	I.2 Hazardous material	I.3 Lightweight material	I.4 Sustainable material	I.5 Material carbon footprint	I.6 Material water footprint	I.7 Number of renewable parts	I.8 Number of reused parts assembled	I.9 Reduced water consumption of product	I.10 Product size
To recover used/unwanted products and sell it again							**1**	**1**		
To increase overall profitability during the lease period									*0.5*	
To strengthen community relationships										
To reduce costs over directly sourcing the products/services										
To increase utilization rate of products and services								**1**		
To create an entirely new product from the source material (waste)										
To attract consumers to the cause (to donate a portion of the profits to those in need)				**1**	**1**	**1**				

Table 4 (continued)

Sustainability-oriented business goals	Green indicators									
	I.1 Non-polluting material	I.2 Hazardous material	I.3 Lightweight material	I.4 Sustainable material	I.5 Material carbon footprint	I.6 Material water footprint	I.7 Number of renewable parts	I.8 Number of reused parts assembled	I.9 Reduced water consumption of product	I.10 Product size
To create more 'ethical' products by setting supplier standards or conducting audits (toward sustainable sourcing)	1	**1**		**1**	**1**	**1**				
To extend product lifecycle							**1**	*0.5*		
To increase "stickiness" with the customer, making them less likely to buy from another good/service provider										
To convert non-recyclable waste materials into useable heat, electricity, or fuel										
To reduce waste in the production process and before										

Table 4 (continued)

Sustainability-oriented business goals	Green indicators									
	I.1 Non-polluting material	I.2 Hazardous material	I.3 Lightweight material	I.4 Sustainable material	I.5 Material carbon footprint	I.6 Material water footprint	I.7 Number of renewable parts	I.8 Number of reused parts assembled	I.9 Reduced water consumption of product	I.10 Product size
To cooperate in the production value chain leading to closing material loops										
To reduce environmental impacts and use of hazardous chemical	1	**1**								

Sustainability-oriented business goals	Green indicators									
	I.11 Product weight	I.12 Consumption of fuel	I.13 Final product carbon footprint	I.14 Energy usage	I.15 Water usage	I.16 Amount of waste	I.17 Waste recycled/reused	I.18 Water polluted	I.19 Use of low-emission transport	I.20 Amount of scrap
Impact sum	0,5	2	2	2	2	4	4	*0.5*	2,5	5.5
To minimize raw material and/or energy demand	*0.5*			**1**	**1**	**1**				*0.5*

Table 4 (continued)

Sustainability-oriented business goals	Green indicators									
	I.11 Product weight	I.12 Consumption of fuel	I.13 Final product carbon footprint	I.14 Energy usage	I.15 Water usage	I.16 Amount of waste	I.17 Waste recycled/reused	I.18 Water polluted	I.19 Use of low-emission transport	I.20 Amount of scrap
To avoid over-stocking										
To replace physical infrastructure and assets with digital/virtual services										
To design new products to be durable for a long lifetime (durability)		**1**								
To reuse parts/components with or without repair/upgrade				**1**	**1**		**1**			
To encourage cost-effective product repairs and reduce need for replacement of integrated components, thereby reducing resource consumption										**1**

Table 4 (continued)

Sustainability-oriented business goals	Green indicators									
	I.11 Product weight	I.12 Consumption of fuel	I.13 Final product carbon footprint	I.14 Energy usage	I.15 Water usage	I.16 Amount of waste	I.17 Waste recycled/reused	I.18 Water polluted	I.19 Use of low-emission transport	I.20 Amount of scrap
To put the product back into the market to earn a second or subsequent income										
To create products from secondary raw materials/by-products and recycling										**1**
To recover used/unwanted products and sell it again										
To increase overall profitability during the lease period		**1**								
To strengthen community relationships									**1**	
To reduce costs over directly sourcing the products/services										
To increase utilization rate of products and services										

Table 4 (continued)

Sustainability-oriented business goals	Green indicators									
	I.11 Product weight	I.12 Consumption of fuel	I.13 Final product carbon footprint	I.14 Energy usage	I.15 Water usage	I.16 Amount of waste	I.17 Waste recycled/reused	I.18 Water polluted	I.19 Use of low-emission transport	I.20 Amount of scrap
To create an entirely new product from the source material (waste)						1	1			1
To attract consumers to the cause (to donate a portion of the profits to those in need)			1							
To create more 'ethical' products by setting supplier standards or conducting audits (toward sustainable sourcing)			1							
To extend product lifecycle										
To increase "stickiness" with the customer, making them less likely to buy from another good/service provider										

Table 4 (continued)

Sustainability-oriented business goals	Green indicators									
	I.11 Product weight	I.12 Consumption of fuel	I.13 Final product carbon footprint	I.14 Energy usage	I.15 Water usage	I.16 Amount of waste	I.17 Waste recycled/reused	I.18 Water polluted	I.19 Use of low-emission transport	I.20 Amount of scrap
To convert non-recyclable waste materials into useable heat, electricity, or fuel						**1**	**1**			**1**
To reduce waste in the production process and before						**1**	**1**			**1**
To cooperate in the production value chain leading to closing material loops									*0.5*	
To reduce environmental impacts and use of hazardous chemical								*0.5*	**1**	

The sum presents the most important indicators for the particular business goal. In parallel, each of the sustainable business goals was aligned to the corresponding business model and its impact, together with typology (source), as well as corresponding indicators. Based on the research provided within the developed methodology of assessing indicators' importance for sustainable business goals and business models it can be verified which indicators are more accurate. The assessment has been done based on the occurrence of the indicators that are corresponding to sustainable business goals

Table 5 Assessment of the overarching criterion 1: Indicator's features

Indicator no	Indicator	Availability of data	Durability = low variability over time	Need of monitor—cost of collecting	Preciseness/quality/confidence level	Ease of idicator-related data processing	Standardized indicator	Indicator's features assessment
	Rating	1–3 points	1–3 points	1–3 points	1–3 points	1–3 points	0–1	mean
I.1	Non-polluting material	3	3	3	3	2	1	2,5
I.2	Hazardous material	3	3	3	3	2	1	2,5
I.3	Lightweight material	2	3	2	2	2	0	1,8
I.4	Sustainable material	3	3	3	3	2	0	2,3
I.5	Material carbon footprint	1	2	1	2	2	1	1,5
…	…	…	…	…	…	…	…	…
I.16	Amount of waste	2	3	3	2	2	0	2
I.17	Waste recy-cled/reused	2	3	1	2	1	0	1,5
I.18	Water polluted	1	1	1	1	1	0	0,8
I.19	Use of low-emission transport	3	1	3	3	3	0	2,2
I.20	Amount of scrap	3	1	3	3	3	0	2,2

Table 6 Assessment of the overarching criterion 2: Relevance for the company

Indicator no	Indicator	Relevance for the company (0–1)
I.1	Non-polluting material	1
I.2	Hazardous material	1
I.3	Lightweight material	1
I.4	Sustainable material	1
I.5	Material carbon footprint	1
…	…	…
I.16	Amount of waste	1
I.17	Waste recycled/reused	1
I.18	Water polluted	0
I.19	Use of low-emission transport	0
I.20	Amount of scrap	0

Table 7 Assessment of the overarching criterion 3: Importance to sustainable business goals

Indicator	Importance (full)	Importance (partly)
Number of renewable parts	7	
Number of reused parts assembled	7	1
Sustainable material	5	
Amount of scrap	5	1
Amount of waste	4	
Waste recycled/reused	4	
Non-polluting material	2	
Hazardous material	2	
Material carbon footprint	2	
Material water footprint	2	
Consumption of fuel	2	
Final product carbon footprint	2	
Energy usage	2	
Water usage	2	
Use of low-emission transport	2	1
Lightweight material	1	
Reduced water consumption of product	0	2
Product size	0	1
Product weight	0	1
Water polluted	0	1

Table 8 Assessment of the overarching criterion 4: Importance in terms of subsectors

Indicator no	Indicator	Subsectors				Importance in all subsectos
		Auto Services	Tires	Automobiles	Auto Parts	
I.1	Non-polluting material	1	1	1	1	4
I.2	Hazardous material	1	1	1	1	4
I.3	Lightweight material	0	1	1	1	3
I.4	Sustainable material	1	1	1	1	4
I.5	Material carbon footprint	0	1	1	1	3
…	…	…	…	…	…	…
I.16	Amount of waste	0	1	1	1	3
I.17	Waste recycled/reused	0	1	1	1	3
I.18	Water polluted	0	1	1	1	3
I.19	Use of low-emission transport	1	1	1	1	4
I.20	Amount of scrap	0	1	1	1	3

- match the highest number of sustainability-related business goals,
- are relevant for the highest number of environmental, economic, and social impacts,
- correspond to the highest number of the automotive subsectors,
- achieved the highest scores in terms of desired indicator's features,
- are relevant for the company.

4.3 Step 3: algorithm assessing "greenness" of the product

According to the step 3 of the research methodology, the algorithm assessing "greenness" of the product was applied. It should be noted that the application of the proposed algorithm can differ depending on the need (e.g. promotion/communication aspects), yet it seems that it should be used in the first place as a tool enabling its user to compare a product in its path towards "greenness". A hypothetical situation can be assumed that a company is developing a product "A" and assigns a number of indicators and corresponding values to assess its "greenness". Next, after some time, another product is developed—product "B" (e.g. it can be the next generation of product "A"). The company again assigns a number of indicators with corresponding values to assess the level of "greenness" of product "B". Thus, products "A" and "B" can be compared in terms of their "greenness". If the level of "greenness" has increased, it can be stated that the company is properly addressing the aim of sustainability and is successfully reaching its business goals. The algorithm presented below has been developed for the five selected indicators in the previous part of the analysis. Nevertheless,

Table 9 Assessment of the overarching criterion 5: Environmental, Economic, Social impact

indicator no	Environmental impact				Economic impact					Social impact			sum
	Raw material extraction	Emissions (in air, water and soil)	Modification of natural area	Noise	Material cost of product	Maintenance cost of product	Manufacturing cost of product	End-of-life cost of product	Health and safety	Socio-economic repercussion	Governance by customers	Human rights	
I.1	1	1	1	1	0	0	0	1	1	0	1	0	7
I.2	1	1	1	1	0	1	1	1	1	0	1	0	9
I.3	1	1	1	0	1	0	1	1	0	0	0	0	6
I.4	1	1	1	0	1	1	0	1	1	1	1	1	10
I.5	0	1	0	0	1	0	0	0	1	1	1	0	5
…	…	…	…	…	…	…	…	…	…	…	…	…	…
I.16	1	1	1	1	1	0	1	0	1	1	0	0	8
I.17	1	1	1	1	1	1	1	1	0	0	0	0	8
I.18	1	1	1	0	0	1	0	0	1	1	1	0	7
I.19	1	1	1	1	0	0	1	0	1	0	0	0	6
I.20	1	1	1	1	0	0	1	0	0	1	1	0	7

Table 10 Normalization and calculating mean of overall normalized assessment for all five criteria

Indicator no.	Criterion 1 Indicator's features assessment	Criterion 2 Relevance for the project scope	Criterion 3 Importance to sustainable business goals	Criterion 4 Importance in terms of subsectors	Criterion 5 Environmental, Economic, Social impact	Mean
I.1	0,91	1	0,21	1	0,43	0,71
I.2	0,91	1	0,21	1	0,71	0,77
I.3	0,55	1	0,07	0,75	0,29	0,53
I.4	0,82	1	0,64	1	0,86	0,86
I.5	0,36	1	0,21	0,75	0,14	0,49
…	…	…	…	…	…	…
I.16	0,64	1	0,5	0,75	0,57	0,69
I.17	0,36	1	0,5	0,75	0,57	0,64
I.18	0	0	0	0,75	0,43	0,24
I.19	0,73	0	0,29	1	0,29	0,46
I.20	0,73	0	0,71	0,75	0,43	0,52

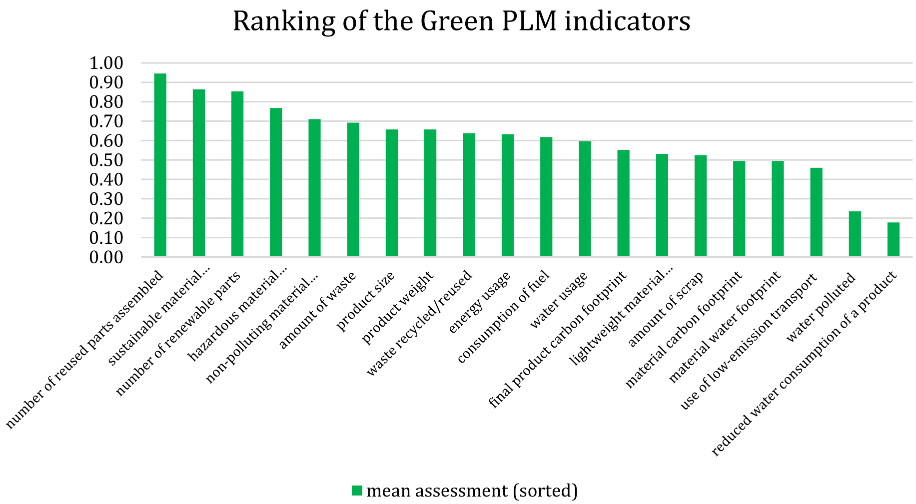

Fig. 4 Final ranking of key sustainability-related indicators for Green PLM

it has to be underlined that the algorithm can be easily adjusted for another set of indicators. To demonstrate the application of the proposed algorithm, the following tables have been developed as an example (Tables 11 and 12).

According to the above-presented example, once the business goals are listed, the appropriate indicators can be selected (according to the step 2 of the methodology). Next, it can be verified whether an indicator is related to the single part (and thus can be directly assessed

Table 11 Algorithm defining "greenness" of a product—exemplification—part 1

Business goals addressed by each indicator	Relation	Indicator no	Indicator
- To create more 'ethical' products by setting supplier standards or conducting audits (toward sustainable sourcing) - To reduce environmental impacts and use of hazardous chemical	Material-related	I.1	Non-polluting material
- To create more 'ethical' products by setting supplier standards or conducting audits (toward sustainable sourcing) - To reduce environmental impacts and use of hazardous chemical		I.2	Hazardous material
- To minimize raw material and/or energy demand - To design new products to be durable for a long lifetime (durability) - To create products from secondary raw materials/by-products and recycling - To attract consumers to the cause (to donate a portion of the profits to those in need) - to create more 'ethical' products by setting supplier standards or conducting audits (toward sustainable sourcing)		I.4	Sustainable material
- To minimize raw material and/or energy demand - To reuse parts/components with or without repair/upgrade - To encourage cost-effective product repairs and reduce need for replacement of integrated components, thereby reducing resource consumption - To put the product back in to the market to earn a second or subsequent income - To create products from secondary raw materials/by-products and recycling - To recover used/unwanted products and sell it again - To extend product lifecycle	Product-related	I.7	Number of renewable parts

Table 11 (continued)

Business goals addressed by each indicator	Relation	Indicator no	Indicator
- To minimize raw material and/or energy demand - To reuse parts/components with or without repair/upgrade - To encourage cost-effective product repairs and reduce need for replacement of integrated components, thereby reducing resource consumption - To put the product back in to the market to earn a second or subsequent income - To create products from secondary raw materials/by-products and recycling - To recover used/unwanted products and sell it again - To increase utilization rate of products and services - To extend product lifecycle		I.8	Number of reused parts assembled

whether a part is "green" or not) or is it related to the assembly. So—for example—in indicator *I.1 non-polluting material* it can be stated that if a part is built of a non-polluting material it can be assessed as 100% green. In case of indicator *I.2 hazardous material* if material is hazardous it is negative situation. Thus, to assess a part as 100% green it is expected that the value of the indicator I.2 is "no"—meaning that the part is built of non- hazardous material. On the other hand, if we consider the indicator *I.8 number of reused parts assembled* which does not refer to a part (but to an assembly) the status is n/a. This type of indicator can be considered and analyzed only on the product level (meaning assembly). In order to assess whether a final product is green or not, or how much green it is, certain aggregation and calculations have to be conducted. So initially, following the example of indicator *I.1 non-polluting material*, all parts in the final product built of non-polluting materials have to be identified. Next, their weights have to be summed up. Subsequently, the total weight of the final product has to be defined. Having the weight of all non-polluting materials in the product and the weight of the final product the proportion of these two can be calculated. In that case, a real percentage value is obtained (e.g. 95.87% for I.1). This value should be compared with the "greenness" threshold which a company should define. If the real percentage value calculated for the given indicator is greater than the "greenness" threshold (so the criterion is met) 1 point can be assigned. For each indicator, a company should set the weights for every criterion (constant values) so that it is clear how important a given indicator for the "greenness" of the whole product is. So for example, the company may assume that indicator *I. 2 non-hazardous material* (criterion = 1,5) is more important than indicator *I.4 sustainable material* (criterion = 1,2). Following the algorithm defining the "greenness" of

Table 12 Algorithm defining "greenness" of a product—exemplification—part 2

Indicator	"Greenness" of the part if criterion equals:	Percentage	Explanation	Weight [kg]	e.g	Weight [kg]	e.g
Non-polluting material	Yes	100%	Proportion of the weight of non-polluting materials [kg] to the total weight of the product [kg] in percentage terms	Weight of all non-polluting materials in the product	1438	Total weight of the product	1500
Hazardous material	No	100%	Proportion of the weight of all non-hazardous materials [kg] to the total weight of the product [kg] in percentage terms	Weight of all non-hazardous materials in the product	1476	Total weight of the product	1500
Sustainable material	Yes	100%	Proportion of the weight of all sustainable materials [kg] to the total weight of the product [kg] in percentage terms	Weight of all sustainable materials in the product	523	Total weight of the product	1500
Number of renewable parts	n/a	n/a	Proportion of the weight of all renewable parts [kg] to the total weight of the product [kg] in percentage terms	Weight of all renewable parts in the product	350	Total weight of the product	1500
Number of reused parts assembled	n/a	n/a	Proportion of the weight of all reused parts assembled [kg] to the total weight of the product [kg] in percentage terms	Weight of all reused parts assembled in the product	290	Total weight of the product	1500

Table 12 (continued)

Indicator	Percentage	"Greenness" threshold	Comment	If meets criterion—1 point	Criterion's weight*	Point x criterion's weight	"Greenness" status of the product*
Non-polluting material	95,87%	90%	Critical value—to be set by the company	1	0,9	0,9	86,00%
Hazardous material	98,40%	95%	Critical value—to be set by the company	1	1,5	1,5	
Sustainable material	34,87%	30%	Critical value—to be set by the company	1	1,2	1,2	
Number of renewable parts	23,33%	20%	Critical value—to be set by the company	1	0,7	0,7	
Number of reused parts assembled	19,33%	20%	Critical value—to be set by the company	0	0,7	0	

* weight to be set by the company

a product, once all the weights of the criteria are set, they can be summed up. Next, for each indicator, a point value resulting from either meeting the "greenness" threshold (1 point) or not (0 points) should be multiplied by the criterion's weight. The values of these products should be summed. In the final step, the "greenness" status of the product can be calculated by simply dividing these two values. As a result, a percentage value will be defined. Here again, the company should define the critical value—when a product can be considered green (e.g. when the "greenness" status of the product exceeds 75%).

5 Conclusions

Within the literature review three main aspects were analyzed. At first, an analysis focused on the identification of business models corresponding to sustainability was performed. Next, current trends and needs were described in terms of the green PLM. Finally, an introduction describing the automotive industry definition and its subsectors was presented together with defining current challenges. Based on the literature analysis and drawn conclusions, the aim of the research was defined. Thus, the main aim of this paper was to develop a new approach to assessing greenness of a product which would be based on a business goals-oriented algorithm and applied to the new product development phase for the automotive industry. This aim was achieved. Three-step research methodology enabled to assess indicators' importance for sustainable business goals and business models (step 1), assess indicators and their importance in the automotive industry (step 2) and finally assess "greenness" of the product (3). This complex approach is innovative as it is based on the business-oriented perspective. Selecting suitable business goals and corresponding business models leads to the selection of the appropriate subset of indicators. Several more aspects are taken into account in this holistic analysis, namely indicator's features, relevance for the company, importance to sustainable business goals, importance in terms of subsectors of the automotive industry as well as environmental, economic, and social impact. In the paper the example of analysis was presented. Obtained results led to the selection of five key sustainability-oriented green Product Lifecycle Management indicators the most important in the automotive industry: number of reused parts assembled, sustainable material, number of renewable parts, hazardous material, non-polluting material. According to the third step of the research methodology, the algorithm assessing "greenness" of the product was applied. It enables the company to compute the value of the "greenness" of the product in reference to the key green PLM indicators (selected according to the step 1 and step 2 of the methodology). "Greenness" threshold should be defined by a company according to its internal policy and be in line with the company's goals and current needs. The exact values of these thresholds may result for example from the expectations of their customers. They can also be imposed by critical values set by the headquarters. Moreover, when setting the "greenness" thresholds, the company should monitor the current corresponding laws and regulations—both national and international. Therefore it is advisable to track regulations based on those mentioned in the Introduction: the European Green Deal, the Fit for 55 package, Circular Economy Action Plan, the Ecodesign Directive, the EU Ecolabel or the EU green public procurement (GPP) and/or join corresponding initiatives, eg.: https://sciencebasedtargets.org/, https://pacecircular.org/, https://www.unglobalcompact.org/).

5.1 Limitations

The authors would like to acknowledge that the presented analysis has several limitations. The first limitation—the assessment of the indicators was limited to the 20 green PLM indicators described within the paper "Towards GreenPLM—Key Sustainable Indicators Selection and Assessment Method Development" (Helman et al., 2023). The points granted in particular parts of the analysis were assigned by the authors of this paper. In the future application of the proposed algorithms, the team assigning the points can be more versatile. The analysis, by definition, was limited to the automotive industry. However, the proposed three-step methodology can be easily adjusted and transferred to another type of industry if needed.

5.2 Further research

Further work will concern issues related to the practical implementation of the methodology developed above. The possibility of building a community of its users in order to maintain and expand the database of green indicators, green products and their components will also be investigated. An interesting issue to research will be the concept of supporting the process of knowledge sharing and cooperation and competition in such a community.

Acknowledgements The research leading to these results was carried out within the GreenPLM project funded by transition Technologies PSC S.A.

Author contributions All authors contributed to the study in the following way: Conceptualization: M. Rosienkiewicz, M. Cholewa, J. Helman, G. Berselli, Literature review: M. Rosienkiewicz, M. Molasy, J. Helman, Methodology—step 1: M. Rosienkiewicz, J. Helman, M. Cholewa, M. Molasy, Methodology—step 2: M. Rosienkiewicz, J. Helman, M. Cholewa, Methodology—step 3: M. Rosienkiewicz, Formal analysis and investigation: M. Rosienkiewicz, J. Helman, M. Cholewa, Visualization: M. Rosienkiewicz, J. Helman, Writing—original draft preparation: M. Rosienkiewicz, Writing—review and editing: J. Helman, M. Cholewa, M. Molasy, S. Oleszek, G. Berselli, Project proposal development: M. Cholewa,
Scientific advisory: G. Berselli, Funding acquisition: M. Cholewa, S. Oleszek, Project administration: S. Oleszek, Supervision: M. Cholewa, S. Oleszek. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The research leading to these results received funding from Transition Technologies PSC S.A.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

References

Bangsa, A. B., & Schlegelmilch, B. B. (2020). Linking sustainable product attributes and consumer decision-making: Insights from a systematic review. *Journal of Cleaner Production, 245*, 118902. https://doi.org/10.1016/j.jclepro.2019.118902

Belkadi, F., Bernard, A., & Laroche, F. (2015). knowledge based and plm facilities for sustainability perspective in manufacturing: A global approach. *Procedia CIRP*. https://doi.org/10.1016/j.procir.2015.01.065

Bocken, N. M. P., Short, S. W., Rana, P., & Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production, 65*, 42–56. https://doi.org/10.1016/j.jclepro.2013.11.039

Boons, F., & Lüdeke-Freund, F. (2013). Business models for sustainable innovation: State-of-the-art and steps towards a research agenda. *Journal of Cleaner Production, 45*, 9–19. https://doi.org/10.1016/j.jclepro.2012.07.007

BS 8001:2017 BSI Knowledge. (2017). Retrieved October 4, 2022, from https://knowledge.bsigroup.com/products/framework-for-implementing-the-principles-of-the-circular-economy-in-organizations-guide?version=standard.

Circular Future - Public Affairs and consultancy about Circular Economy. (2022, July 14). Circular Future. Retrieved October 4, 2022, fromhttp://circular-future.eu/

Clinton, L., & Whisnant, R. (2019). Business model innovations for sustainability. In G. G. Lenssen & N. C. Smith (Eds.), *Managing sustainable business* (pp. 463–503). Springer. https://doi.org/10.1007/978-94-024-1144-7_22

Commission, E., & Communication, D.-G. for. (2020). *Circular economy action plan—For a cleaner and more competitive Europe*. Publications Office of the European Union. https://doi.org/10.2779/05068

Council agrees on the Carbon Border Adjustment Mechanism (CBAM). (n.d.). Retrieved October 26, 2023, from https://www.consilium.europa.eu/en/press/press-releases/2022/03/15/carbon-border-adjustment-mechanism-cbam-council-agrees-its-negotiating-mandate/.

de Medeiros, J. F., Ribeiro, J. L. D., & Cortimiglia, M. N. (2016). Influence of perceived value on purchasing decisions of green products in Brazil. *Journal of Cleaner Production, 110*, 158–169. https://doi.org/10.1016/j.jclepro.2015.07.100

Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast) (Text with EEA relevance). , 285 OJ L (2009). Retrieved October 26, 2023, from http://data.europa.eu/eli/dir/2009/125/oj/eng.

Driving Innovation for Automotive Manufacturing Tier 1 Suppliers. (n.d.). *Engineering USA*. Retrieved September 30, 2023, from https://www.engusa.com/en/posts/driving-innovation-for-automotive-suppliers.

Ellen MacArthur Foundation. (2021). Circularbusinessmodels:redefininggrowthforathrivingfashionindustry. Retrieved October 4, 2023, from https://ellenmacarthurfoundation.org/publications.

Ferasso, M., Beliaeva, T., Kraus, S., Clauss, T., & Ribeiro-Soriano, D. (2020). Circular economy business models: The state of research and avenues ahead. *Business Strategy and the Environment, 29*(8), 3006–3024. https://doi.org/10.1002/bse.2554

Fit for 55. (2023, October 10). Retrieved October 26, 2023, from https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

Främling, K., Holmström, J., Loukkola, J., Nyman, J., & Kaustell, A. (2013). Sustainable PLM through intelligent products. *Engineering Applications of Artificial Intelligence, 26*(2), 789–799. https://doi.org/10.1016/j.engappai.2012.08.012

Global Industry Classification Standard. (2018). S&P Global Market Intelligence.

Golinska-Dawson, P. (2019). Materials management in remanufacturing of automotive components—A small remanufacturers perspective. *IFAC-PapersOnLine, 52*(13), 1738–1743. https://doi.org/10.1016/j.ifacol.2019.11.452

Golinska-Dawson, P., & Pawlewski, P. (2015). Multimodal approach for modelling of the materials flow in remanufacturing process. *IFAC-PapersOnLine, 48*(3), 2133–2138. https://doi.org/10.1016/j.ifacol.2015.06.404

Green Public Procurement. (n.d.). Retrieved October 26, 2023, from https://green-business.ec.europa.eu/green-public-procurement_en.

Helman, J., Rosienkiewicz, M., Cholewa, M., Molasy, M., & Oleszek, S. (2023). Towards GreenPLM—Key sustainable indicators selection and assessment method development. *Energies, 16*(3), 1137. https://doi.org/10.3390/en16031137

Industry Classification Benchmark. (2022). FTSE Russell. https://research.ftserussell.com/products/downloads/ICB_Rules_new.pdf.

Jonker, J., & O'Riordan, L. (2016). New business models: examining the role of principles relating to transactions and interactions. In H. G. Brauch, Ú. Oswald Spring, J. Grin, & J. Scheffran (Eds.), *Handbook on sustainability transition and sustainable peace* (Vol. 10, pp. 543–557). Cham: Springer.

Kochańska, J. (2024). Categorization of production losses in the context of assessing production effectiveness indicators. In A. Burduk, A. D. L. Batako, J. Machado, R. Wyczółkowski, E. Dostatni, & I. Rojek (Eds.), *Intelligent systems in production engineering and maintenance III* (pp. 658–676). Springer. https://doi.org/10.1007/978-3-031-44282-7_50

Kochańska, J., & Burduk, A. (2023). a method of assessing the effectiveness of the use of available resources when implementing production processes. *Applied Sciences, 13*(13), 7764. https://doi.org/10.3390/app13137764

Kochańska, J., Musiał, K., Łapczyńska, D., & Burduk, A. (Early Access). The solution of MRSLP with the use of heuristicalgorithms. *Bulletin of the Polish Academy of Sciences Technical Sciences; Early Access*; e146407. https://journals.pan.pl/dlibra/publication/146407/edition/128124.

Kosacka-Olejnik, M., Werner-Lewandowska, K., & Golińska-Dawson, P. (2020). Scanning effectiveness of material flow management in remanufacturing—Case study on diesel particulate filter remanufacturing. *Procedia Manufacturing, 51*, 1688–1695. https://doi.org/10.1016/j.promfg.2020.10.235

Łapczyńska, D. (2023). The possibilities of improving the human-machine co-operation in semi-automatic production process. *Technologia i Automatyzacja Montażu, 119*(1), 30–36. https://doi.org/10.7862/tiam.2023.1.4

Laubscher, M., & Marinelli, T. (2014). Integration of Circular Economy in Business. https://doi.org/10.13140/2.1.4864.4164

Lewandowski, M. (2016). Designing the business models for circular economy—Towards the conceptual framework. *Sustainability, 8*(1), 43. https://doi.org/10.3390/su8010043

Marcon, A., Ribeiro, J. L. D., Dangelico, R. M., de Medeiros, J. F., & Marcon, É. (2022). Exploring green product attributes and their effect on consumer behaviour: A systematic review. *Sustainable Production and Consumption, 32*, 76–91. https://doi.org/10.1016/j.spc.2022.04.012

Mentink, B. (2014). Circular business model innovation. *MSc thesis*, p. 168.

Molasy, M., Rosienkiewicz, M., Helman, J., & Cholewa, M. (2023). Gamification-based crowdsourcing as a tool for new product development in manufacturing companies. In A. Burduk, A. Batako, J. Machado, R. Wyczółkowski, K. Antosz, & A. Gola (Eds.), *Advances in production* (Vol. 790, pp. 368–379). Springer. https://doi.org/10.1007/978-3-031-45021-1_28

Osterwalder, A., Pigneur, Y., & Clark, T. (2010). *Business model generation: A handbook for visionaries, game changers, and challengers*. Wiley.

Osterwalder, A., Pigneur, Y., & Tucci, C. L. (2005). Clarifying business models: origins, present, and future of the concept. *Communications of the Association for Information Systems*. https://doi.org/10.17705/1CAIS.01601

Rasmussen, B. (2007). Business models and the theory of the firm. *Working Paper*, 32: 12

Regulation (EC) No 66/2010 of the European Parliament and of the Council of 25 November 2009 on the EU Ecolabel (Text with EEA relevance). 027 OJ L (2009). Retrieved October 26, 2023 http://data.europa.eu/eli/reg/2010/66/oj/eng.

Ritala, P., Huotari, P., Bocken, N., Albareda, L., & Puumalainen, K. (2018). Sustainable business model adoption among S&P 500 firms: A longitudinal content analysis study. *Journal of Cleaner Production, 170*, 216–226. https://doi.org/10.1016/j.jclepro.2017.09.159

Rudnicka, A. (2016). Business models based on sustainability. Practical examples. *Modern Management Review*. https://doi.org/10.7862/rz.2016.mmr.54

Sanghavi, P., Rana, Y., Shenoy, S., & Yadav, R. (2015). A review on green supply chain management in automobile industry. *International Journal of Current Engineering and Technology, 5*, 3697–3702.

Schaltegger, S., Hansen, E. G., & Lüdeke-Freund, F. (2016). Business models for sustainability. *Organization & Environment, 29*(I), 3–10. https://doi.org/10.1177/1086026615599806

Sliż, P., & Wycinka, E. (2021). Identification of factors that differentiate motor vehicles that have experienced wear or failure of brake system components during the warranty service period. *Eksploatacja i Niezawodność – Maintenance and Reliability, 23*(3), 430–442. https://doi.org/10.17531/ein.2021.3.4

The European Green Deal. (2021). Retrieved October 24, 2023 https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

TRBC Sector Classification. (n.d.). Retrieved September 30, 2022, from https://www.lseg.com/en/data-analytics/financial-data/indices/trbc-business-classification.

Vila, C., Abellán-Nebot, J. V., Albiñana, J. C., & Hernández, G. (2015). An approach to sustainable product lifecycle management (Green PLM). *Procedia Engineering, 132*, 585–592. https://doi.org/10.1016/j.proeng.2015.12.608

Wells, P. (2013). Sustainable business models and the automotive industry: A commentary. *IIMB Management Review, 25*(4), 228–239. https://doi.org/10.1016/j.iimb.2013.07.001

Žvirblis, T., Hunicz, J., Matijošius, J., Rimkus, A., Kilikevičius, A., & Gęca, M. (2023). Improving diesel engine reliability using an optimal prognostic model to predict diesel engine emissions and performance using pure diesel and hydrogenated vegetable oil. *Eksploatacja i Niezawodność – Maintenance and Reliability*. https://doi.org/10.17531/ein/174358