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Conceptual Framework focused on the elements of the circular economy oriented to product development process applied to automotive sector

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Conceptual Framework focused on the elements of the circular economy oriented to product development process applied to automotive sector.

Por

Andrea Maria Chanquini

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O que vale na vida não é o ponto de partida e sim a caminhada. Caminhando e semeando, no fim, terás o que colher.

(Cora Coralina)

RESUMO

A economia circular (EC) emerge como um caminho alternativo para o desenvolvimento sustentável de produtos, focando na otimização do uso de energia e recursos naturais para mitigar o aumento de resíduos e o uso de energia não renovável, consequências do aumento da população, crescimento do consumo e globalização. O conceito de EC visa mudar o comportamento do consumidor, produção e descarte de um modelo linear para um modelo circular, em que cada fase do ciclo de vida de um produto pode ser repensada, em um ciclo fechado, baseado no princípio da reutilização. Assim, o descarte pode se tornar matéria-prima para outro processo. O processo de desenvolvimento de produto (PDP) tem seu papel na geração da vantagem competitiva e percepção de valor para o cliente, desempenha um papel fundamental nessa transição. Suas principais fases são a de definição dos requisitos dos clientes, design do produto, definição de materiais, cadeia de suprimentos, mercados-alvo e seu ciclo de vida. A literatura está num estágio inicial sobre a integração de ambos os campos, portanto, o objetivo deste estudo é contribuir para ampliar a literatura e responder à seguinte pergunta de pesquisa, quais são os principais elementos capazes de integrar as estratégias de EC com as etapas do PDP para melhorar a eficiência do processo de desenvolvimento de produtos? Através de uma Revisão Sistemática da Literatura para compreender e identificar os principais elementos de conexão existentes nessas áreas que são: modelos de negócio, métodos de design, processos industriais, influência do consumidor e programas de recolhimento de produtos. Foi proposto um framework preliminar, seguido do painel com especialistas do setor via método Delphi para validação do framework final, o qual revelou a perspectiva de propriedade de produto e a aplicabilidade das estratégias da EC e os elementos de integração.

Key words: Sustentabilidade, Desenvolvimento de produto, Framework, RSL, Delphi

ABSTRACT

Circular Economy (CE) emerges as an alternative path for sustainable product development, its focus is on the energy and natural resources usage optimization to support to mitigate the waste increase and non-renewable energy use driven by population increase, consumption growth, and globalization. The concept of CE is to change our consumption behavior, production, and disposal from a linear model to a circular model, in which each phase of the life cycle of a product can be rethought, so that it has an increase in the value chain in a closed loop of the value chain, is based on the reuse principle in a closed-loop chain, disposal can become raw material for another process. Product development process (PDP) has its role of generating competitive advantage and customer value, and a leading role in this transition, main phases are in the definition of customers' requirements, product design, materials definition, supply chain, target markets and its life cycle. Literature is incipient about the integration of both fields, so the objective of this study is to contribute to enhance the literature and answer the following research question, what are the main elements capable to integrate CE strategies with PDP stages to improve the efficiency of the process? Through a systematic literature review (SLR) to understand and identify the main connections elements existing in these areas, business models, design methods, industrial processes, consumer influence, and product take-back programs. A preliminary framework was proposed, followed by an expert panel using the Delphi method to validate the final framework, which revealed the perspective of product ownership and the applicability of CE strategies and integration elements.

Key words: Sustainability, Product Development, Framework, SLR, Delphi

TABLE OF ACRONYMS

BAH *Booz, Allen, and Hamilton model*

C2C *Cradle-to-cradle*

CE *Circular economy*

CPDF *Circular product development framework*

EMAF *Ellen MacArthur foundation*

EOL *End-of-life*

ESG *Environmental, social and governance*

LCA Lifecycle assessment

LCC *Lifecycle costing*

NPD *New product development*

PDP *Product development process*

PSS *Product-service systems*

SLR *Systematic literature review*

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1. INTRODUCTION

This chapter introduces the contextualization, motivation, justifications, research question and objectives (general and specifics), theoretical and practical foundation. The study focuses in providing with insights for the automotive parts industry and alternatives paths to achieve a more sustainable development. Its emphases on two fields of study Circular Economy (CE) and the Product Development Process (PDP), the integration between both fields involves rethinking about product design, product manufacturing, product use, and disposal of to minimize resource consumption, waste generation, and environmental impact. By shedding light on these aspects, the study seeks to highlight opportunities for the industry to transition towards more sustainable practices, thereby contributing to broader environmental and economic goals.

It is structure as follows: section 2 corresponds to the literature review of CE foundation, followed by the PDP and, nexus of CE and PDP perspectives. Section 3 is related to the methodological procedures to present the Circular Product development (CPD) preliminary framework, followed by the Delphi panel with experts to finetuning the final Circular Product Development Framework (CPDF). Section 4 corresponds to the results and discussions. Section 5 is the conclusion and limitations of this research.

1.1 CONTEXTUALIZATION

The phenomenon of globalization has brought both benefits and impacts. The increase in consumption and population has been beneficial for economic development. However, this pattern places pressure on our economic system, particularly on the linear approach of take, make, and dispose. This model relies on extracting natural resources to produce products, which are then consumed and discarded. As a result, waste and pollution increase, contributing to the acceleration of global warming. Climate change is the main threat to the planet, and its consequences have been observed not only in the environment but also in the rise of social inequality. The CE presents an alternative to help mitigate some of these impacts, such as reducing waste and pollution.

The Glasgow Climate Change Pact, with its ambitious target of limiting global temperature rise to 1.5°C, underscores the urgent need for collective and comprehensive action to address the challenges posed by climate change. This global initiative emphasizes four key pillars: i) mitigation, which involves concerted efforts to reduce greenhouse gas emissions, crucial for achieving the temperature targets; ii) adaptation, recognizing the need to support communities and ecosystems already facing the impacts of climate change, and enhancing their resilience to future challenges; iii) finance, setting clear and robust climate finance goals to fund sustainable initiatives and projects; and iv) collaboration, highlighting the importance of nations, organizations, and communities working together to create a unified front against climate change. The Glasgow Climate Change Pact serves as a rallying point for international cooperation and commitment, acknowledging the interconnectedness of efforts required to address the complex and multifaceted issues related to climate change (COP26, 2021).

This reinforces the urgency of creating different solutions based on the current situation, with each region needing to take responsibility. The European Green Deal, a comprehensive initiative proposed by the European Commission, is pivotal in this regard, aiming to position Europe as the first climate-neutral continent by 2050 (COM, 2015). This ambitious strategy encompasses various policies and actions across sectors to achieve a sustainable development and significantly reduce greenhouse gas emissions. The collective efforts of these regions underscore the global commitment to addressing climate change and fostering a more sustainable future.

In 2015, the United Nations (UN) developed the sustainable development agenda as a comprehensive framework to promote global peace and prosperity to the people and the planet. This initiative introduced 17 Sustainable Development Goals (SDGs) as per figure 1 designed to guide societies, organizations, and governments worldwide towards achieving a more inclusive and sustainable future by 2030. These goals encompass a wide range of priorities, including poverty eradication, quality education, gender equality, clean water and sanitation, affordable and clean energy, sustainable cities and communities, responsible consumption and production, climate action, and the protection of terrestrial and marine ecosystems. By addressing these interconnected challenges, the agenda seeks to foster economic growth, social inclusion, and environmental sustainability on a global scale.

Figure 1: Sustainable development goals UN

Source: United Nations archive (2020)

In Latin America, particularly in Brazil, the implementation of critical environmental regulations is gaining momentum, demonstrating the country's necessity to be aligned with a sustainable development. The National Solid Waste Policy *(Política Nacional de Resíduos Sólidos – Lei 12.305/2010)* serves as a cornerstone, addressing comprehensive waste management strategies and environmental responsibility. This legal framework, enacted in 2010, underscore Brazil's proactive approach towards balancing economic growth with environmental conservation (Reche, A. et al., 2020).

Sustainable development is seen through the combination of environmental, social and governance actions, Environmental, Social & Governance (ESG), these principles were presented in 2004 in Europe, America, and other incorporated countries (LI, Ting -Ting et al., 2021) and is the basis of this work within the area of sustainability. CE has been discussed as an alternative path for transition from of linear economic system, decoupling economic grow from natural resources extraction and consumption behaviors. Its main principle is eliminating waste, aiming to preserve natural resources and to prolong the lifetime of what has been processed already. This path is crucial for the sustainability of future generations.

Circular concept is not new, it emerged in 1927 with Leontif who presented the economy as a circular flow, economic transactions follow the natural circular flow, from individual to markets, business, governments, economies. Other ideas continued to arise in this direction such as Industrial Ecology (Graedel, 2001) which addresses integration between the industrial sector and the environment, seeking a balance between production, profit, and environment impacts. Closer to the CE is the Cradle-to-Cradle approach into the biological and technical flow, the waste of a certain process can feed the start of another process, everything could be reused in an infinite cycle (Braungart et al., 2003).

The PDP steps presented by Booz, Allen, and Hamilton (1982), emphasizing that prosperity and long-term growth are not automatic outcomes but rather the result of intensive labor, investments, and concerted efforts (Cooper, 2001). The process is delineated into seven stages: (1) new product strategy development, which establishes a foundational base and starting point for collecting ideas; (2) generation of ideas; (3) screening and evaluation; (4) business alignment; (5) development; (6) testing; and finally, (7) commercialization (Cooper, 2019). This structured approach provides a systematic guide for organizations seeking to navigate the complexities of product development, ensuring a methodical progression from ideation to market launch. The Booz, Allen, and Hamilton (BAH) model has been foundational in shaping perspectives on effective product development strategies.

The approach to competitiveness focuses on increasing resource productivity. Corporate pollution often reflects waste from inefficient resource use, including energy and materials. Enhancing environmental performance through technology and methods can lower costs and boost productivity. PDP aligned with CE principles will increase focus on improve efficiency, consumer behavior and mindset and natural resources usage.

1.2 MOTIVATION

Many studies are focusing on the CE as an alternative path to sustainable development. The main objective is to minimize waste and pollution discarded into nature by using a regenerative system that recovers waste and disposals, feeding them back into a new industrial process through a closed-loop system that considers the entire supply chain. This closed-loop supply chain encompasses production, consumption, collection, and reuse. CE plays a crucial role in the context of sustainability. It aims to reduce waste and pollutants by creating regenerative systems where waste from one process can feed another, or components are designed to prolong their lifespan through reuse and repurposing while maintaining the same functionality. This aligns with the Closed Loop Supply Chain (CLSC) concept, where 'waste equals food' (McDonough et al., 2002). It creates a closed loop that covers production, consumption, and collection.

A holistic perspective that balances environmental, social, and economic areas in the business environment offers a possible way to preserve finite natural resources for future generations while delivering benefits to stakeholders. This can be achieved by applying the principles of the Environment, Social, and Governance (ESG) concept, which advocates for responsible investment and transparency in performance evaluation. In this context, CE elements become enablers for organizations in the ESG field, contributing to achieving economic and social balance, improving cost and resource efficiency, and reducing waste (EMAF, 2013; Schroeder, 2021).

Investments in the development and launch of new products are massive and yet it is estimated that 40% fail when launched, which is why evaluating success factors is a differentiator (Cooper, 2019). Some segments have products with a subjective period of obsolescence, that is, the product is no longer desired and loses its value to the consumer (Cooper, 2022), in other cases, due to lack of technological possibility or due to wear, the product becomes unserviceable. Understanding the PDP and its stages is essential for proposing updates. Rethinking the PDP considering the principles of CE can be a facilitator in the search for minimizing environmental, social, and economic impacts, as well as creating a competitive advantage for organizations.

1.3 RESEARCH QUESTION

There is an increase interest in find new paths to mitigate climate changes and its consequences, CE field has been discussed largely by governments, organizations, and society as an alternative way to move forward in this direction, especially when it comes to reduce the usage of natural finite resources extraction. New products development demands a decision on raw materials and energy utilization. PDP literatures are abundant about processes possibilities and frameworks, however only few studies are connecting CE and PDP fields to understand the possibilities of cost reduction, increase of quality and reducing time of development, based on this gap, the proposal of this study is to shed a light in the interrelation of CE strategies and

PDP stages, through the research question: *What are the main elements capable to integrate CE strategies with PDP stages to improve the efficiency of the PDP?*

1.4 RESEARCH OBJECTIVES

This study seeks to develop a preliminary framework capable of relating the concepts of the PDP and CE with the aim of identifying the main elements of the CE operating in the different stages of the PDP. To achieve this, the following specific objectives were defined:

i. To understand the concepts, theories and gaps that exist in the literature involving the relationship between the PDP and CE.
ii. To identify the main connection elements existing in these areas.
iii. To propose a preliminary framework based on the elements defined in the previous step.
iv. To test the preliminary framework through application using a panel of experts and update the framework with the results.

In session 3, details of the study structure and its stages are presented, how these objectives will be met, as well as the research question.

1.5 THEORETICAL AND PRACTICAL FOUNDATION

The new thinking of competitiveness arises from the increase in productivity in the use of resources, in this case continuous improvement never ends, virtually all forms of corporate pollution are manifestations of waste, such as the inefficient use of resources, which also generates from inefficiency energy to the waste of materials. If environmental performance is improved through technology and methods, this can also reduce costs and increase productivity (Porter, 2008). PDP oriented towards the principles of CE is considered an alternative to improve the efficiency of the supply chain and consumption behavior. Rethink waste, raw material extraction, industrial, logistics, all and all products development process is vital for future generations life.

Climate change is the greatest global risk; during the Glasgow Climate Pact (COP26, 2021), discussions revolved around mitigation actions, aiming to limit global warming to 1.5°C. The collaboration between countries set goals for decarbonization, reduction of greenhouse gas emissions, and the protection of communities and habitats. This initiative aligns with sustainable development, where businesses, society, and governments increasingly seek alignment and collaboration for its realization.

There was a transformation in second half of the 20^{th} century from an economy based on products to an economy based on services (Barrett et al., 2008), however this viewpoint is not changing the necessity of a physical product, in fact a combination between both products and services (Vargo et al., 2004). Service is a complex concept that covers many meanings (Edvardsson et al., 2005). According to Lovelock et al. (2011) service is considered as “access to a variety of value-creating elements rather than from transfer of ownership”. There are many definitions of services and its relationship to the transition to CE as an enabler, nevertheless in this study the concept of services is associated to the fact of facilitator to the backflow of physical products and components for possibilities of reusage as per the CE concept.

Given that it is an emerging field of study, there are few studies addressing the integration of the proposed themes; furthermore, CE is a complex and challenging field of study (Korhonen et al., 2018). The theoretical justifications for the study aim to contribute to the development of literature on CE and its implementation in PDP, enhance its robustness in the academic field, and advance its practical application in organizations. The study also seeks to analyze how organizations perceive and implement CE (Barreiro et al., 2020). The choice of CE and PDP is driven by their evolving nature, particularly in practical development, offering significant academic potential for exploration (Korhonen et al., 2018), and providing a broad perspective from the standpoint of consumption and supply chains.

Europe pioneered the shift towards a CE in 2015 with the "Closing the Loop" initiative (COM, 2015). In 2019, the European Green Deal was introduced, aiming to make the continent energy self-sufficient to combat global warming and reduce greenhouse gas emissions. Key goals of Europe's carbon-zero plan (COM, 2019) include a 55% reduction in CO2 emissions from cars by 2030 (compared to 2021), a complete cessation of CO2 emissions from vehicles by 2035 (effectively banning the sale of internal combustion engine vehicles) and achieving zero CO2 emissions from vehicles by 2050 to support the European Union's environmental neutrality target in the next 30 years.

Brazil exhibits a strong inclination towards sustainability, driven by its unique developmental context. Unlike mature economies, where industrial infrastructure and technology are well-established, Brazil's infrastructure is still evolving. This provides a significant opportunity for the country to integrate and adopt new, innovative technologies and approaches early in their development stages (Pinsky et al., 2017). The nation’s approach to sustainability is reflected in its practices related to reuse, repair, and recycling. These practices, while influenced by various socio-economic factors, contribute to Brazil’s greater openness to sustainable methodologies. The relative novelty of Brazil's industrial infrastructure means there is more flexibility and potential for implementing sustainable solutions compared to economies where existing systems are deeply entrenched. This openness allows Brazil to experiment with and adopt practices that might be more challenging to integrate into more established industrial systems. In this context, Brazil's focus on sustainability can be seen as both an opportunity and a challenge. The country is able to shape its industrial and technological development with sustainability at the core, potentially leading to more effective and integrated sustainable practices that could serve as a model for other emerging economies.

From a practical standpoint, it is crucial to establish a new approach to product development. The current moment provides an opportune time to reconsider the way we think, create, consume, and dispose of products. Additionally, the impacts of the COVID-19 pandemic have introduced unprecedented pressures on supply chains. Major global supply chains, including those in the manufacturing sector such as the automotive industry, have been significantly affected due to a heavy reliance on China as a global supplier for over two decades. This has prompted the need for a structural shift, a new strategy in conducting business (Belhadi et al., 2021).

It is imperative to seek and present a tangible alternative to the current state of production, consumption, and disposal. Distinguishing the roles each actor plays in the value chain and co-creating a more sustainable consumer experience is essential. Given the market dynamics and significant societal transformations, sustainable strategies that provide a competitive advantage for companies, deliver value to consumers, and have a neutral impact on the environment are necessary. Therefore, facilitating the integration of CE principles in the PDP can be viewed as a facilitator for this evolution.

2 - LITERATURE REVIEW

In this chapter, it is presented the theoretical foundation that shapes the study, discussing relevant literature and its concepts to support our research. We explore the advancements in academic studies within CE and PDP, and their integrations. It is crucial to consider, at the study's core, the business perspective on strategic definitions for creating competitive advantage and, consequently, financial sustainability (Porter, 2008). Since the late '80s, with the publication of the report "Our Common Future" (Brundtland, 1987), concerns about human progress and environmental impacts have become more pronounced. The movement to decouple economic growth from dependence on finite natural resources has gained momentum in the pursuit of sustainable and responsible development (Sanyé-Mengual et al., 2019).

Despite contemporary society using fewer resources to produce the same wealth, the absolute pressure on resources continues to grow due to excess consumption (Pinsky et al., 2017). Sustainability seeks to balance the integration of economic performance, social inclusion, and environmental resilience for the benefit of the current and future generations (Elkington, 1997). The ESG concept, adopted by companies to measure sustainability and social impacts in their business activities, enables investor evaluation, aiming for sustainable long-term growth (LI, Ting-Ting et al., 2021).

The field of sustainability has gained prominence in academic research, public discourse, government, and corporate sectors in recent years. The pursuit of alternatives and concepts supporting improved energy efficiency and the reduction of the impacts of global warming is pivotal. Numerous study avenues within this evolving field include Green Supply Chain, Shared Economy, Industrial Ecology, Blue Economy, and most recently CE, the concept employed in this study to shed light on the sustainability perspective.

The shift from a linear economy to a CE arises as a viable solution to mitigate environmental impacts by promoting material reuse (EMAF, 2015). Additionally, this transition carries positive social implications and offers a competitive edge, potentially leading to cost reductions through decreased consumption of new raw materials, as suggested by Porter (2008).

2.1 CIRCULAR ECONOMY

The research field and the concept of CE are primarily discussed within political, governmental, and business contexts, as well as by industry professionals. Academic research in this area holds significant untapped potential (EMAF, 2013; COM, 2014; Korhonen et al., 2018). Therefore, the concept is composed of fragmented ideas derived from other scientific fields, such as ecological economics, which has a long tradition in recycling and other macroeconomic aspects of the CE (Korhonen et al., 2018). It is an emerging concept, recently viewed as an umbrella term (Blomsma et al., 2017). The notion of an umbrella concept aims to establish connections among pre-existing concepts that are otherwise disconnected, with the intention of focusing on a common point for in-depth exploration (Hirsch et al., 1999).

As CE is a multi-disciplinary field, it contains elements from various disciplines and paths of research that are predecessors of current knowledge. The relevant theories and aspects were grouped to the following themes: transformation of economic structures and business rationales, regenerative design and critical materials, industrial ecology, remanufacturing and closed-loop supply chains, resource conservative manufacturing, governmental CE initiatives (Lieder et al. 2016).

The Cradle-to-Cradle (C2C) concept is closely associated with the CE, sharing a direct relationship with its principles, and serving as one of its primary early inspirations. In this concept, the aspects of reduction, reuse, and recycling are integral (McDonough et al., 2010). The Blue Economy concept, on the other hand, is grounded in physical solutions, utilizing natural systems of nutrients, matter, and energy as an ideal model. Gravity, for example, is considered a primary energy source in this concept, and it emphasizes the avoidance of toxic, chemical, and complex catalysts in line with nature's processes (Pauli, 2010).

Industrial Ecology, with the goal of explicitly managing resource use for preservation, advocates for turning the output of one process into the input of another for optimization. This requires analyzing flows and key resources throughout the entire life cycle (Allenby et al., 1995) and has influenced material flows, optimized energy use, and resource utilization for CE development. Stahel's perspective views CE as a cyclical system seeking to eliminate waste by reintroducing end-of-life products back into the value chain. According to Geissdoerfer et al. (2017, 2020) detailed outlook, circularity is achievable through durable designs, proactive maintenance, recycling, repair, refurbishing, and remanufacturing.

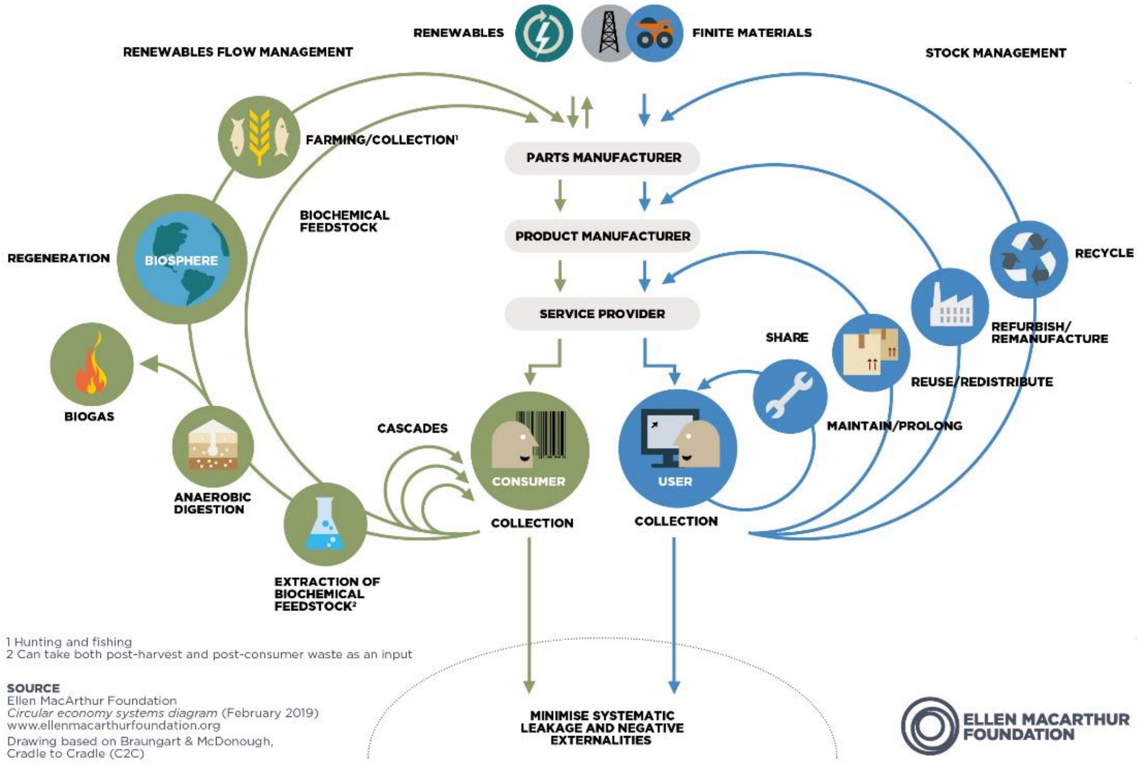
The holistic vision of the CE presented by the Ellen MacArthur Foundation (EMAF) is encapsulated in the Butterfly diagram, there are two main cycles, the biological and the technical and differences between both are that in biological cycle the materials are biodegradable and return to earth to be regenerate naturally, so the continuous flow is oriented to processes for regeneration, farming, composting and anerobic digestion. In the technical cycle the materials are industrialized and takes longer to be naturally decomposed, so the continuous flow is oriented to processes for reuse, repair, remanufacture and recycling.

In Figure 2, the biological cycle is illustrated, depicting materials that decompose, regenerate, or have applications that evolve throughout their lifespan, representing renewable resources. The technical cycle, on the other hand, involves processed materials, therefore focus is on extending their lifespan or exploring possibilities to maximize utility, considering renewable energy sources and efficient use for this continuous flow, so the renewable energy generated in the biological flow can used in the technical flow.

The key points of the overall Butterfly diagram are:

- Rethink and Redesign Materials: Eliminate waste and pollution from the outset by reimagining and redesigning materials.
- Maintain Materials in Use: Consider waste as a resource and an essential tool for circularity, emphasizing the ongoing use of materials.
- Regenerate Natural Systems: Keep natural systems alive after their initial use.

Figure 2: Butterfly diagram



Source: EMAF, 2019

2.2. PRODUCT DEVELOPMENT PROCESS

Increase of globalization also means increase of competition, companies are adapting their processes and searching ways to respond customers and market requirements more effectively, to gain sustainable competitive advantage and protecting their market positions (Kotler, 2007). There is a consensus of the definition of PDP with slightly differences (Cazeri et al, 2019).

Product development is a complex process for the firms and managers, it is the bridge between customers and markets needs with a technical and commercial solution, (Whitney et al., 1990; Fu et al., 2013), this complex PDP network involving areas such as design & resources (Human, tool, knowledge). From the strategic point of view, the success of a new product launch is the company`s success, to develop a new product with technical superiority, with budget and launch ahead of the competition it is a real competitive advantage (Calantone et al., 1979; Cooper et al., 1987; Crawford, 1994; Hultink et al., 1997).

PDP involves a sequence of stages constituted by tasks, activities, validations, and decisions. According to Cooper (1990), these stages can be better understood as gates, that managers can navigate to avoid go and no-go errors during the development process. The stage gate from Cooper (2017) has 6 stages, starting from the idea generation, scoping, building a business case, followed by the development, testing and validation, launch and finally the post-launch review.

Steps are complementing each other and ranging from simultaneous to sequential, depending on the development specifications of a product. Macro pre-development phase is related to the innovations, macro development phase is related to the technical characteristics, details definition for the creation of the product such as material, components, production flow, quality controls, sketches to further creating the detailed product design and specifications. It comprehends to the complete supply chain including packaging and, logistics details, it integrates the product production and product maintenance. Macro post-development phase consists in the target audience acceptance, results on the business case, it is the total life cycle of the product including the disposal (Urnau et al., 2021).

The idea generation is the starting point of PDP, it is the stage for identifying problems, unmet customer needs, market situations, opportunities to transform in products. This transformation requires conceptualization such as strategic thinking and occurs in the concept stage, the best ideas come from customers. This phase is critical to the success of the product in the market, so it is important to promote activities for market-oriented ideas generation focus group and Voice of customer research, a robust market and technical assessment, business, and financial analysis before investment decision (Cooper, 2019).

Product concept and samples are designed in development stage, it is combination of previous stage with product design methodologies to transform an idea into a product concept and product samples. Involves cross-functional collaboration with teams (Jugend et al., 2012). In the table 1 this a description about roles in an organization that are participating as cross-functional team. Design methods are crucial in this phase to fulfill cost targets, technical capability, and legal and market requirements. This phase is the foundation for new product which solutions are defined and tested before the launch phase (Setti et al., 2021). Collaborating development supports the product definition, requirements, and specifications.

Table 1: Roles & Practices of cross functional team

Role	General Activities
Engineering	Definitions on the product based on the market & legal requirements, product process design and product validations, as well as preparations for production.
R&D	Identifying new technologies, new processes, and legal aspects, developing and domination product and process design technologies and preparing for the product.
Production	Preparing prototype and pilot production; Assessing infrastructure capability and required investments, addressing issues to transition the pilot scheme to full-scale commercial production, enhancing process capabilities, and reducing product process costs.
Marketing	Market and customer requirements collection. Providing PDP with this information during pre-development, development, and post development phases. Business case evaluation. Market launch preparation and execution
Project Manager	Definitions of team, selection of methods, processes, and tools. Developing communication plan, integration of areas and risk assessments. Budget, scope, and timeline coordination.
Controlling	Market information and business case calculation for decision taken during the pre-development. In the development phase monitoring the budget and in the post-development monitoring the profit and loss.

Source: Adapted from Jungend, 2023

Manufacturing stage transforms a product sample into a series product, it is determined to the implementation of the product design into production process. The importance of this phase is the infrastructure and technology regarding to energy sources, adaptations, efficiency to keep cost and quality under control, investment decisions. Efficient production processes and technology integration are crucial aspects addressed during the manufacturing stage (Tukker, 2015). Ensuring product reliability and meeting quality standards are paramount objectives in this phase. As organizations navigate the manufacturing stage, attention to these factors contributes not only to the overall success of the product but also to the competitiveness and sustainability of manufacturing processes in the broader market context.

The usage and maintenance stage holds pivotal importance in the trajectory of new product development, serving as the interface with customers and validating the product's benefits and value proposition, a determinant factor in distinguishing successful ventures from unsuccessful ones (Cooper et al., 2018). Additionally, user education and training, as promoted by Brown et al. (2020), are imperative for promoting proper product usage and handling, which can mitigate wear and tear and minimize the likelihood of malfunctions.

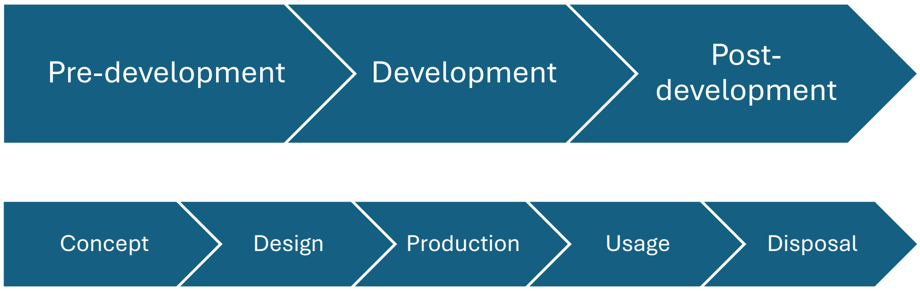
Maintenance practices play a pivotal role in sustaining product performance and preventing premature failure. Proactive maintenance strategies, such as regular inspections and preventive maintenance routines, are essential for identifying and addressing potential issues before they escalate (Smith et al., 2019). Furthermore, monitoring and feedback mechanisms facilitate continuous improvement efforts, enabling manufacturers to refine product design and enhance reliability based on user experiences and performance data (Anderson et al., 2018).

End-of-life of product occurs during the disposal stage, when product become obsolete, the obsolete definition may vary from segment to segment, in summary means product is not functional or not fashion anymore, the moment of a product does not satisfy the initial purchaser of user (Almeida et al., 2017). It is fundamental to have a waste management to recovery resources and avoid the waste of materials via landfill or incineration (Ghisellini et al., 2014). This stage in the closed-loop concept presented by CE is integrated in the Concept stage due to the possibilities for reuse of materials, disposal and design must be dependents each other to avoid virgin materials extraction (Ragaert et al., 2019).

PDP field has a broader approach in terms of processes, it varies depending on particularities of segments and product characteristics. In simultaneous engineering for instance as per figure 2, a methodology cultivated from the principles of the Toyota Production System in the late 1980s, the various stages of product development are intricately interconnected. This approach enables the concurrent processing of different elements within the design and manufacturing phases, fostering a dynamic environment where adjustments can be made promptly and iteratively to meet evolving requirements and challenges. The essence of simultaneous engineering lies in its ability to synchronize activities across different stages of the development process, facilitating seamless collaboration and adaptability throughout the product lifecycle (Hartley et al., 1997). The V model approach is originally design for software, however, can be applied for products as well, as per the simultaneous engineering, the process of development occurs in parallel with test process, i.e., components development and tests, only after conclusion of this step it can be moved to the next step (Pereira et al, 2014).

Most definitions within the PDP can be succinctly categorized into three primary phases: pre-development, development, and post-development (Rozenfeld et al., 2006). In the pre-development phase, preliminary activities such as market research, idea generation, and feasibility assessments lay the groundwork for subsequent stages. The development phase encompasses the actual design, engineering, prototyping processes, testing and production. Finally, the post-development phase involves activities such, market launch, ongoing support and maintenance and disposal as per figure 3.

Figure 3: Macro and Meso stages of Product development process



Source: Research context adapted from Rozenfeld et al. (2006)

2.3 NEXUS PDP STAGES AND CE STRATEGIES

There is a growing interest in the concept of the CE within organizations, especially those in manufacturing, as it offers the possibility of aligning organizational objectives with those of sustainable development (Diaz et al., 2021). The literature development on the integration of CE into PDP has underscored the strategic role of circular product design in organizations. The implications of integrating CE into existing products or in the development of new products remain uncertain, with managerial factors, such as the strong influence of corporate sustainability maturity levels, being necessary for implementation (Diaz et al., 2022).

The Eco-design concept, focusing on prevention before reuse and reuse before recovery, is linked to the reduction of waste and residues, although with fundamental differences from CE, where waste and residues should ideally not exist, instead they should be considered as resources input for another process (den Hollander et al., 2017). It brings important elements to the PDP. Among corporate processes, product design and development are pivotal in defining the product's life cycle and represent 80% of the product's sustainability impact (IRP, 2018).

The stages of product development and its life cycle are related to factors such as consumption (purpose and usage of the product, types of consumers), product design (choice of materials and a format that enables reuse, recycling, and product cascading), business models (ownership or sharing to optimize use, for example), production (manufacturing circumstances, energy efficiency, e.g., the use of renewable energy sources), and reverse logistics (related to collection or reverse cycle, involving submitting the old product to a new process such as reuse, remanufacturing, or recycling). The integration between CE and PDP is initiated by their concepts and objectives, aiming to foster economic development and efficiency.

Several methodologies are commonly employed to foster sustainable and eco-friendly practices. One prevalent approach is Design for Disassembly (DfD), which emphasizes creating products with components that are easily disassembled for repair, reuse, or recycling. C2C design is another widely embraced method, focusing on the continuous cycling of materials, ensuring that they remain in closed loops rather than becoming waste. Life Cycle Assessment (LCA) is a rigorous analytical tool commonly used to evaluate the environmental impact of a product throughout its entire lifecycle, guiding designers in making informed decisions for resource efficiency. Additionally, biomimicry, inspired by nature's design principles, is gaining prominence as a method to create sustainable and efficient products. Integrating these methods into the product design process not only aligns with the principles of CE but also promotes responsible consumption and production practices, contributing to a more sustainable and regenerative approach to product development.

3- METHODOLOGICAL PROCEDURES

This chapter defines the methodology and stages that will be followed based on the scope and objectives of the study that were presented in section 1.4. The present study is exploratory due to availability of few studies about the interrelation of the fields and qualitative approach, Gray (2012) describes the qualitative approach as a method for subjectively understanding the research objective by explaining the context surrounding the object of study.

For the research development the methodological procedures follow the Systematic Literature Review based Tranfield et al. (2003) and Morioka et al., (2016), followed by the 3 steps of planning, conducting and report & dissemination. The reason to choose these documents procedures is due to their contributions and crescent citations.

This process involves three stages, with the first consisting of literature review planning, the second involving the actual review, and the third focusing on reporting and dissemination. Table 2 illustrates the relationships between these stages and the objectives of this study.

Table 2: Stages of the research and objectives

Systematic Literature Review – State of the art		
STAGE 1 **PLANNING**	**STAGE 2** **CONDUCTING**	**STAGE 3** **REPORT & DISSEMINATION**
• Exploratory search of themes to generate and define research ideas. • Initial research question proposal. • Refinement of the research question and definition of search parameters for selection criteria in the Scopus database. • Data collection & analysis via network bibliometric review	• State of the art: Execution of the SLR, search and study selection based on the previous stage saved in a .CSV electronic file. • Content analysis (conducted in rounds and saved in a .CSV electronic file) carried out as follows: I. Titles, abstracts, and keywords: Reading titles, abstracts, and keywords to eliminate studies that were not related to the research objective saved in the .CSV database. The refinement resulted in 137 documents. II. Reading abstracts and introduction with a focus on the categorization of approaches (Case study, Review & Survey) to select the Cases study for the preliminary framework	• Mind map of key elements and the preparation of reports with mutual benefits for the deepening processes. • Framework Structure I. Preliminary framework matrix II. Delphi approach with experts for validation III. Final Framework

	preparation. The refinement resulted in 29 documents. III. Descriptive - Full articles: IV. Critical analysis: Full articles: In-depth content analysis of CE elements intersection with PDP phases on a CE strategy level • Data synthesis: Preparation of matrix with main elements to illustrate the key findings.	
Objective 1: To understand the concepts, theories and gaps that exist in the literature involving the relationship between the PDP and CE.	**Objective 2:** To identify the main connection elements existing in these areas.	**Objective 3:** To propose a preliminary framework based on the elements defined in the previous step. **Objective 4:** To test the preliminary framework through application using a panel of experts and update the framework with the results.

Source: adapted from Tranfield et al. (2003) & Morioka (2016) with adjustments related to this study.

3.1 – PLANNING

In the planning stage, an exploratory search was conducted concerning the research field and its theoretical foundations including main authors, and the field evolution, followed by the research question definition, selection criteria for the string creation, and the bibliometric review. For the exploratory search one of the key considerations was a deeper exploration at the micro-level, such as how organizations perceive and implement CE (Barreiro et al., 2020), its origins, its relationship with 9R frameworks, and its transition strategies. Subsequently, a search was conducted on the PDP and New product development (NPD) fields, including its main phases, concept, design, production, usage and disposal, followed by an exploration of the connections between CE and the PDP, i.e., industrial ecology, eco-design, blue economy, C2C.

This analysis was conducted in an unstructured manner to form an initial understanding of the research field, employing a snowball logic, reference analysis of references, keyword combination testing, and preliminary formulation of the research question. After refining the research question and defining the criteria, a search for articles was carried out and archived in the Research rabbit platform for further analysis. Finally, a method selection process was undertaken, and research question was defined.

3.2 CONDUCTING

In this chapter, it delves the state-of-the-art of the literature. The process of conducting the systematic literature review and content analysis were based on the studies *Semantic interoperability for an integrated PDP: a systematic literature review" (Szejka et al, 2017) and* "philosophical conceptualization" method (Meredith, 1992) which selected documents are read and re-read. The process is organized in four steps:

- **Step 1:** Search, analysis, and selection of the article database
- **Step 2:** Categorization of articles from the previous step.
- **Step 3:** Descriptive analysis (main journals, citations, publication trends) of the database.
- **Step 4:** Critical analysis (title, abstract, and approach) of key works in parallel with the initiation of the content analysis phase and the development of the preliminary framework.

This second stage involves the review itself, the most extensive part of the research in terms of data collection, analysis, and categorization, representing the review process according to Tranfield et al. (2003). Concepts that promote intersection between CE and PDP, their objectives, gaps, limitations, and future recommendations will be analyzed. Key references for in-depth exploration will be presented, and key points and strategies will be identified.

Following Fink's (1998) definition, this review is a systematic, replicable, and explicit model for identifying, evaluating, and interpreting a set of documents. In this study, the goal is to identify the elements of intersection of CE and PDP phases in the literature and integrate them to develop a preliminary framework.

3.3 – REPORT AND DISSEMINATION

The third stage of this research involves constructing the preliminary framework, followed by a panel of experts to test the framework from a practical point of view. Research activities at this stage are conducted simultaneously.

3.3.1 - PRELIMINARY FRAMEWORK

The development of the study involves seeking points of correlation between the known literature based on the results of previous stages. The choice of the framework is because it promotes clear steps to be followed and a high quality of structuring results, especially in multidisciplinary projects (Gale et al., 2013). A conceptual model is a set of concepts, with or without hypotheses, used to represent or describe a process, not to explain it. To proceed with conceptualization, the initial step is theoretical construction, the philosophical conceptualization, which is based on reading and rereading documents (Meredith, 1993).

This stage is to validate the preliminary framework with an expert panel to present a final framework that demonstrates the interrelation between CE and PDP in practice, and to propose a PDP in which products can be conceived with the concept of circularity, promoting more sustainable development. Furthermore, the study aims to qualitatively assess the benefits generated.

3.3.2 – EXPERT PANEL DELPHI APPROACH

To present the final framework, a Delphi approach is conducted via an expert panel from a multinational automotive parts company. This panel is to refine and assess how well the theoretical preliminary framework is understood and applicable in practice. The choice of the Delphi approach is based on the following key reasons: i) it does not require the physical presence of participants, allowing for multicultural participation; ii) it enables the collection of expert opinions without biases, such as those related to hierarchical positions or halo effects, as the process is anonymous; and iii) it seeks to achieve a certain level of consensus in an area of uncertainty or lack of empirical evidence (Delbecq et al. 1975, Dawson et al., 1995, Murphy et al. 1998).

Delphi method was first used in 1950 by the RAND Corporation. According to Barrett (1981), this method is based on multiple stages that seek the most reliable consensus based on the opinions of experts on a particular topic. It is a structured process in which information is collected and aggregated. The techniques of the Delphi methodology are based on the premises that the opinion of a group of experts is more valuable than that one individual expert (Gbededo, 2020).

In various cross-domain studies, a consensus level of 75% is appropriate, and this is always predetermined as a percentage (Chang et al., 2010). Qualification of experts and diversity are important to gathering a valid contribution, as well as the number of participants, it can vary and does not call for expert panels to be representative samples for statistical purposes (Powell, 2002). Additionally, it is possible to address the forms online, another relevant factor for its selection is to seek consensus through different views on the same theme. In other words, it provides evidence of how different sectors are operating, which is relevant to the process of developing and validating the framework proposed in this work.

As this study is empirical research and given that the study field is still in its infancy within both the academic literature and industrial practices, a minimum of 10 respondents was deemed appropriate for evaluating the panel results (Powell, 2002). This decision was made to ensure that the findings gleaned from the panel discussion are sufficiently robust and representative of the emerging trends and perspectives within the field. Despite the relative novelty of the subject matter, gathering insights from a diverse group of respondents enables a comprehensive exploration of the topic, offering valuable insights that contribute to the advancement of knowledge in this burgeoning area of study.

This case study was conducted at a German multinational technology company that offers reuse, repair, and remanufacturing services. The decision to select only one company was based on the feasibility of information exchange, the absence of issues with sensitive data collection, the high accuracy of information quality, and the professional experience of the researcher. It is important to highlight the need to understand cultural aspects in a multinational company environment. For this panel, experts from different countries (Germany, the United States, and Brazil), different genders, various areas, functions, and levels of experience within the same multinational company were selected. All the respondents had responsibilities and decision-making roles related to PDP and CE strategies, specifically in the reuse, repair, and remanufacturing businesses.

Structure of Delphi approach is organized in the design and pretest of the questionnaire based on the outcome of the preliminary framework, adjustments were made in the questions to improve clarity and structure. Preparation for round 1 with qualitative questions to collect knowledge and opinions of the participants regarding the challenges of CE transition and customer requirements for CE products, after the responses received, a review is performed to validate the understanding and inputs of participants. Simultaneously, round 2 is performed with the qualitative questions related to the validation of the framework. In this round the consensus objective is to achieve 75% of agreement of the elements in each PDP stage, if consensus is not achieved the relevance of the elements will be questioned in a next round. The additional elements suggested by respondents will be included in this round too. This relevance of the elements will be classified as low, medium, and high impact, only high and medium impact will be considered in the consensus validation. See table 3

The questionnaire is applied online per e-mail via Qualtrics software, results and details can be access further.

Table 3: Delphi approach structure with experts

	Purpose	Process	Results
Experts selection	Experts on engineering, marketing, controlling, sales, manufacturing areas.	Experts are invited first to participate voluntarly, after confirmation the link for the questionnaire is sent.	Panel with experts of a German multinational organization.
Round 1	Exploratory for qualitative questions.	To define qualitative questions based on the conceptual framework.	Forms are fullfilled for feedback and analysis.
Round 2	Quantitative: 75% agreement of proposed CE elements for PDP	To define quantitative questions based on the conceptual framework.	Forms are fullfilled for feedback and analysis.
Retrive data analysis	Feedback development	Codified the responses.	Analysis and preparation for next round.
Feedback	Exchange information with experts anonimously	Analysis of responses to check consensus achivement.	Feedback for reflection and preparation for next round.
Round 3	Quantitative: Identified CE relevant elements for PDP	Previous results are used as input for questions definition.	
Retrive data analysis	Feedback development	Codified the responses.	Analysis and preparation for final framework or next round if necessary.
Feedback	Exchange information with experts anonimously	Analysis of responses to check consensus achivement.	Final framework conclusion or next round preparation.

Source: the author, 2023

3.4 - STATE OF THE ART OF PRELIMINARY FRAMEWORK

In this chapter is presented the Systematic Literature Review (SLR), content analysis, preliminary framework of strategies of CE integrated to the PDP and, research contributions.

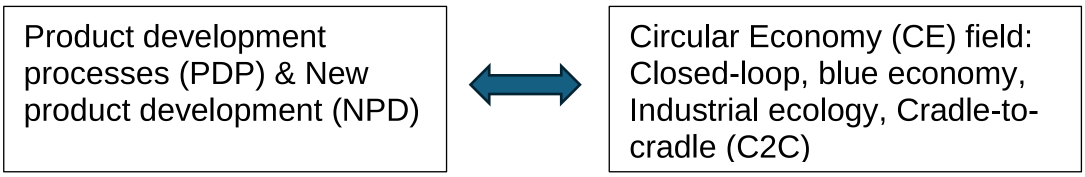
3.4.1 – SYSTEMATIC LITERATURE REVIEW

For the SLR, the Scopus database was selected because it comprehends a broader range of journals in business management than Web of Science, for example (Casprini et al., 2020) in additional it is compatible to software which support to the bibliometric review (Ferrasso et al., 2022). Scopus is a source-neutral abstract and citation database curated by independent subject matter experts who are recognized leaders in their fields. (SCOPUS, 2023).

In the first step exploratory research was performed to investigate its roots in an interdisciplinary field approach. The aim is to reveal uncharted territories in the CE fields interrelated to the PDP, to gain a deeper understanding of the subject, to identify key variables, formulate hypotheses, and refine research questions for further investigation. It was realized trial and errors tests with key words combinations to find the better results for the database.

For the research the key terms were selected based on the combination of PDP, new product development (NPD) and CE umbrella field, i.e. closed-loop, blue economy, industrial ecology and, cradle-to-cradle (C2C) and their relationship as per figure 4. It supported to find papers relevant to this study. By combining these key words, the research seeks to investigate the intersection of CE with the intricate processes and strategies PDP, fostering a comprehensive understanding.

Figure 4: Relationship between key terms



Source: Author, 2023

3.4.1.1 Data collection

In the first attempt the data were collected from Scopus database, the string proposed was ("product develop*" OR "PDP" OR "new product dev*") AND ("circular strateg*" OR "closed loop*" OR "circular economy" OR "reuse" OR "remanufactur*" OR "refurbish" OR "repair" OR "recycl*" OR "cradle-to-cradle"), these terms were selected based on the relation with the automotive industry. The asterisk (*) was added to account for variations in keyword endings. In this search, titles, abstracts, and keywords of each publication were considered. Subsequently, publications were filtered by document type ("article") to identify the main contributions in the field. The publication date was restricted between 2012 and 2022, and only English-language publications were included without thematic restrictions. This search resulted in a total of 556 documents. After documents review, it was noted that many articles did not meet the necessary requirements for the research, prompting a second trial.

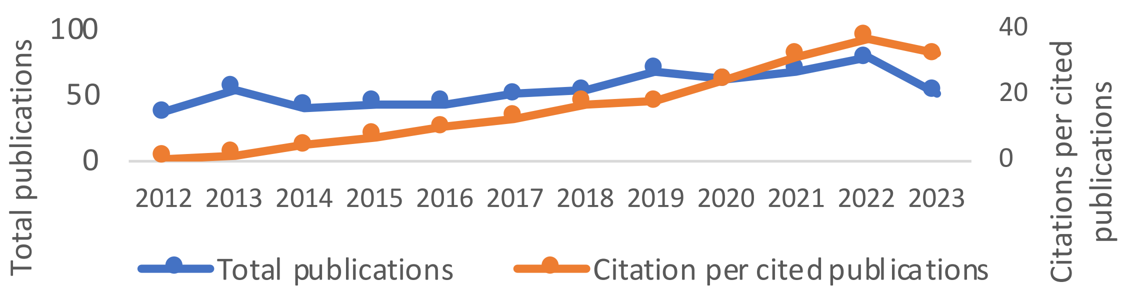
Final and second attempt were collected in May 2023. It was identified publications via a Boolean search by running a query for the following keywords: (“product develop*” OR “PDP” OR “new product dev*” or “NPD”) AND (“circular*” OR “circular economy” or “CE” or “closed loop*” OR “circular economy” OR “reuse” OR “remanufactur*” OR “industrial ecology” or “blue economy” OR “repair” OR “recycl*” OR “crade-to-cradle”), afterward first attempt reviewed the key words were selected based on the articles base return, some terms were not included because there was no documents related to the field i.e. refuse, rethink, reduce, repurpose and recover and some fields were included based on its relationship to the foundation of CE, i.e. industrial ecology and blue economy. The asterisk (*) was used to account for the variations in the keywords. The search terms were performed on “title, abstract, and keywords” of publications, filtered by type of document (“article”) in (“final”) stage from (“Journals”), to identify the most influential contributions in the field, the timeframe set definition was from 2012 to 2023 to capture the most recently contributions, only written in English, subject area was filtered by Engineering, Environmental Science, Computer Science, Business, Management and Accounting, Energy, Materials Science, Social Science, Economics Science , Decision and Mathematics. A total of 640 publications resulted from this search, the metadata from all documents were stored in *.RIS and, *.CSV formats for further analysis. After cleaning up and elimination of duplicate papers with support of Research Rabbit app, the final base is a total of 590 papers.

3.4.1.2 Bibliometric review

A bibliometric review was applied to understand the research field, opportunities, and theoretical foundations. The database analysis and selection were conducted followed by the network bibliometric approach used by Bandeira et al (2022). To explore the structure of scientific knowledge, a co-citation analysis was built via the software CiteSpace 6.2.R4 version and a co-occurrence of key words via VOSviewer 1.6.17 version.

Figure 5 shows the publications evolution and citation trends between 2012 and May 2023. The publication trend demonstrates a pic of TP (total publications) in 2013 with low rate of C/CP (cited per citer publications), which started to increase from 2014 onwards while TP was more stable until 2017. It indicates that intersection of CE and PDP had not captured much academic attention before 2016, a stabilization of publications between 2016 to 2019 and, from 2020 the acceleration of interest.

Figure 5: Total publications and citation evolution of CE and PDP fields (Scopus database)



Source: The author, 2023

3.4.1.3 Co-citation network analysis

The reveal the theoretical roots of studies regarding CE and PDP areas, a co-citation analysis was performed. Co-citation is a form of coupling and analyzes the frequency of two documents are jointly cited in a third article [3]. This analysis is to understand the base of the research domain and its main clusters.

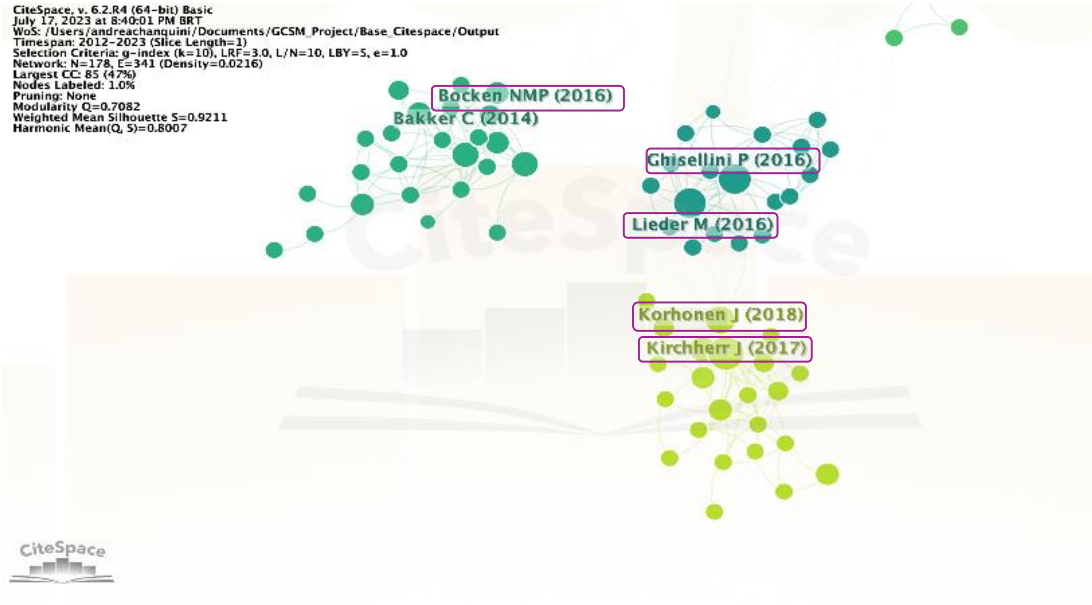
By employing the co-citation analysis, it was identified the theoretical foundation, main authors, and recurrent concepts that form the intellectual backbone of the research field at the nexus of CE and PDP. The co-citation patterns will be instrumental in unveiling influential papers and authors, providing a basis for categorizing publications based on their theoretical underpinnings and establishing thematic clusters within the preliminary framework.

This approach will enhance the depth and granularity of analysis, allowing to trace the evolution of ideas and the interconnected relationships among key concepts. As we proceed, the preliminary framework will serve as a dynamic tool for organizing and interpreting bibliometric data, ultimately contributing to a more nuanced and comprehensive understanding of the intricate interplay between CE principles and the PDP.

It was used *.RIS file is an input for data conversation in CiteSpace. The software recognized a total of 32,476 references from 590 papers in the sample. Out of these, 31,380 were successfully converted at an acceptance rate of 96.0%. The converted data was run with the frame period of January 2012 until May 2023, text processing: title, abstract, author keyword; node types: references; links: Cosine; scope: within slices; g-index, scale factor k = 10; top N levels of most cited references in each slice = 10 (top N% = 10.0%); no pruning procedures; visualization cluster view static + merged network. To define the parameters that best suit the network, multiple tests were done according to chronological slices, the number of top-cited references, and exploring the criteria thresholds. These tests are highly recommended to mitigate an excessive number of nodes and blurring the raised network.

The co-citation network was built to identify the theoretical roots, main publications and most influential cited by research in the intersection fields of CE and PDP. The figure 6 shows the network of CiteSpace software, the nodes represent the most cited references in the sample, the top-five most cited papers in the sample were: Kirchherr et al. (2017) (count: 12; centrality: 0.07); Lieder et al. (2016) (count: 10; centrality: 0.09); Ghisellini et al. (2016) (count: 10; centrality: 0.13); Korhonen et al. (2018) (count: 9; centrality: 0.14); Bocken et al. (2016) (count: 6; centrality: 0.08).

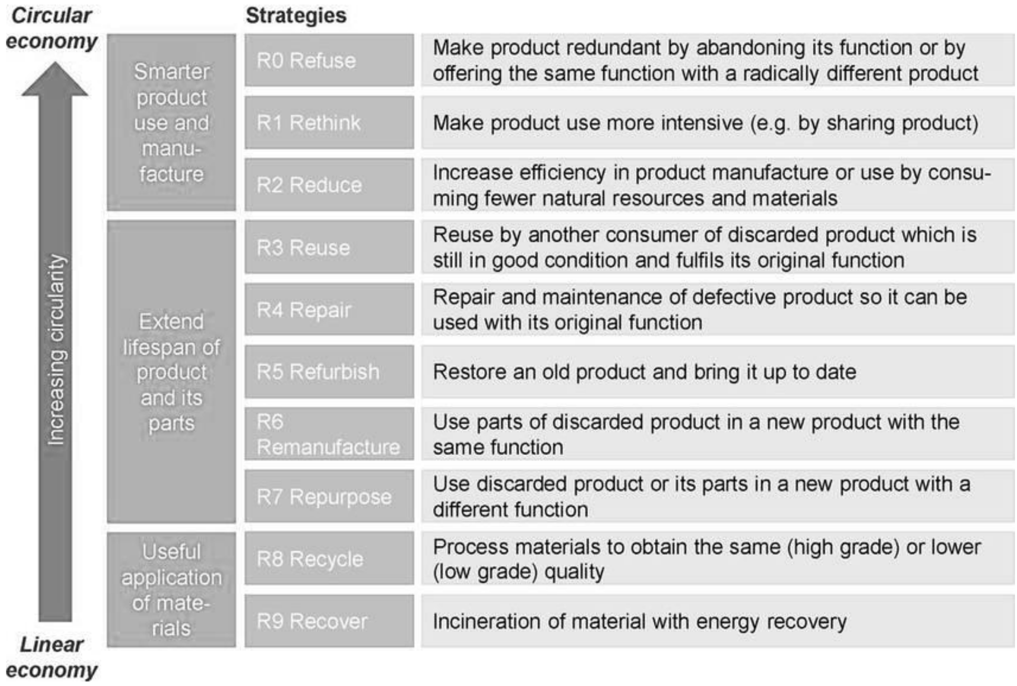
Figure 6: Network of co-citation generated by CiteSpace



Source: Author, 2023

The study from Kirchherr et al. (2017) is dedicating to the understand of different definitions of CE to contribute with the concept evolution and coherence. In this study the increasing of circularity is related to the strategies used of product development principles, based on the 9R framework adapted from Potting et at., (2017). It is structured accordingly strategies in the production chain, in the order from more circular to less circular: Refuse, Rethink, Reduce, Re-use, Repair, Refurbish, Remanufacturing, Repurpose, Recycle & Recovery. The more circular practices, the first three, are considered products of intelligent use and manufacturing. From reuse to repurposing, they are seen as extending the product and its components' life cycle. In terms of recycling and recovery, these are considered applications of useful materials, with the latter two being closer to the linear economy. Figure 7.

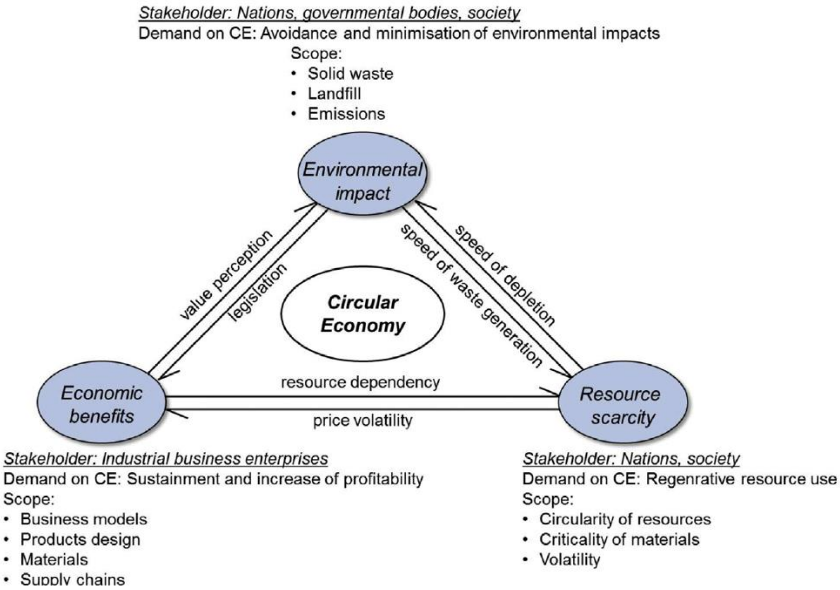
Figure 7: 9R Framework



Source: J. Kirchher et al (2017), adapted from Potting et al. (2017).

The study from Lieder et al. (2016) is presenting a comprehensive framework to propose a strategy for CE implementation, the CE landscape is presented in three aspects: resources scarcity, environmental impact, and economic benefits. These elements are seamlessly linked, to gain economic benefits industrial activity depends on resources necessary to transform raw materials into products via manufacturing operations, at the same time the industrial activity influences natural environment offering impacts i.e. waste generation as per figure 8.

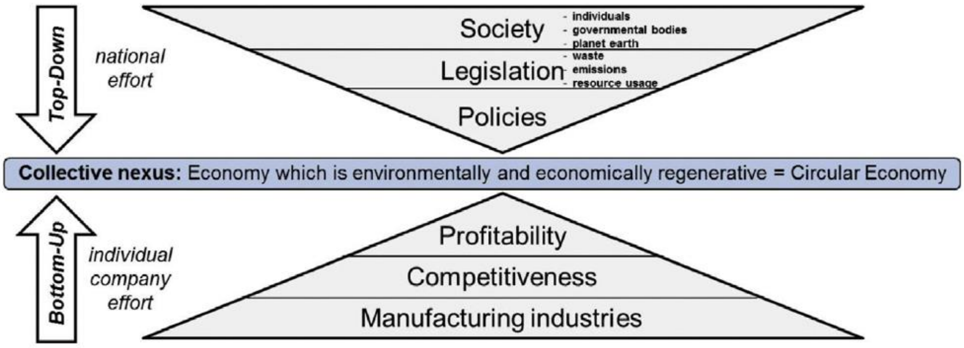
Figure 8: Comprehensive framework of Circular Economy



Source: Lieder et al. (2016) – comprehensive framework

Implementation of CE concept is a challenging task due to prevailing linear mind-set and established structures in industry and society, and the natural environment benefits are simple to grasp. Despite of success cases of CE implementation, for large scale implementation it requires a radical change in the way business and management requirements operate. The feasibility of implementation depends on the collaboration and support of a top-down from society, legislation and policies efforts and bottom-up approach from manufacturing industries, presented in the figure 9.

Figure 9: Proposed CE implementation strategy applying top-down and bottom-up approach



Source: Lieder et al. (2016)

The study from Ghisellini et al. (2016) is aiming to present the main CE features and perspectives. In this research is presented the origins, principles, advantages and disadvantages, modeling, and implementation of CE in different scales (i. Micro: company or consumer level, ii. Meso: eco-industrial parks level, iii. Macro: city, region, and nation level). The goal of promoting CE is the decoupling of environmental pressure to the economic growth development. For that there are two conceptual groups: CE Models and CE principles.

The main CE strategy implementation in the micro level is the production process, and designs options i.e., eco-design and design for environment (DFE). Both are about a blend of environmental aspects into a product design and development at a product conception to enhance the product its environmental performance. The promotion of consumers responsibility is highlighted as crucial for choices about services and more sustainable products. Landfill and incineration are no longer options to an effective waste management. Better options are recovering resources or better choices of material for lower environmental impacts (Ghisellini et al., 2016).

The study from Korhonen et al. (2018) is about the concept of CE and its boundaries, such as in thermodynamics in terms of reusage or recycling. According to Korhonen, CE scientific field has a high potential to be explored due to unorganized and superficial level of concepts, CE seems to be a collection of vague and separate ideas from several fields. In this study six challenges about sustainable development through CE are presented to support concept definition. CE is considered an inner circle of product reuse, remanufacturing, and refurbishment, demanding less resources and energy, so a more economic option than conventional recycling. The win-win potential of CE is to contribute to the three dimensions of sustainability: environmental, social, and economic, should utilized nature's cycles for preserving materials, energy, and nutrients for economic use.

There are the six challenges of CE concept are the following:

i) Thermodynamics limits, the link between physical flows of matter and energy, abstract monetary flows or the exchange value that influence decision making.

ii) Spatial and temporal system boundaries, physical flow of materials energy cross organizational, administrative, and geographical boundaries, local and regional business.

iii) Limits posed by physical economic growth, this is related to the production efficiency, when it increases, production costs decrease and eventually prices of end-products decrease, so consumption increases, it is the rebound effect.

iv) Path dependencies and lock-in, in CE innovations, models and systems are designed for product reuse, remanufacturing and refurbishing and must compete with more conventional recycling for low quality raw materials, existing infrastructures and financial investments directed to slow down payback time, even if the innovation is better from environmental and societal perspectives, the conventional structure prevailed.

v) Intra-organizational vs Inter-organizational strategies and management, physical flows of materials and energy extracted from nature travel through different interdependent parts before they end-up as waste, new business models including product design for multiple lifecycles, leasing and renting the product, this requires a cooperation between suppliers and customers, so who is going to control and profit and who is going to loses is an open question.

vi) Definition of physical flows, the definition of material flow is temporal, spatial, and cultural, concept of waste is dynamic and changing (Pongracz, 2002), when waste is perceived as resource, the flow has an economic value, and the distinction of waste and product is problematic.

The study from Bocken et al. (2016) developed a framework of strategies to guide designers and strategists in the transition to CE. Practical challenges are presented to the business transition from a linear economy approach to a CE approach. This research addresses this topic to present a framework to guide designers and business strategists to move to CE based on a list of product designs and business models. The two strategies approached in this article are for closing and slowing resources loops.

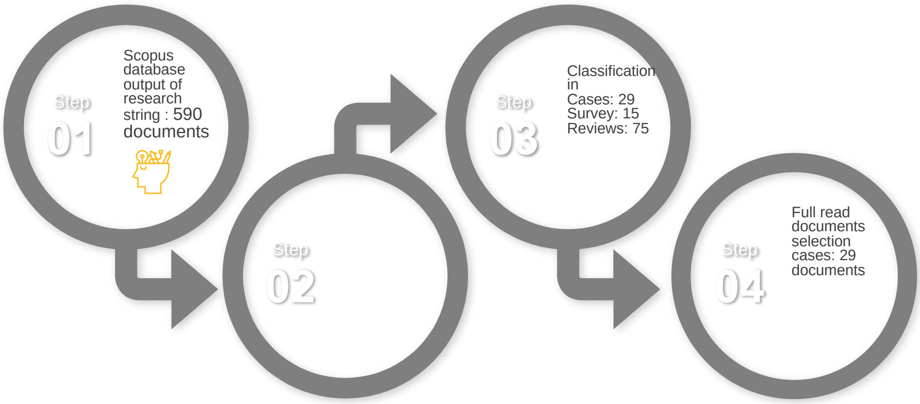
Slowing resources strategy is focused on lifetime extension, increasing efficiency, and reducing usage of resources. Durability of a product is described as emotional, reliable, and physical. Closing loop strategy is inspired in the concept of McDonough and Braungart, when product is designed for technological cycle, biological cycle, and for dissembling/reassembling, closing a loop of resources, there is no disposal in this material flow. In both strategies the early stage in the product delivers process is important for the circularity later (Bocken et al., 2016).

According to Teece every new product development should be coupled with the development of the business model, which is responsible for defining the go to market approach and capturing value strategy. For the CE business is required a new way of thinking and doing business. In combination with the product strategy of slowing or closing resources loops the alternatives business models are sharing ownership, extending product value via remanufacturing, and collecting back products, longer product durability, transform waste into new forms of value and rewarding the product return, and finally a process-oriented solution using residual outputs from a certain process into another different process (Bocken et al., 2016).

3.4.1.4 Selection of papers

The final database was refined based on the titles, abstracts, and keywords to eliminate studies that did not match the research requirements, i.e., cross-domain approach of CE and PDP and services as a product, resulted in 119 documents. The database was classified in research methods: i) case study, ii) survey, iii) Literature review, see figure 10. After this stage, it was decided by the researcher to retain in the final base the documents which are about case studies of implementation to understand the contributions, findings, factors, future recommendations, and limitations, resulted in 29 papers to build up the preliminary framework.

Figure 10: Selection of papers



Source: Author, 2023

3.4.1.5 Main journals

The main journals include the *Journal of Cleaner Production, Resources, Conservation and Recycling, Applied Soft Computing, Journal of Fashion Marketing and Management, Journal of Industrial Ecology, Journal of Intelligent Manufacturing* all with a high impact factor (SJR >1; Q1). This is followed by the journals *International Journal of Sustainable Engineering, Johnson Matthey Technology Review, Journal of Mechanical Design, Journal of remanufacturing, Sustainability*, among others. Details are presented in Table 4.

Table 4: Publications & Journals

Journal	Authors	Year	Title
Applied Soft Computing	Zhiqiao Wu,C. K. Kwong,Chun Kit Kwong,Ridvan Aydin,R. Aydin,Jiafu Tang	2017	A cooperative negotiation embedded NSGA-II for solving an integrated product family and supply chain design problem with remanufacturing consideration
Design Journal	Sonja van Dam,Froukje Sleeswijk Visser,Conny Bakker	2020	The Impact of Co-Creation on the Design of Circular Product-Service Systems :

Journal	Authors	Year	Title
			Learnings from a Case Study with Washing Machines
International Journal of Sustainable Engineering	Morgane Bigolin,Ângela de Moura Ferreira Danilevicz,Marc A. Weiss,Luiz Carlos Pinto da Silva Filho	2021	Sustainable New Product Development: a decision-making tool for the construction industry
Johnson Matthey Technology Review	Daniel Jugend,Paula de Camargo Fiorini,Paula de Camargo Fiorini,Marco Antonio Paula Pinheiro,Hermes Moretti Ribeiro da Silva,Bruno Michel Roman Pais Seles	2020	Building Circular Products in an Emerging Economy: An Initial Exploration Regarding Practices, Drivers and Barriers: Case studies of new product development from medium and large Brazilian companies
Journal of Cleaner Production	Francesco De Fazio,Conny Bakker,Bas Flipsen,Ruud Balkenende	2021	The Disassembly Map: A new method to enhance design for product repairability
Journal of Cleaner Production	Jagdeep Singh,Isabel Ordoñez	2016	Resource recovery from post-consumer waste: Important lessons for the upcoming circular economy
Journal of Cleaner Production	Jaime Mesa,Ivan E. Esparragoza,Ivan E. Esparragoza,Heriberto Maury	2018	Developing a set of sustainability indicators for product families based on the circular economy model
Journal of Cleaner Production	Jessika Luth Richter,Leena Tähkämö,Carl Dalhammar	2019	Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts
Journal of Cleaner Production	Magnus Schulz-Mönninghoff,Michael Neidhardt,Monia Niero	2022	What is the contribution of different business processes to material circularity at company-level? A case study for electric vehicle batteries
Journal of Cleaner Production	Sergio Tadeu De Almeida,Milton Borsato,Cássia Maria Lie Ugaya	2017	Application of exergy-based approach for implementing design for reuse: The case of microwave oven
Journal of Cleaner Production	Srujana Kandukuri,Elif Elçin Günay,Omar Al-Araidah,Omar Al-Araidah,Gül E. Okudan Kremer	2021	Inventive solutions for remanufacturing using additive manufacturing: ETRIZ

Journal	Authors	Year	Title
Journal of Fashion Marketing and Management	Ida Marie Sandvik,Wendy Stubbs	2019	Circular fashion supply chain through textile-to-textile recycling
Journal of Industrial Ecology	Louise Laumann Kjær,Daniela Cristina Antelmi Pigosso,Monia Niero,Nynne Marie Bech,Tim C. McAloone	2019	Product/Service-Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption?
Journal of Intelligent Manufacturing	Chun-Che Huang,Wen-Yau Liang,Shan-Ru Yi	2017	Cloud-based design for disassembly to create environmentally friendly products
Journal of Mechanical Design	Khalil Al Handawi,Petter Andersson,Massimo Panarotto,Ola Isaksson,Michael Kokkolaras	2021	Scalable Set-Based Design Optimization and Remanufacturing for Meeting Changing Requirements
Journal of remanufacturing	Nina Boorsma,David Peck,Tanya Bakker,Conny Bakker,Ruud Balkenende	2022	The strategic value of design for remanufacturing: a case study of professional imaging equipment
Resources Conservation and Recycling	Fábio Ribeiro de Oliveira,Sergio Luiz Braga França,Luís Alberto Duncan Rangel	2017	Challenges and opportunities in a circular economy for a local productive arrangement of furniture in Brazil
Resources Conservation and Recycling	Kim Ragaert,Sophie Huysveld,Gianni Vyncke,Sara Hubo,Lore Veelaert,Jo Dewulf,Els Du Bois	2020	Design from recycling: A complex mixed plastic waste case study
Resources Conservation and Recycling	Monia Niero,Stig Irving Olsen	2016	Circular economy: To be or not to be in a closed product loop? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements
Sustainability	Andrea Urbinati,Davide Chiaroni,Giovanni Toletti	2019	Managing the Introduction of Circular Products: Evidence from the Beverage Industry
Sustainability	Fernando Tobal Berssaneti,Simone Berger,Ana Maria Saut,Rosangela Maria Vanalle,Rosangela Maria Vanalle,José Carlos Curvelo Santana	2019	Value Generation of Remanufactured Products: Multi-Case Study of Third-Party Companies

Journal	Authors	Year	Title
Sustainability	Irina Albastroiu Nastase,Cristian Negrutiu,Mihai Felea,Carmen Acatrinei,Andrei Cepoi,Adrian Istrate	2021	Toward a Circular Economy in the Toy Industry: The Business Model of a Romanian Company
Sustainability	Jelle Joustra,Conny Bakker,Riel Bessai,Ruud Balkenende	2022	Circular Composites by Design: Testing a Design Method in Industry
Sustainability	Julie Kamp Albæk,Sasha Shahbazi,Sasha Shahbazi,Tim C. McAloone,Daniela Cristina Antelmi Pigosso	2020	Circularity Evaluation of Alternative Concepts During Early Product Design and Development
Sustainability	Louise Lindkvist Haziri,Erik Sundin,Tomohiko Sakao	2019	Feedback from Remanufacturing: Its Unexploited Potential to Improve Future Product Design
Sustainability	Mohamad Kaddoura,Mohamad Kaddoura,Marianna Lena Kambanou,Anne-Marie Tillman,Tomohiko Sakao	2019	Is Prolonging the Lifetime of Passive Durable Products a Low-Hanging Fruit of a Circular Economy? : A Multiple Case Study
Sustainability	Riikka Piippo,Kirsi Niinimäki,Maarit Aakko	2022	Fit for the Future: Garment Quality and Product Lifetimes in a CE Context
Sustainability	Xiaohui He,Dongmei Su,Wenchao Cai,Alexandra Pehlken,Guofang Zhang,Guofang Zhang,Aimin Wang,Jinsheng Xiao	2021	Influence of Material Selection and Product Design on Automotive Vehicle Recyclability
Sustainability	Yana K. Ramsheva,Yana Konstantinova Ramsheva,Rikke M. Moalem,Leonidas Milios	2020	Realizing a Circular Concrete Industry in Denmark through an Integrated Product, Service and System Perspective

Source: The author, 2023

3.4.2 CATEGORIZATION

In this session the selected documents were categorized according to the CE strategies proposal by Potting et al., (2017) and reviewed from a perspective of the PDP phases organized by Concept, Development, Production, Usage, and Disposal based on adaptation of definitions presented by Rozenfeld et al. (2017), Szejka et al. (2017), Uche et al. (2020). The dimensions of CE strategies were adapted from the 9R framework and adjusted by the author in three main definitions: i) Optimize function; ii) Prolong lifecycle; iii) Reprocessing.

The definition of CE elements presented in this research is based on terms found in the documents about economic and social balance, improving cost and resource efficiency, and reducing waste. These elements are based on the interrelation between CE strategies and PDP stages. The foundation of these elements stems from CE principles applied to examples of product development, as illustrated in Table 5.

In the concept stage, CE is interrelated with the business model through idea generation and business strategy. The development stage is linked to design methods, grounded in the principles of design definition and requirements. The production stage connects to industrial processes, based on established procedures and industrial infrastructure. The usage stage is tied to consumer influence, relying on consumer behavior, and the disposal stage is connected to take-back programs, established through end-of-life (EOL) strategies, including product collection and reverse logistics.

These CE elements are aligned with the three key CE strategies—Optimize Function, Prolong Lifecycle, and Reprocessing—across the PDP stages.

Table 5: CE elements interrelation with PDP stages

PDP stages	Concept	Development	Production	Usage	Disposal
CE Elements	Business models	Design Methods	Industrial process	Consumer influence	Take-back programs

Source: The author, 2023.

Research documents have been assigned to the perspectives of CE strategy of *Optimize function* if the research topic or motivation is about product sharing to enhance usage efficiency, possibilities of maintenance services to enlarge lifetime. For CE strategy of *Prolong lifecycle* the research topic or motivation was about product ownership principle with possibilities of maintenance services to enlarge lifetime or upcycling. If research motivation or topic was about product ownership, large scale with possibilities to be recycling, reusing or downcycling after lifetime the perspective of CE strategy of *Reprocessing*.

Initially some articles were categorized in more than one CE strategy since research topic were related to a comprehensive definition of both CE strategies. After re-reding these documents the final categorization was defined based on the most relevant findings, 9 documents were related to the Optimize function; 11 documents were related to Multiple-life cycles, and 9 documents were related to the Reprocessing, see table 6.

Table 6: Categories by authors

Authors		
Optimize function	Prolong lifecycle	Reprocessing
Mesa et al. (2018)	Wu et al. (2017)	Jugend et al. (2020)
Richter et al. (2019)	van Dam,et al. (2021)	Singh et al. (2016)
De Almeira et al. (2017)	De Fazio et al. (2021)	Sandvik et al. (2019)
Kjær et al. (2019)	Schulz-Mönninghoff et al. (2023)	Huang et al. (2017)
Urbinati et al. (2019)	Kandukuri et al. (2021)	Ragaert et al. (2020)
Nastase et al. (2022)	Al Handawi et al. (2021)	Niero et al. (2016)
Albæk et al. (2020)	Boorsma et al. (2022)	Joustra et al. (2022)
Piippo, et al. (2022)	Oliveira et al. (2018)	He et al. (2021)
Ramsheva et al. (2020)	Berssaneti et al. (2019)	
	Haziri,et al. (2019)	
	Kaddoura et al. (2019)	

Source: The author, 2023

3.4.3 CONTENT ANALYSIS

Focal point of these documents is around case studies, with the primary goal of comprehending the factors influencing possibilities and constraints encountered during evaluations. The selection and assessment of documents were predicated upon their incorporation of case studies. Consequently, a synthesis of these articles has been structured according to their respective cases, focus, results, and limitations. See table 7.

Table 7: Overview of selected papers (Objectives, results & limitations)

Authors	Year	Title	Cases	Focus	Results	Limitations
Jagdeep Singh,Isabel Ordoñez	2016	Resource recovery from post-consumer waste : Important lessons for the upcoming circular economy	50 examples of products developed from discarded material.	Classification of type of materials and recovery routes for business with recovered resources. Recovery routes were Reuse, Maintenance, Remanufacture, Recycle, Biodegradable and Energy Recovery. The characteristics of the examples were product type, production, value, waste type and recycling system.	3 main routes were classified based on: material recorey location (centralized or descentralized), materials usage purpose (the same or not the same). Main challenges are uncertainties at the use and EOL stage, Quality of products from recovered materials, Product complexity, Agency and ownership issues.	Different levels of detailed information about these products. Limited information about type of design phylosophy, whether products was developed for demonstratios and individual self-motiviation by designers
Monia Niero,Stig Irving Olsen	2016	Circular economy: To be or not to be in a closed product loop? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements	One case about Life-cycle Assessment (LCA) of 30 loops of Aluminium can production and recyling.	Investigation of effects of material composition to support increase the recycling rates of cans (can-to-can). LCA application to understand alloy composition.	Resource reduction possibility by reduction of weight of lid, to develop methods to separate the body and the lid at the point of collection.	Transportation for collection used can was not included in the system boundaries. Focus on bevarege can, however it can be extend to other sectors i.e. automotive.
Zhiqiao Wu,C. K. Kwong,Chun Kit Kwong,Ridvan Aydin,R. Aydin,Jiafu Tang	2017	A cooperative negotiation embedded NSGA-II for solving an integrated product family and supply chain design problem with remanufacturing consideration	One case about integrated product family and supply chain design.	Integration of product product family and supply chain design is conducted to investigate the effects of envorinmental penalty, quantity of demand and marginal cost of remanufaturing on used product return rate, manufacturers' and suppliers' profits and joint payoffs.	Proposal of a multi-objective optimization model considering remanufacture. The validation of the outperform of cooperative negotiation embedded NSGA-II (NSGA-CO) compared to previous nondominated sorting genetic algorithm-I (NSGA-II)	No informaiton about manufactures incentives to retailers to induce the collection, suppliers information about subcontracting the collection activities.
Sergio Tadeu De Almeida,Milton Borsato,Cássia Maria Lie Ugaya	2017	Application of exergy-based approach for implementing design for reuse: The case of microwave oven	One study case: design for reuse of microwave oven.	It aims to build, present and evaluate a new exergy-based method for energy efficiency assessment and material depletion aiming to overcome gaps on current attempts.	An exergy-based approach would unbiasedly drive Reuse EoL that facilitate Design for the Environment (DfE) as well as focus efforts on specific disassembly technologies.	The approach is limited to the energy-flows and not in other relevant ecosystems services. Presented method is still not included in a sofware package which facilitates the applicaiton.
Chun-Che Huang,Wen-Yau Liang,Shan-Ru Yi	2017	Cloud-based design for disassembly to create environmentally friendly products	One case: Electronic industry.	The goals include modeling component relationships, exploring disassemblability, recognizing patterns, providing guidelines and recyclable component classification, and facilitating design information exchange for sustainable product development via cloud computing architecture	Design for dissassembling consideration supported the product modularization to simplify configuration. Solutions can be provided from the cloud-based environment.	Consideration on "dismountability," with potential for more impactful contributions to the scientific community by addressing challenges related to dismounting products in degraded states and preventing the separation of incompatible parts, particularly with regard to recycling efforts.
Fábio Ribeiro de Oliveira,Sergio Luiz Braga França,Luís Alberto Duncan Rangel	2017	Challenges and opportunities in a circular economy for a local productive arrangement of furniture in Brazil	One study case about 23 companies specilized in wooden furniture in a local productive arrangements (LPA).	This study seeks to enhance CE in Brazil by analyzing opportunities and challenges for implementing a LPA in the furniture sector. It involves identifying solid waste streams and disposal practices to assess the potential for LPA integration.	Environmental symbiosis for residuals of material, besides the energetic source have been adopted in funiture industry. Adoption of CE strategic guidelines for planning and development of products.	Qualitative approach to idetified opportunities and trends of CE. Other topics were not included such as supply chain design and management, marketing and customer behavior, manufacturing and remanufacturing technologies.
Jaime Mesa,Ivan E. Esparragoza,Ivan E. Esparragoza, Heriberto Maury	2018	Developing a set of sustainability indicators for product families based on the circular economy model	One case about product families based on CE model (prosthetic fingers).	This study proposes six indicators regarding material flow, reusability, reconfiguration, and functional performance.	The indicators' contributions are highlighted through comparing two main modifications to the original product family: changes in manufacturing material and component geometry alongside material adjustments.	The approach is limited to one product family.

Authors	Year	Title	Cases	Focus	Results	Limitations
Jessika Luth Richter,Leena Tähkämö,Carl Dalhammar	2019	Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts	One case of LCA application built in product cases from 2012 to 2017.	The research aims to examine trade-offs related to LED lamp lifespan extension, building upon previous LCA-based durability studies and lighting product research, while identifying environmentally favorable contexts for longer lifetimes.	Product replacement with newer versions offers environmental benefits over retaining longer-life products, despite some trade-offs. However, these trade-offs diminish in decarbonized electricity contexts and are expected to decrease further as LED lamp technology matures and product development slows.	The approach is limited to one product, considering past product cases.
Ida Marie Sandvik,Wendy Stubbs	2019	Circular fashion supply chain through textile-to-textile recycling	One case about fashion industry.	The study aims to explore the drivers, inhibitors and enablers of creating a textile-to-textile recycling system in the Scandinavian fashion industry.	There is a limited technology which creates a challenge for separating materials; high costs of R&D and building the supporting logistics, complexity of supply chains including the multitude of stakeholders involved in product development. Understanding the context is a key for identified enablers specially in design and use of new materials, increased garment collection and collaboration.	The approach is limited to one context of industry. Small sample size and lack of representation of all key stakeholder groups, which limits the ability to generalise the findings.
Louise Laumann Kjær,Daniela Cristina Antelmi Pigosso,Monia Niero,Nynne Marie Bech,Tim C. McAloone	2019	Product/Service-Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption?	One case about Textile industry cases.	This study aims to inspire a more critical assessment of the role of Product-Service Systems (PSS) in enabling Circular Economy (CE) strategies, emphasizing the need to clarify how PSS contribute to relative resource reduction and achieve absolute resource decoupling.	PSS strategies and enablers, aimed at resource reduction, encompass operational support, maintenance, take-back/EOL management, sharing, optimized outcomes, operational efficiency, extended product longevity, intensified usage, and system substitutions.	This framework is limited to the context of the cases, not in a business context.
Andrea Urbinati,Davide Chiaroni,Giovanni Toletti	2019	Managing the Introduction of Circular Products: Evidence from the Beverage Industry	Multiple cases analysis (2 companies)	The aim of this paper is to study what managerial practices companies follow and implement in their business model to manage the introduction of Circular Products.	Introduction of CE is based in 4 main principles to be adopted in product leval: i) Energy efficiency and usage of renewable sources of energy, ii) product and process optimisation for resource efficiency, iii)product design for circularity, iv) Exploitation of waste as a resource.	This study does not clarify the level of each principle should be fulfilled, the barriers that hamper the managerial practices, technological limitations. Lack of quantitative approach.
Fernando Tobal Berssaneti,Simone Berger,Ana Maria Saut,Rosangela Maria Vanalle,Rosangela Maria Vanalle,José Carlos Curvelo Santana	2019	Value Generation of Remanufactured Products: Multi-Case Study of Third-Party Companies	Multiple cases analysis (5 companies)	The objective of this study is to identify the variables related to value generation in the reverse logistics of electronic products from the perspective of third-party companies.	The potential value generated by recycled and remanufactured products presents opportunities for various stakeholders across the supply chain. However, challenges such as product unavailability, disorganized processes, and inadequate planning or partnerships currently hinder the realization of this value, emphasizing the need for a strategic approach by all parties involved.	The primary limitations of this study stem from its methodological decisions. Further research is needed to delve into external factors, models, and the roles of industry players in the sales of remanufactured products, along with the development of quantitative indicators for selling remanufactured and recycled products in Brazil. Additionally, exploring variables that capture value addition from the perspectives of manufacturers and retailers would enhance understanding in this area.

Authors	Year	Title	Cases	Focus	Results	Limitations
Louise Lindkvist Haziri,Erik Sundin,Tomohiko Sakao	2019	Feedback from Remanufacturing: Its Unexploited Potential to Improve Future Product Design	Multiple cases analysis (3 companies)	This study is focusing in understand the integration of feedback flows in the product design for remanufacturing products as a factor to facilitate this possibility during the product development.	It was revealed five barriers and five enablers via the cross-case analysis, the barriers are lack of internal awareness, lack of knowledge, lack of incentives, lack of feedback channels and non-supportive organisational structures. The five enablers are business opportunities, integrated design process, customers'demand, laws, regulations and standards, and finally new technologies.	Limitations of this study is in the lack of quantitative analysis and broader sample of cases. Also, a deep dive in the barriers and in how to effectively integrate feedbacks from remanufacturing into design process.
Mohamad Kaddoura,Mohamad Kaddoura,Marianna Lena Kambanou,Anne-Marie Tillman,Tomohiko Sakao	2019	Is Prolonging the Lifetime of Passive Durable Products a Low-Hanging Fruit of a Circular Economy? : A Multiple Case Study	Multiple cases analysis (5 product cases)	This study proposes to assess the viability of introduce the Product-service system (PSS) for passive products (products that do not consume materials or energy during the use stage)for extending lifetime via repair or refurbishment, quantifying via life cycle assessment (LCA) and life cycle costing (LCC) changes in environmental impacts and economic outcome.	There was a reduction of environmental impacts (global warming potential during the life cycle) for all cases. A reduction from 45%-72% for most cases influenced by number of reuses, cost were also reduced from manufature's perspective.	Limitations of this study is about the application of LCC, the cost reduction by itself is not reflecting the business and financial gains, so other aspect may influence and they must be further evaluate.
Sonja van Dam,Froukje Sleeswijk Visser,Conny Bakker	2020	The Impact of Co-Creation on the Design of Circular Product-Service Systems : Learnings from a Case Study with Washing Machines	One case: Washing machines	This paper presents a case of how we applied co-creation in practice and the impact this has had on developing a circular product-service system (PSS).	It was presented a conceptual model that identifies the tangible impacts of co-creation and visualizes at what stages and levels co-creation can impact both the development of product-service systems and a company's shift along the servitization continuum.	Limitations are in the limited number of participants, ideas should be evaluated in the context of circular PSS and sustainability.
Daniel Jugend,Paula de Camargo Fiorini,Paula de Camargo Fiorini,Marco Antonio Paula Pinheiro,Hermes Moretti Ribeiro da Silva,Bruno Michel Roman Pais Seles	2020	Building Circular Products in an Emerging Economy: An Initial Exploration Regarding Practices, Drivers and Barriers : Case studies of new product development from medium and large Brazilian companies	Multiple cases analysis (3 companies)	This article aims to identify and analyse practices, barriers and drivers to the development of circular products.	The results show that the companies' circular product designs already foresee waste and recycled components as raw materials. In addition, it was found that infrastructural aspects and low awareness of customers regarding sustainability are challenges to overcome. Finally, for the adoption of CE practices, regulatory legislation stood out as a significant driver.	Limitations of this study is from methodological viewpoint, results cannot be widely generalised due to its base of 3 companies in a single country.
Kim Ragaert,Sophie Huysveld,Gianni Vyncke,Sara Hubo,Lore Veelaert,Jo Dewulf,Els Du Bois	2020	Design from recycling: A complex mixed plastic waste case study	One case about product development case	The aim of this research is to apply the MDD method Design from Recycling to develop a product, suitable for manufacture with the challenging sink fraction but different from typical 'bulk' solutions like outdoor furniture.	The Design from Recycling strategy was applied to successfully develop a new product with this material, called the Greentile.	Limitations are in terms of mass production of the raw material, since the study case was focused in the development and test production.
Julie Kamp Albæk,Sasha Shahbazi,Sasha Shahbazi,Tim C. McAloone,Daniela Cristina Antelmi Pigosso	2020	Circularity Evaluation of Alternative Concepts During Early Product Design and Development	Multiple cases analysis (4 companies)	The aim of this study is to present the development of the concept circularity evaluation tool (CCET), which aims to support the evaluation of alternative product concepts in terms of their circularity potential in the early stages of product design and development.	The CCET presents a detailed approach to (i) identifying relevant Circular Economy strategies, (ii) establishing the circularity strategic focus, and (iii) evaluating concept performance based on the strategic goals in the early stages of product development. Circular product design and development is, in many ways, inspired by existing frameworks such as ecodesign and design for X (DfX).	Limitations are in the number of study cases in small and medium companies and focused in simpler products,, so it cannot applied in the large companies and more complex products.

Authors	Year	Title	Cases	Focus	Results	Limitations
Yana K. Ramsheva,Yana Konstantinova Ramsheva,Rikke M. Moalem,Leonidas Milios	2020	Realizing a Circular Concrete Industry in Denmark through an Integrated Product, Service and System Perspective	One case: Concrete industry	The propose of this study is to shed a light into the questions about how the product, service, and system perspective support to realize the CE in the concrete industry.	Results indicate that adopting a product perspective can lead to savings on input material costs, improved resource use efficiency, and reduced concrete waste. A 'service' perspective offers new market opportunities for concrete producers to tailor solutions to user needs. A system focus necessitates new organizational forms and collaboration, as well as the expansion of networks among different stakeholder groups.	This study is focused in a sigle case, so focus could be expanded in other conexts to increase the robustness of findings.
Morgane Bigolin,Ângela de Moura Ferreira Danilevicz,Marc A. Weiss,Luiz Carlos Pinto da Silva Filho	2021	Sustainable New Product Development: a decision-making tool for the construction industry	One case about construction industry	This paper deals with the proposition and application of a systematic decision-making tool in the context of the construction industry.	The results contributed to the identification of trade-offs associated with the challenge of comparing alternative construction materials. It was also possible to identify that the use of recycled materials does not necessarily ensure that a product is more environmentally friendly than others.	The presented tool could be tested in other construction materials, in other cases of study. Requirements in each production process steps could be further explored.
Francesco De Fazio,Conny Bakker,Bas Flipsen,Ruud Balkenende	2021	The Disassembly Map: A new method to enhance design for product repairability	One case about vacuum cleaners	The focus of this paper is to create and describe the development of a method to visually map the disassembly of a product, showing different routes towards target components.	These components can be those with a high potential failure rate (important for repair), embodied environmental impact (important for recycling) and economic value (relevant for component harvesting), depending on the circular strategy under consideration.	The tool has some limitations, such as cannot be applied in early stages of product design, it cannot be used as a proxy of other methods i.e. ease dissassembly and repair. It can be further explore in quantitative assessments to become more precise.
Srujana Kandukuri,Elif Elçin Günay,Omar Al-Araidah,Omar Al-Araidah,Omar Al-Araidah,Gül E. Okudan Kremer	2021	Inventive solutions for remanufacturing using additive manufacturing: ETRIZ	Multiple cases analysis (2 cases)	The focus on this research is on the implementation of Additive manufacture (AM) in remanufacturing towards to sustainable product development.	There is a great potential for AM techniques that can be applied in the DfRem and repair of parts which could not be achieved before AM. The enhance-TRIZ matrix offers to pratitioners to improve designs in terms of remanufacturability, it is a systematic of problem-solving methodology that presents a comprehensive framework to design-related problems and implement AM in remanufacture process.	The presented matrix has some limitations, it does not determine the benefits of remanufacturing a component, it provides with steps and guidelines. It is too abstract abd difficult to translate in tangible concepts.
Khalil Al Handawi,Petter Andersson,Massimo Panarotto,Ola Isaksson,Michael Kokkolaras	2021	Scalable Set-Based Design Optimization and Remanufacturing for Meeting Changing Requirements	One case about aeroengine	The aim of this reaseach is to propose a set-based design methodology to obtain scalable optimal solutions that can change requirements through remanufacturing in satisfaying approach.	The set of parametric optimal design solutions was generated and scalable design solutions were successfully extracted. This research enables design changes via remanufacturing through the derive transition rules.	Specifics conditions of the component core to be remanufactured were not considered, so this conditions can vary. The operational history of core could add another dimension for future studies.
Irina Albastroiu Nastase,Cristian Negrutiu,Mihai Felea,Carmen Acatrinei,Andrei Cepoi,Adrian Istrate	2021	Toward a Circular Economy in the Toy Industry: The Business Model of a Romanian Company	One case about toys industry	This study has the objective to analyze a business model from a Circular Economy perspective.	The company could be considered a role model for sharing economy in its domain, drivers for new business opportunities and innovations were captured, as well as barriers in the implementation of circular economy practices.	Since Evertoys is a start-up, the business model sustainability is not yet proven. So future studies could focus on identify challenges and maintained in older companies in different sectors to enhance the findings of this study.

Authors	Year	Title	Cases	Focus	Results	Limitations
Xiaohui He,Dongmei Su,Wenchao Cai,Alexandra Pehlken,Guofang Zhang,Guofang Zhang,Aimin Wang,Jinsheng Xiao	2021	Influence of Material Selection and Product Design on Automotive Vehicle Recyclability	One case about practical dismentling in the automotive industry	The aim of this study is to find rational technical solutions for maximizing recyclability and recoverability, to achieve sustainable development with the focus on nonmetallic components and parts, the connection of components and parts materials, and the product life cycle of each stage.	As a result, it is found that the main methods, which are conducive to recycling, are increasing the use ratio of materials that are easy to recycle. In addition, general principles of material selection are summarized. On the other hand, vehicles' dismantling is considered in the initial stage of product design and methods of structural design are summarized.	This study was focused more in the nonmetallic components and parts, so other components can have different routes which can be further developed.
Magnus Schulz-Mönninghoff,Michael Neidhardt,Monia Niero	2022	What is the contribution of different business processes to material circularity at company-level? A case study for electric vehicle batteries	One case about eletric vehicle batteries	This study aims to present an illustrative case study of an automotive manufacturer seeking to improve the material circularity of its' electric vehicle battery portfolio.	This findings provides guidance for companies on how to model material circularity for batteries at company-level based on EV market projections. Showing combination of a closed-loop production with different end-of-life strategies such as remanufacturing, repurposing and recycling, automotive manufacturers can increase material circularity for critical battery materials from 5% today to 23% by 2030. And finally, how different business processes can contribute to increasing material circularity, including a) which business processes collaborate, b) the affected material streams (i.e. inflow or outflow), c) through which activities and d) to what extent, i.e. the impact on the quantitative results for material circularity	Findings are based on illustrative case derive from EV market projections. The study is based on sensitive data for modeling the battery material flows, so future studies should investigate how to ensure that manufacturers can publish data without competitive disadvantage. Also investigate CE indicators in pratice.
Nina Boorsma,David Peck,Tanya Bakker,Conny Bakker,Ruud Balkenende	2022	The strategic value of design for remanufacturing: a case study of professional imaging equipment	One case: Producer of professional imaging equipment industry	The focus is to understand what remanufacturing means to its wider strategic context, related to product design, and in what ways additional value can be created if remanufacture possibility is incorporated in early design-stage.	The results identified that remanufacturing was found to be separate from, and secondary to, the development of newly manufactured products. If the strategy of a company is not attuned to developing products that serve multiple use-cycles, its execution will remain sub-optimal and remanufacturing will be a value-retention strategy in isolation.	This study is focused in a single company, so approach could be extended to other companies to enhance and corroborated the findings.
Jelle Joustra,Conny Bakker,Riel Bessai,Ruud Balkenende	2022	Circular Composites by Design: Testing a Design Method in Industry	Multiple cases analysis (5 cases in construction, furniture, and automotive industries)	The focus of the study is to develop a novel circular composites design method for products containing composite materials to support designers and improve product circularity.	The findings are abou the effectiveness of the method, designers considered the method accessible and usable, however its effectiveness was restricted by the existing business, logistics, reprocessing technology, and policy contexts. These factors are intertwined and partly dictate the boundary conditions of the design, which means that to successfully implement the proposed method, the transition to a circular economy requires a holistic approach to adjust the design process, organisations, and value chains.	The method approach in the interview, bias of respondents cannot be avoided. The quantity of cases is limiting the results generalization. Recommendation is to performe similiar design studies to other industries.
Riikka Piippo,Kirsi Niinimäki,Maarit Aakko	2022	Fit for the Future: Garment Quality and Product Lifetimes in a CE Context	One case about fashion industry.	This study focused on the issue of garment quality and how it can be connected to product lifetime.	High quality allows products to remain in use longer and be used by multiple people. When consumers perceive a garment as high quality, they care for it better, maintaining its condition and extending its lifespan, known as quality in use. Additionally, good quality at the end of the product's life facilitates fiber recycling, extending the material's life, referred to as quality for recycling.	Limitations of this study are on measuring the impacts of the connections between the product lifecycle.

Source: The author, 2024

3.5. CE & PDP CATEGORIES

In this section the three categories of CE strategies and PDP will be elaborated, the Optimize function which is related to the product life cycle extension through maintenance services focused on optimization of its performance and function via product sharing. Prolong lifecycle approach the product life cycle extension via aftermarket services, such as repair, remanufacturing and reusage. Reprocessing is the category which focused on identified new alternatives for reusage of obsolete components and products different from its original function.

3.5.1 OPTIMIZE FUNCTION: product sharing to enhance usage efficiency and possibilities of maintenance services to enlarge lifetime.

In the strategy of Optimize function one of the ideas is to offer a mix with tangible products and intangible services that are designed and combined jointly to fulfill customer needs (Tukker et al., 2006). CE is a regenerative system from the perspective of resource input, waste, emission, and energy leakage can be minimized by slowing, closing, and narrowing materials and energy loops. (Geissdoerfer, 2017). The focus of this CE strategy is on the product shared ownership. See figure 11.

Long lasting designs via product life cycle extension and product sharing i.e. maintain, reuse, and redistribute, and recycle. Keep the value of products, materials, and resources as long as possible to minimize waste generation (McAloone et al., 2020). The product/ service systems in three types, product-oriented, use-oriented and result oriented. In this strategy the focus is on the product function efficiency, decoupling value from the delivery of physical products.

In the concept stage the resource reduction emerges as path to decouple economic growth from escalating resources consumption, rather than relying exclusively on increased resource extraction and consumption to fuel economic expansion, resource reduction emphasizes reuse and material efficiency, and circularity strategic focus (Albæk et al., 2020, Ramsheva et al., 2020). For that, product substitution and business model are alternatives to sustain the principle of resource reduction, especially focusing on product and service systems (PSS), shared ownership (Albastroiu et al., 2021) and exergy awareness (Almeida et al., 2017).

The design stage is the most complex phase of PDP which requires combination of materials, methods, and processes application. During this development stage is important to understand customer requirements and industrial infrastructure capabilities, design plays a key role in the determination of economic and environmental benefits of products, especially when considering EOL strategy i.e. designed for disassembly and reuse, for instance Reuse is the smallest loop and most appropriate EOL (Almeida et al, 2017).

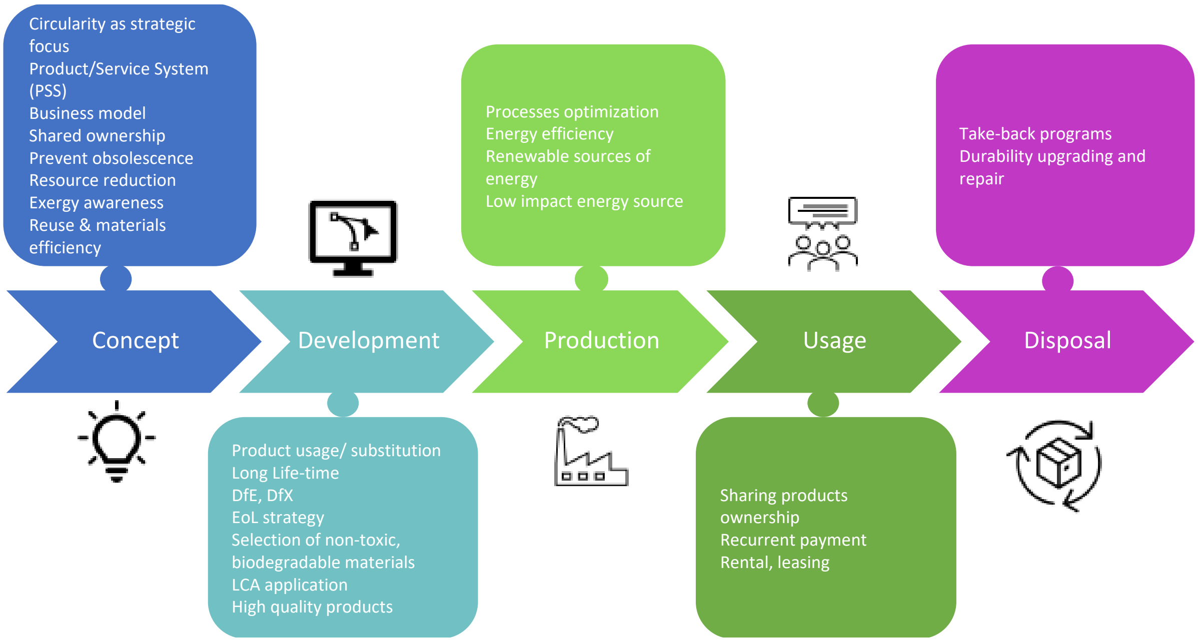
The foundation of the product life cycle is established in the design phase, the use of design practices are relevant to support decision-making, the most common methods appearing in the literature are the Design for Environment (DfE),Design for circularity (DfC), Design for disassembly (DfD), Design for reuse (DfR), Design for X (DfX), their application is associated to the user requirements and End-of-life strategy. Life cycle assessment (LCA) application is supporting the material selection, it is focused on the environmental impacts. High-quality products align with the concept of an extended product lifecycle, facilitating second-use scenarios and shared product models. By emphasizing durability, these products contribute to a more sustainable and CE, challenging traditional consumption patterns (Albastroiu et al., 2021).

The synergy between energy-efficient practices and robust industrial infrastructure not only reduces environmental impact but also enhances operational resilience and cost-effectiveness in the production stage. From production perspective, energy efficiency combined with the usage of renewable sources of energy, as well as processes optimization are the paths for the transition to a CE approach (Urbinati et al, 2019). Alternatives production models or modularity possibilities are essential to enable life-cycle extension, via increase of product durability, adaptability, upgradability to assure the fulfillment of different customer requirements (Mesa et al, 2018).

The usage & maintenance stage in the Optimize function strategy is oriented to the alternatives business models, such as product sharing, and product adjustments, these approaches can influence the realization of product circularity, by adopting them, the value of the product can be kept for a longer lifetime and the necessity of resources can be reduced, it is an alternative to intensify the usage of products that are underutilized during their lifetime (McAloone et al., 2020), it allows to offer more people to access the product function (Madsen, 2015). Trade-off situations about parts reuse and maintenance must be points to be checked in the design stage via methods and tools.

In Optimize function strategy, disposal stage is influenced by alternatives of end-of-life (EOL) strategies for avoiding as much as possible the traditional waste practices. EOL strategy is one of the alternatives to reduce environmental loads, material consumption and waste generation, on the other hand can support in enhance corporate profitability (Almeida et al, 2017). Take-back programs for increasing durability via upgrade and repair alternatives are present along the PDP. Integrating these initiatives into the development process aligns with a commitment to environmental responsibility, promoting resource efficiency and reducing the overall environmental impact of products.

Figure 11: Optimize function main terms



Source: Author, 2024

3.5.2 PROLONG LIFECYCLE: product ownership with possibilities of maintenance services to enlarge lifetime.

The CE strategy of Prolong lifecycle is suitable to the concept of product ownership with life extension alternatives via repairing, refurbishing, and remanufacturing. This strategy comprehends to product categories with expected stable performance, high durability, high quality, and value. Slowing resources strategy is focused on lifetime extension, increasing efficiency, and reducing usage of resources (Bocken et al, 2016). Since the early stage of concept, the aim is pollution prevention, aligned with social and environmental commitments (Oliveira et al, 2017). See figure 12.

In the concept stage the article "*Feedback from Remanufacturing: Its Unexploited Potential to Improve Future Product Design"* from Lindkvist et al, 2019 presented the remanufacturing as an industrial process that products are reprocessed to return as a new product, so the importance of the internal company awareness and knowhow about the specifications to be considered as remanufactured product. This requires a comprehensive business model combining product and services for passive durable products (Kaddoura et al, 2019). During this stage the EOL strategy definition is fundamental for circularity increase (Schulz-Mönninghoff, 2023).

Design stage encapsulating a multitude of considerations beyond visual aspects and functionality, prolonging lifetime as well as Prolong lifecycle possibilities via repairing, remanufacturing is intrinsic disassembly, reassembly, modular components possibilities elements in the design phase (Kaddoura et al, 2019). Designing a product while keeping its end of life in mind and making minor design changes that would aid in the remanufacturing process helps make remanufacturing cost-effective and efficient (Kandukuri et al, 2021). Waste management tools to promote the reduction of residues plays an important role during this stage to identify disposals models and final destinations (Oliveira et al, 2017).

The utilization of design methods, i.e., Design for remanufacturing (DfRem), Design for repair (DfRepair), Re-design including spare parts disassembly map methods are elements to support with the complexity of combining these requirements into the product design comprehend to the complete life cycle, including transferring in a scalable process to the manufacturing stage as well as cost benefits (Al Handawi et al, 2021). Co-creation with users offers new possibilities for the designers, it can influence materials selection and requirements, depending on the business models such as servitization (van Dam et al., 2021).

In the production stage, concept and design are the base to minimize environment impacts, the product design should focus in reduce production inputs, such as solid residues, waste possibilities at production process (Oliveira et al, 2017). These points are relevant to the manufacturing total cost, as well as the supplier payoff, this combined product configuration and suppliers' selection. A relevant aspect of this integration of production and supply chain design is the used-product return for remanufacturing process, upgrading process, discount price strategies to stimulate used-product return rate are often strategies for enabling the increase of return rate, as a profit-driven decision-making process (Wu et al. 2017).

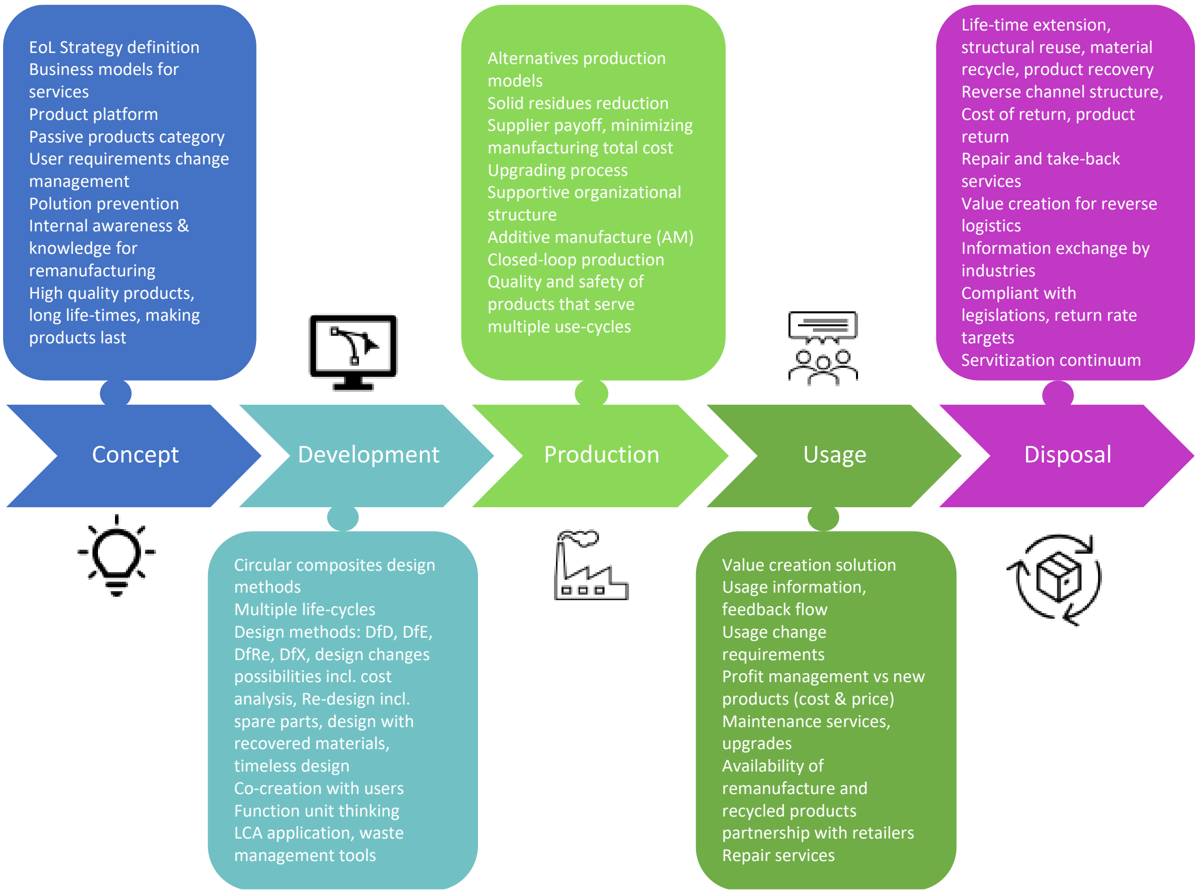
The internal organization has a central role in the production process feasibility, as well as in alternatives production models, a supportive organizational structure can promote information exchange especially when new unit production line is different from remanufacturing/ refurbishing or repairing production line, information is vital for mutual interactions and build managerial decisions (Lindkvist et al, 2019). Product high-quality and safety are characteristics for multiple use and lifecycles possibilities i.e. remanufacturing (Boorsma et al., 2022). Additive manufacturing is an opportunity to respond the CE design feasibility especially in remanufacturing process (Kandukuri et al., 2021).

Usage stage in the multiple life-cycle CE strategy is decisive for the success of the whole product lifetime extension, it comprehends the consumer behavior and retailers' interests, partnership with retailers creates add-value and it's a differential in the return chain for instance. Reverse logistics is relevant for products that are remanufacturable, refurbishable or repairable and depends on local context and regulations (Berssaneti et al., 2019). Usage information is highly contributing as a feedback flow and knowledge transfer to the design and productions processes to upgrade/ update products (Lindkvist et al, 2019).

Customer value perception evaluates the way to create value to the market via remanufacturing, likewise, keeping consumer satisfaction through multiple use-cycle, both generates a brand image of remarketed products (Boorsma et al., 2022). Maintenance services and product upgrades provide avenues for extending the lifespan and enhancing the functionality of products. These services ensure that products continue to perform optimally over time, reducing the need for premature replacements and contributing to sustainability and promoting a circular approach to product usage (Kaddoura et al, 2019).

Design for EOL such as remanufacturing possibilities are key driver for multiple lifecycles which requires a reverse channel structure in place in usage stage, considering costs of return and return rate in the take-back programs, compliant with legislation (Boorsma et al., 2022). In the end-of-life stage, combining a closed-loop production with EOL strategies can increase material circularity considering repurposing, and recycling strategies (Schulz-Mönninghoff, 2023). Destination for main solid residues is an important point for preventing pollution, so the adoption of CE in a systematic way likewise the recycling or reusing of post-production and disposal of residues (Oliveira et al, 2017). Servitization continuum, such as pay-per-use concept is emerged as a new business model seeing as key success factor in closing loops in CE, is an alternative to avoid discard products generation (van Dam et al., 2021).

Figure 12: Prolong lifecycle main terms



Source: Author, 2024

3.5.3 REPROCESSING: product with large scale with possibilities to be reprocessing after lifetime.

The reprocessing CE strategy comprehends products with large-scale production, ownership principles regardless durability expectations. Upcycling and downcycling are possibilities to be adopted, upcycling involves transforming discarded materials into products of higher value, contributing to resource efficiency and waste reduction (Papanek, 1995). In contrast, downcycling refers to the process of converting materials into products of lower quality or value, often resulting in a loss of original properties (McDonough et al., 2002). See figure 13.

This strategy is the combination of type of materials more friendly to the environment and EOL possibilities of recycling or recovering after lifetime, products that are developed from discarded materials or waste considering energy efficiency balance the original function can be modified or adapted. Product type is an enabler for deciding the better fit strategy, for instance remanufacturing products is well established for high value products, in the case of recycling or recovered the material can close the loop by making the same type or different one. The value definition in this case is based on commercial value, material quality or the use-related value (Singh et al., 2016).

In the concept stage, ideas can be explored in terms of new business opportunities, contributing to reach sustainability targets, engage with consumers (Sandvik et al, 2019). Waste and recovered materials are alternatives for new developments, especially for business models which take back used products is established, this ensures the cycle for own material resources (Singh et al., 2016). Packaging is an intrinsic part of a product, so is considered in this CE strategy, beverage industry for instance has a great focus in optimized the recyclability of cans maintaining the function unit (Niero et al., 2016). Products with a high number of different materials and components offers a challenge to energy efficiency and resource recycling in the end-of-life strategy, early stages play a critical role in this direction based on material selection that offers high level of recyclability and recoverability (He et al., 2021).

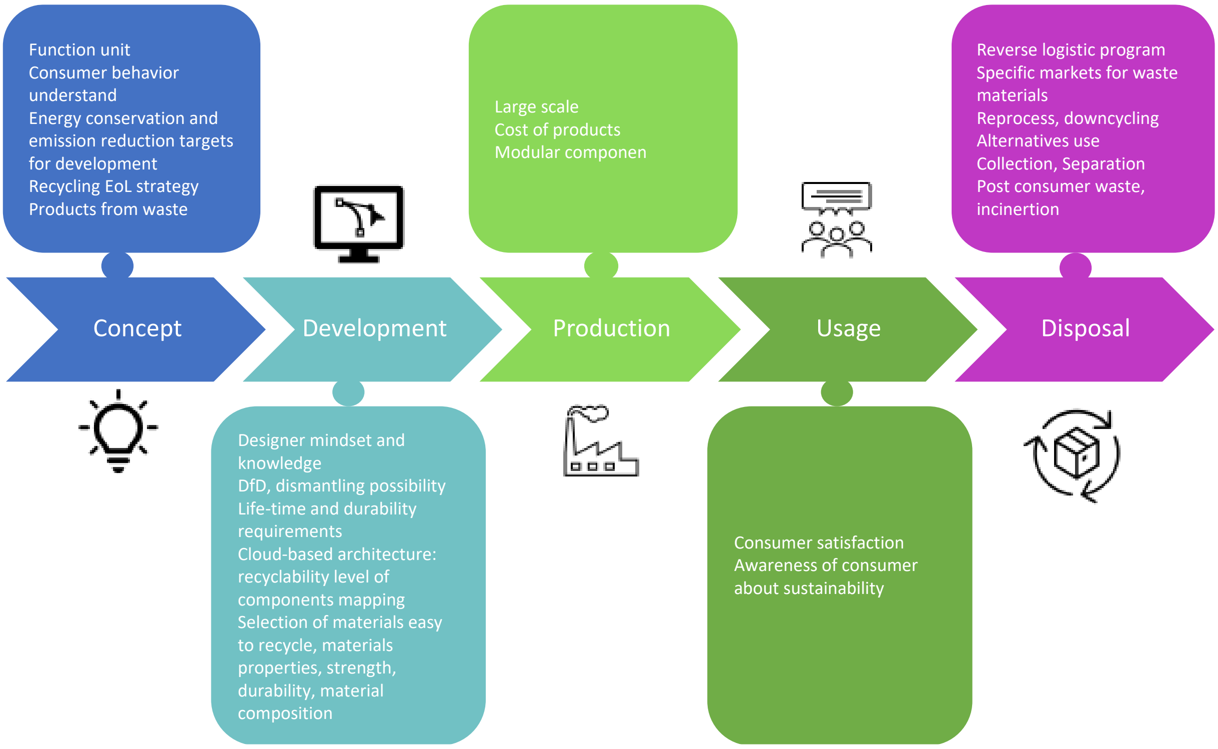
Product development out of waste and recovered materials is an opportunity during the early PDP stages to implement CE strategy, through a resource recovery route. Environmental impact is determined in the early stage, material properties is a relevant point for the designers. In the design stage occurs the selection of materials to develop a product, professional designers have the key role, selection of materials that has possibilities to be easily dismantled or recycled optimizing the energy consumption (He et al., 2021). Adopted existing methods such as DfRecycling, mapping recyclability level of components can enhance efficiency in the reuse and disassembly process in the EOL based on cloud-computing architecture for designers to exchange information and knowledge (Huang et at., 2017). Life-cycle exploration, re-design are alternatives to transform existing products in existing business in more circular in different industries (Joustra, J., et al., 2022)

Manufacturing stage involves the company infrastructure, capabilities, and processes for industrial production scale, in the case of recycled materials used as raw material input, for instance the so called Greentile, it is resulted of successful design for recycling strategy, it is composed by different polymers, a complex blend of PET, PS, filled PP. PVC and a variety of minor components, it is a mix of post-consumer packaging waste (Ragaert et al, 2019). Benefits of reused materials is not necessarily positives for CE, the process for collecting, separating, reprocessing must be analyzed, there is a trade-off in this stage that must be evaluated in the product concept & design phase, the principle of energy reduction as well as renewable sources (Jugend et al., 2020). Selection of materials and possibilities for modular components during the production stage facilitates the technical solutions for maximizing recoverability and recyclability (He et al., 2021).

Usage stage comprehends to the consumer relation with the product, the consumer awareness of sustainability is the key role of CE reprocessing strategy, this is a critical stage for promoting material recirculation, the consumer is responsible for choosing and, demanding more environmentally sustainable products and disposal solutions, promote the return of used products for instance (Jugend et al., 2020). Consumer practices and preferences influence the EOL strategies possibilities, such as life-time extension, structural reuse, material recycle and, product recovery in the design phase, the interaction between consumer and PDP can support the designers in anticipating recovery paths (Joustra et al., 2022).

Reverse logistics principle is the most important step to build up CE alternatives in the disposal stage of PDP, through take back programs' establishment, designers can consider used materials as baseline for product development, as well as secure own material resources via materials composition development (Singh et al., 2016, Ragaert et al, 2019). Creating a relationship matrix between customer, environmental and technical requirements allow the prioritization of requirements and possibilities as proposed by Bigolin et al. (2021). Separation is the second most important principle for waste or post-consumer waste, the downcycling or upcycling chances depends on the successfully material identification and its trade-off (Bigolin et al., 2021).

Figure 13: Reprocessing main terms



Source: the author, 2024

3.6. PRELIMINARY FRAMEWORK

The framework is composed of three dimensions: the integration of CE elements into CE strategies and PDP stages within a closed loop, the CE strategies themselves, and the PDP stages. The steps to build the Circular Product Development Framework (CDPF) followed the results of the systematic literature review (SLR). The first step involved constructing CE strategies and defining their application in each PDP stage. This analysis was conducted individually for each document, considering each stage of the PDP. The results were identified as terms related to the PDP; these terms were presented previously for each category. The second step involved discovering CE elements and correlating them with PDP stages, followed by an individual analysis to connect the terms identified in the previous step and concluded the framework.

These dimensions form the preliminary framework: i) CE strategies, including Optimize Function, Prolong Lifecycle, and Reprocessing; and ii) PDP stages, consisting of Concept, Development, Production, Usage, and Disposal. Addressing the integration of both fields' perspectives allows for a broader understanding. This holistic approach helps to discern the complex interplay between the PDP stages. The terms presented in each CE strategy and PDP stage were defined based on key terms identified during the categorization phase and are summarized and classified into methods, processes, or customer behavior.

The selection of these terms was driven by their relevance to CE principles and their alignment with the goals of sustainable product development. Optimize Function was chosen to emphasize performance improvements that reduce waste and resource use, Prolong Lifecycle reflects the importance of extending product durability, and Reprocessing highlights the need for recovery and recycling of materials. These strategies were paired with the PDP stages to ensure that sustainability considerations are integrated at each phase of the PDP, from initial concept to end-of-life management. The identified terms provide a structured way to categorize actions and outcomes essential for a circular approach.

The proposal framework as per figure 14 presents the five CE elements: Business models, design methods, processes, consumer influence and take-back programs as interrelation to the CE strategies and PDP stages, the interrelation is following the linear approach as per the PDP starting from concept linked to business models, followed by Design methods linked to development, Processes linked to production, consumer influence linked to Usage, take-back programs linked to disposal, all these links following the respective CE strategy of Optimize function, Prolong lifecycle and reprocessing. Additionally, the environmental impact related to each CE strategy based on energy and material necessity, less impact means less energy and material usage.

For the CE Strategy of Optimize function, determined as the closer to the CE concept due to its circularity principles of consuming less natural and finite resources including materials and product use more intensive (Potting et. al., 2017). Shared ownership, Product/service systems are connected to the business model element as initial step for building a product concept, they influence in the design methods alternatives to be chosen. Design methods and tools such as LCA application are fundamental to develop high quality products for long and intensive use (McAloone et al., 2020).

The manufacturing process is anchored in the fundamental principle of utilizing renewable energy sources and optimizing operations to minimize overall resource consumption. Utilization strategies are geared towards maximizing product efficiency through leasing, recurring payment models, and pay-per-use or rental agreements, with the aim of ensuring continuous product availability throughout its lifecycle. Maintenance, repairs, and disposal are responsibility of service provider or outsourced, relieving users of these responsibilities. The primary focus lies on delivering the intended function or value creation of the product, rather than on individual brand-new product. This approach embodies the principles of the CE, promoting resource efficiency and waste reduction across the product lifecycle (Nastase et al., 2021).

For the CE Strategy of Prolong lifecycle, determined as intermediate step to the CE concept due to its circularity principles of reusing parts and components via repairing, remanufacturing alternatives to enlarge product lifetime and applicability (Potting et. al., 2017). Individual ownership and Prolong lifecycle are inputs for design methods and tools selection. The product development and usage are based on the principle of maintenance possibilities, this influence directly the business model and investments implementation, it should be in place maintenance and services pillars outside the company location, the value chain must also be involved for the product assistance, including partnerships such as with retailers for warranty and take-back programs for instance (Berssaneti et al., 2019).

Manufacturing infrastructure, processes and supportive organizational structure are vital for ensuring Prolong lifecycle, it is more complex than only delivery brand-new products, it must be modelling for disassembly and components reuse possibilities, in this case the consumer has co-participation in the reusability of the product, it shares responsibility, information flow of usage is relevant to improve product development (Haziri et al, 2019). Cost structure and profitability is not comparable to new product, there are more aspects in place such as reverse channel structure leading to a cost of return, so it must be built specifically for repaired and remanufactured products (Zhiqiao WU et al, 2017). Disposal is related directly to a EOL strategy (Repair, remanufacture, refurbish) and is highly dependent on the customer participation since ownership is present. In some product cases, the reverse logistics is linked to a legislation. Take-back programs in partnership with customers and consumers, creates value for reverse logistics (Berssaneti et al., 2019).

For the CE Strategy of Reprocessing, determined as far from to the CE concept, however a basic step to move forward due to its principles of recycling and reprocessing materials (Potting et. al., 2017). In this strategy, ownership becomes less relevant, as the focus shifts towards creating opportunities for obsolete products regardless of ownership status. Shared ownership products also have a designated end-of-life. The strategy entails exploring alternatives such as reprocessing, creating new materials, and end-of-life (EOL) alternatives like downcycling and alternative reuse, instead of resorting to incineration. The primary ambition is to minimize solid residues, thus avoiding the creation of scrap without further potential for utilization (Ragaerta et al., 2020). This strategy's contribution is particularly significant for products that were not originally designed with a focus on Prolong lifecycle or obsolescence prevention.

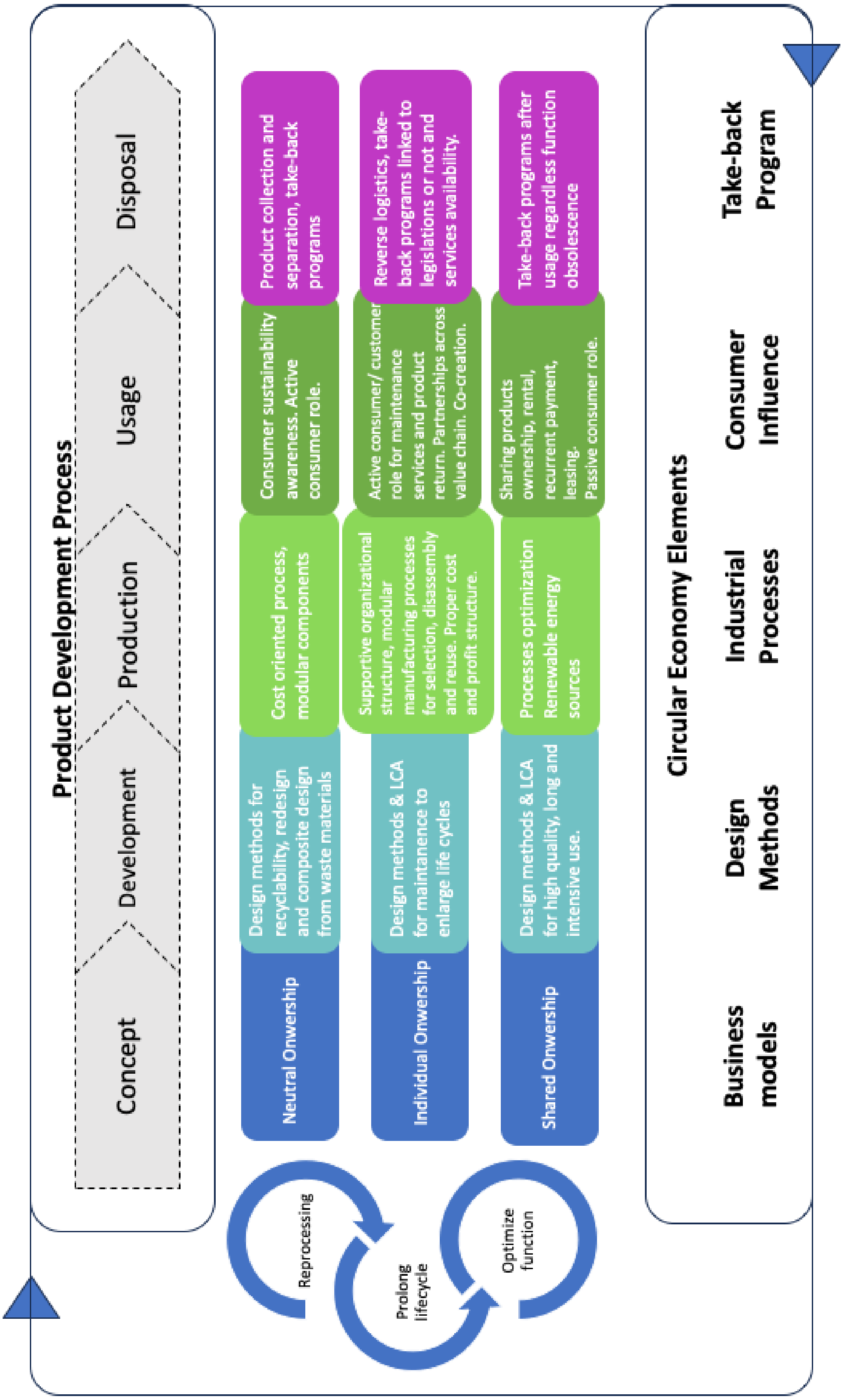
The selection of design methods and tools is influenced by considerations such as the ease of material recycling and dismantling (He et al., 2021). Likewise, there is a growing emphasis on designing products using recycled materials, which involves approaches like redesign, composite design methods, and designing from waste (Joustra et al., 2022; Jugend et al., 2020). Manufacturing practices prioritize the use of modular components and cost-effective product elements. Additionally, customer engagement plays a crucial role, with an increasing focus on sustainability awareness and disposal practices. Implementing take-back programs for product collection and separation is essential to support this strategy, although the sustainability of such programs may depend on the value or demand for the used materials (Singh et al., 2015). The summary of integration elements proposal in each stage is driven by the most relevant elements found in the literature for each CE strategy, see table 8.

Table 8: Description of CE elements

Business model	Shared ownership, Individual ownership, aftersales services & maintenance. Proper cost and profit structures
Design Methods	Design for environment, Design for X, Design for repair, design for disassembly, Design for remanufacturing, Re-design, Design with recovery materials.
Industrial processes	Optimization, renewable sources of energy, closed loop production, upgrading process, Additive manufacturing, Alternatives production models for disassembly, used components selection and reuse, large scale, modular components production, cost oriented processes.
Consumer influence	Active and Passive influence, value co-creation solutions, usage information feedback flow, Usage change requirements Profit management vs new products (cost & price) Maintenance services, upgrades Availability of remanufacture and recycled products partnership with retailers.
Take-back program	Take-back programs, Life-time extension, structural reuse, material recycle, product recovery, Reverse channel structure, Cost of return, value creation for reverse logistics, Information exchange by industries, compliant with legislations, return rate targets, servitization continuum, Specific markets for waste materials, reprocess, downcycling, alternatives use, Collection, Separation, Post-consumer waste, incineration.

Source: The author, 2024

Figure 14: Preliminary Framework CPD (Circular Product Development)



Source: The author, 2024

3.7 EXPERTS' PANEL

The questionnaire development for the panel with experts was carefully aligned with the approach of the Preliminary framework variables in the preceding chapter. Illustrating upon the foundational principles and identified elements, meticulously craft a set of questions designed to extract insights and perspectives from our selected experts of a multinational company.

These questions are strategically formulated to address the key dimensions and intricacies identified in the preliminary framework, ensuring a comprehensive exploration of the research domain. The Delphi technique, known for its iterative and anonymous nature, allows for a systematic refinement of responses over multiple rounds, promoting consensus-building among the expert panel. By intertwining the questionnaire development with the previously established preliminary framework, it aims to extract nuanced and informed opinions from our panel, ultimately contributing to a robust and well-grounded research outcome.

It was in total three rounds, 1st round focusing on exploratory qualitative questions, 2nd round focusing on quantitative approach with 75% of agreement pursued, both rounds were performed in the same timeframe during September 2023. 3rd round was focusing on identified CE relevant elements for PDP stages using as base the results of 2nd round.

A pre-test was developed and conducted to validate the questionnaire with a group of participants. Adjustments were made based on the respondents' feedback, including corrections of grammatical errors and modifications to the sections.

4. RESULTS

This section presents the three rounds of the Delphi expert panel and their results, followed by the final framework and discussions. Conducting the Delphi study within a single company has certain implications. While it allows for a focused, in-depth analysis specific to the organization's context, it may limit the generalizability of the findings to other companies or industries. The insights gained are highly relevant to the company's operations, but broader validation across diverse organizations would be necessary to confirm the framework's applicability in different contexts

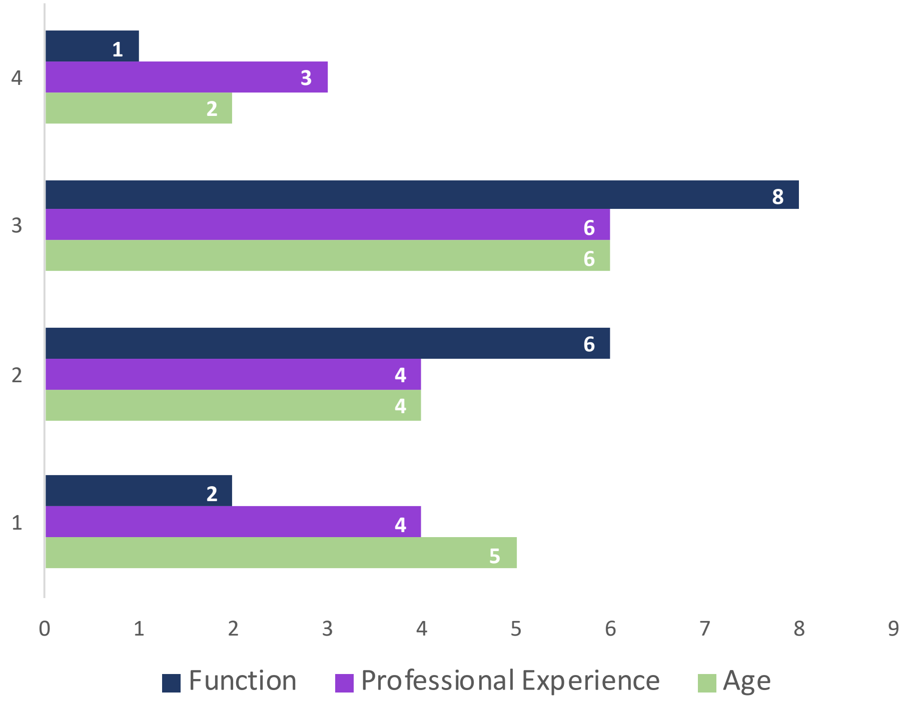
4.1. DELPHI EXPERT PANEL

The expert panel is composed in three rounds, the first is presented the results of the qualitative questions to have a better understand of the participants profile and their knowledge about the research theme. The round 2 is the quantitative results in regard the agreement of the participants about the CE elements found in the literature and the third round is about to obtain the consensus of participants regarding the CE elements which integrates CE and PDP.

4.1.1 ROUND 1

Exploratory questionnaire was designed to identify the patterns and profile of participants with questions regarding professional experience, function in the company, education degree, gender, age, nationality, and country of residence, followed by open qualitative questions about their understanding of integration of CE and PDP. It was reached 17 respondents, and as per graph 1 it was captured a broader perspective in terms of generations and professional experience considering the profiles, 5 participants between 20 up to 30 years-old (Green no.1), 4 participants between 30 up to 40 years-old (Green no. 2), 6 participants between 40 up to 60 years-old (Green no. 3) and, 2 participants more than 60 years-old (Green no. 4). From professional experience viewpoint was 4 participants with up to 4 years (Purple no. 1), 4 participants between 5 up to 15 years (Purple no. 2), 6 participants between 15 up to 30 years (Purple no. 3) and, 3 participants with more than 3 years of professional experience (Purple no. 4). 2 participants were Technician (Blue no. 1), 6 participants were Engineering (Blue no. 2), 8 participants were Managers (Blue no. 3), and 1 participant was Director (Blue no. 4).

Graph 1: Generations and professional experience



Source: the author, 2024

Concerning location, it was captured a cross-location, cultural and regional regulation's view consisted in 5 participants from the company headquarter in Germany (Europe), 2 participants from the United States (North America) and, 10 participants from Brazil (South America), divided by 1 director, 2 technician, 6 engineering and 8 managers from product related areas such as marketing, engineering, and manufacturing. The majority is male accounting for 14 and 3 females, Graph 2.

Regarding the qualitative viewpoint, it was questioned: i) What, in their opinion are the main challenges for the integration of CE and PDP and ii) What are the main customer and/or market requirements related to circular products development. Respondents raised as main challenges and customer requirements for the integration of CE and PDP

Graph 2: Respondents nationality and gender profile

Source: Author, 2024

4.1.2 ROUND 2

The second round of the questionnaire was developed to delve into the iterative process of gathering qualitative evaluation of participants about the identified elements in the preliminary framework. It was asked regarding the agreement or disagreement of these elements presented as integration between CE strategies and PDP stages. Questions were applied considering each CE strategy in the different stages of PDP.

4.1.2.1 Optimize function

In the concept stage of PDP, the proposed CE elements have achieved a substantial consensus, reaching an agreement level surpassing 75%. This indicates a strong alignment among participants on the incorporation of these elements into the first stage of PD. Especially, an important addition to the proposed elements involves the integration of measures to avoid scheduled obsolescence, reflecting awareness of the importance of sustainable product lifecycles. On the other hand, shared ownership emerged as an element with a lower agreement level, falling below 65%. This lower consensus may suggest varying perspectives or considerations among participants regarding the implementation or feasibility of shared ownership within the context of PDP. The nuanced levels of agreement on different elements highlight the complexities and diverse viewpoints inherent in integrating CE strategies into the initial phases of the PDP.

In the development stage of PDP, the proposed CE elements have achieved a high agreement level surpassing 75%. This demonstrates the alignment among participants on these elements into PD. Additional element has been proposed to integrate the methods of development stage which is design easy disassembled joints. This suggests an intention to enhance the efficiency and flexibility of the development stage by prioritizing the ease of disassembly, which can contribute to streamlined processes, increased adaptability, and potentially facilitate maintenance or modifications during the product lifecycle. See table 9.

In the production stage of PDP, the proposed CE elements have achieved a high agreement level surpassing 75%. This demonstrates the alignment among participants on these elements into PD, the elements remain in the production infrastructure and not in the product itself, this might indicate the importance of production infrastructure and operations. No additional element has been proposed to integrate into PD.

In the utilization stage of PDP, two of the three proposed CE elements have achieved high level of agreement above 75%, however the element of sharing products ownership achieved a disagreement above 40%, this might indicate the different perspectives about the element. Maintenance was highlighted as additional to the list; this suggestion supports the fact of customer education might be a relevant element to the product lifecycle extension.

In the disposal stage of PDP, the proposed CE elements have achieved a high agreement level surpassing 75%. This demonstrates the alignment among participants on these elements into PD. Additional elements like recycling rate and rigorous recycling practices have been highlighted, further enriching the framework. This heightened agreement signifies collective acknowledgment of the significance of these elements in guiding disposal practices and promoting sustainable waste management.

Table 9: Summary of results for Optimize function

Stages	Proposed Elements / Agreement level
Concept	**High agreement level: above 75%** Circularity as strategic focus Product/Service system Business model transformation Optimize function Resource reduction Exergy awareness Reuse & materials efficiency

Stages	Proposed Elements / Agreement level
	Low agreement level: Below 75% Shared ownership **Additional elements suggestion** Avoid scheduled obsolescence
Development	**High agreement level: above 75%** Product usage/ substitution Long Lifetime DfE, DfX EoL strategy Selection of non-toxic, biodegradable materials LCA application High quality products **Low agreement level: Below 75%** None **Additional elements suggestion** Design for easy disassembled
Production	**High agreement level: above 75%** Processes optimization Energy efficiency Renewable sources of energy Low impact energy source **Low agreement level: Below 75%** None
Usage	**High agreement level: above 75%** Recurrent payment Rental, leasing **Low agreement level: Below 75%** Sharing products ownership **Additional elements suggestion** Maintenance
Disposal	**High agreement level: above 75%** Take-back programs Durability upgrading and repair **Low agreement level: Below 75%** None **Additional elements suggestion** Recycling rate Stringent recycling activities

Source: The author, 2024

4.1.2.2 Prolong lifecycle

In the concept stage of PDP, the proposed CE elements have achieved a substantial consensus, reaching an agreement level surpassing 75%. This indicates a high alignment among participants on these elements into the first stage of PD considering Prolong lifecycle principle. On the other hand, passive products category emerged as an element with a lower agreement level, falling below 65%. Low agreement may indicate divergency about perspectives or uncertainties regarding the implementation in this products category. See table 10.

In the development stage of PDP, the proposed CE elements have achieved a high agreement level surpassing 75%. This demonstrates the alignment among participants on these elements into PD. Moreover, it has been proposed to integrate an additional element focusing on "design in not fatigue strength dimensions". By emphasizing design aspects related to fatigue strength dimensions, this proposed element underscores a forward-thinking perspective that aligns with the principles of a Prolong lifecycle approach. This perspective recognizes the importance of not only addressing immediate requirements but also proactively designing program components to withstand prolonged and varied operational demands across Prolong lifecycle, thereby enhancing program resilience, durability, and long-term effectiveness.

In the production stage of PDP, the proposed CE elements have achieved a high agreement level surpassing 75%. This demonstrates the alignment among participants on these elements into PD, the elements are balanced between production models alternatives and supply chain system, this might indicate that looking for Prolong lifecycle there is a higher complexity which involves not only the internal production infrastructure but also the suppliers and processes. No additional element has been proposed to integrate into PD.

In the utilization stage of PDP, proposed CE elements have achieved high level of agreement above 75%, this demonstrates a collective understanding and recognition of the importance of proposed elements. The absence of additional elements suggested by participants highlighted the broader coverage of proposed elements identified in the literature.

In the disposal stage of PDP, the proposed CE elements have achieved a high agreement level surpassing 75%. This demonstrates the alignment among participants on these elements into PD. Additional elements have been proposed to integrate this stage, recycling rate, common remanufacturing standards for example definition of remanufacture. This maximizes the importance of materials selection to avoid waste generation, including the definition of remanufacture, aims to promote consistency and transparency in remanufacturing processes, facilitating market development and consumer confidence in remanufactured products.

Table 10: Summary of results for Prolong lifecycle

Stages	Proposed Elements / Agreement level
Concept	**High agreement level: above 75%** EoL Strategy Business models for services Product platform consideration User requirements changes management Pollution prevention Internal awareness & knowledge for remanufacturing High quality products, long lifetimes, making products last **Low agreement level: Below 75%** Passive products category
Development	**High agreement level: above 75%** Circular composites design methods Prolong lifecycle Design methods: DfD, DfE, DfRe, DfX, design changes possibilities incl. cost analysis, Re-design incl. spare parts, design with recovered materials, timeless design Co-creation with users Function unit thinking LCA application, waste management tools **Low agreement level: Below 75%** None **Additional elements suggestion** Design in not fatigue strength dimensions
Production	**High agreement level: above 75%** Alternatives production models Solid residues reduction Supplier payoff, minimizing manufacturing total cost Supportive organizational structure Additive manufacture (AM) Closed-loop production Quality and safety of products that serve multiple use-cycles **Low agreement level: Below 75%** None
Usage	**High agreement level: above 75%** Value creation solution Usage information, feedback flow Usage change requirements Profit management vs new products (cost & price) Maintenance services, upgrades Availability of remanufacture and recycled products partnership with retailers Repair services **Low agreement level: Below 75%** None
Disposal	**High agreement level: above 75%** Life-time extension, structural reuse, material recycle, product recovery Reverse channel structure, Cost of return, product return

Stages	Proposed Elements / Agreement level
	Repair and take-back services Value creation for reverse logistics Information exchange by industries Compliant with legislations, return rate targets Servitization continuum **Low agreement level: Below 75%** None **Additional elements suggestion** Recycling rate Common remanufacture standards e.g. definition of remanufacturing

Source: The author, 2024

4.1.2.3 Reprocessing

During the concept stage of PDP, the proposed CE elements have achieved a substantial consensus, reaching an agreement level surpassing 75%. This indicates a high alignment and shared understanding among participants on these elements related to the reprocessing concept in the PD. Furthermore, an additional element has been suggested for integration, focusing on the willingness to invest in CE, even at the expense of profitability. This proposal highlights a forward-thinking perspective that prioritizes long-term investments, sustainability, and social responsibility over short-term financial gains. See table 11.

In the development stage of PDP, the proposed CE elements have achieved a high agreement level surpassing 75%. This demonstrates the alignment and understand among participants on these identified elements into PD related to the reprocessing strategy. The absence of additional proposed elements for integration further underscores the effectiveness of the identified CE in addressing the integration of both fields CE and PDP.

In the production stage of PDP, the proposed CE elements have achieved a high agreement level surpassing 75%. This validates the alignment among participants on these identified elements into PD during reprocessing. However, among this consensus, it is important that the element related to "Large scale" has emerged with a lower agreement level, falling below 65%. This discrepancy may indicate varying perspectives or challenges among stakeholders regarding the incorporation of large-scale production practices within the framework. Despite this, no additional elements have been proposed for integration of CE into PD at this stage, highlighting the comprehensiveness and effectiveness of the identified elements.

In the utilization stage of PDP, the proposed CE elements have achieved a substantial consensus, reaching an agreement level surpassing 75%. This indicates a high alignment and shared understanding among participants on these elements. Furthermore, an additional element has been suggested for integration, specifically focusing on active customer information. This proposal highlights a proactive approach towards enhancing customer engagement and feedback mechanisms within the utilization phase, emphasizing the importance of customer engagement and continuous improvement in product utilization practices.

During the disposal stage of PDP, there is a substantial agreement among participants surpassing 75% of agreement level of proposed CE elements. This reflects the high level of consensus on these identified elements for the integration of CE into PDP. The absence of additional proposed elements for integration further emphasizes the effectiveness of the identified elements in the reprocessing stage.

Table 11: Summary of results for reprocessing

Stages	Proposed Elements / Agreement level
Concept	**High agreement level: above 75%** Function unit Consumer behavior understand Energy conservation and emission reduction targets for development Recycling EoL strategy Products from waste **Low agreement level: Below 75%** None **Additional elements suggestion** Willingness in invest in CE (even with loss of profitability)
Development	**High agreement level: above 75%** Designer mindset and knowledge DfD, dismantling possibility Lifetime and durability requirements Cloud-based architecture: recyclability level of components mapping Selection of materials easy to recycle, materials properties, strength, durability, material composition **Low agreement level: Below 75%** None

Stages	Proposed Elements / Agreement level
Production	**High agreement level: above 75%** Cost of products Modular components **Low agreement level: Below 75%** Large Scale
Usage	**High agreement level: above 75%** Consumer satisfaction Awareness of consumer about sustainability **Low agreement level: Below 75%** None
Disposal	**High agreement level: above 75%** Reverse logistic program Specific markets for waste materials Reprocess, downcycling Alternatives use Collection, Separation Post-consumer waste, incineration **Low agreement level: Below 75%** None

Source: The author, 2024

4.1.3. ROUND 3

The third round of the questionnaire was specifically designed to explore deeper into elements that exhibited a lower level of agreement and suggested elements, falling below the 75% threshold as outlined in Table 12. This round aimed to provide a more comprehensive investigation into the relevance and practical applicability of these elements within each stage of the PDP. By focusing on elements that garnered less consensus among participants, the objective was to gain understanding of the nuanced perspectives and relevancy throughout the various stages of PDP. Through this targeted inquiry, this research sought to identify any discrepancies or areas of contention regarding the interpretation or implementation of these elements for complementing the preliminary framework.

Questionnaire was developed considering the 5 stages of PDP: i) concept, ii) development, iii) production, iv) usage and v) disposal. Questions were about how likely participants consider relevant and applicable the presented CE elements in each stage of PDP regardless the CE strategy, the idea is to understand whether these elements are relevant/ applicable or not to increment the preliminary framework with a practical perspective. So, options were strongly disagreed, somewhat agree, neither agree nor disagree, somewhat agree and strongly agree.

In the assessment of the consensus levels within the group, it was observed that only one element, pertaining to the avoidance of scheduled obsolescence, failed to achieve a satisfactory agreement level above 75%. This aspect highlights an area of divergence among participants regarding the strategic approach to mitigating planned obsolescence in product design. However, it is important that other elements that initially lacked consensus in the second round were reconsidered and recognized as relevant and applicable in this subsequent round, achieving above 75% of consensus. Furthermore, the observation that certain elements may have attained lower agreement levels due to their inherent complexities within the CE strategy previous defined underlines the nature of the fit in each CE strategy.

Table 12: Summary of results for round 3

Stages	Relevant and applicable / Agreement level
Concept	**High agreement level – above 75%** Passive products Shared ownership **Low agreement level – below 75%** Avoid scheduled obsolescence
Development	**High agreement level – above 75%** Design for easy disassembled joints Design in not fatigue strength dimensions **Low agreement level – below 75%** None
Production	**High agreement level – above 75%** Upgrading process Large scale **Low agreement level – below 75%** None
Usage	**High agreement level – above 75%** Maintenance Active customer information Shared ownership **Low agreement level – below 75%** None
Disposal	**High agreement level – above 75%** Recycling rate Stringent recycling activities Common remanufacturing standards and definition **Low agreement level – below 75%** None

Source: The author, 2024.

4.2. FINAL FRAMEWORK

This section presents the final Circular Product Development Framework (CPDF) as per figure 14. The integration of the results from experts panel in the preliminary frameworks marks a significant synthesis, as it involves translating theoretical concepts and practical professional practices, insights, and methodologies. This process serves to bridge the gap between theory and practice by aligning abstract theoretical constructs with real-world applications, validation in practice. It represents a crucial transition where the theoretical underpinnings are brought to life through their implementation in practical settings.

The expert panel revealed the product complexity aspects to elaborate the final Framework. Despite of in concept stage the elements passive products and shared ownership have reached a high agreement level above 75%, the shared ownership element is in the initial business model phase of the CDP framework. This is a multifaceted element due to the variances of products possibilities, especially in the automotive segment once many subcomponents are involved. The systematic thinking for sharing ownership should be in the final product, so components and subcomponents needs to be in a different CE strategy level.

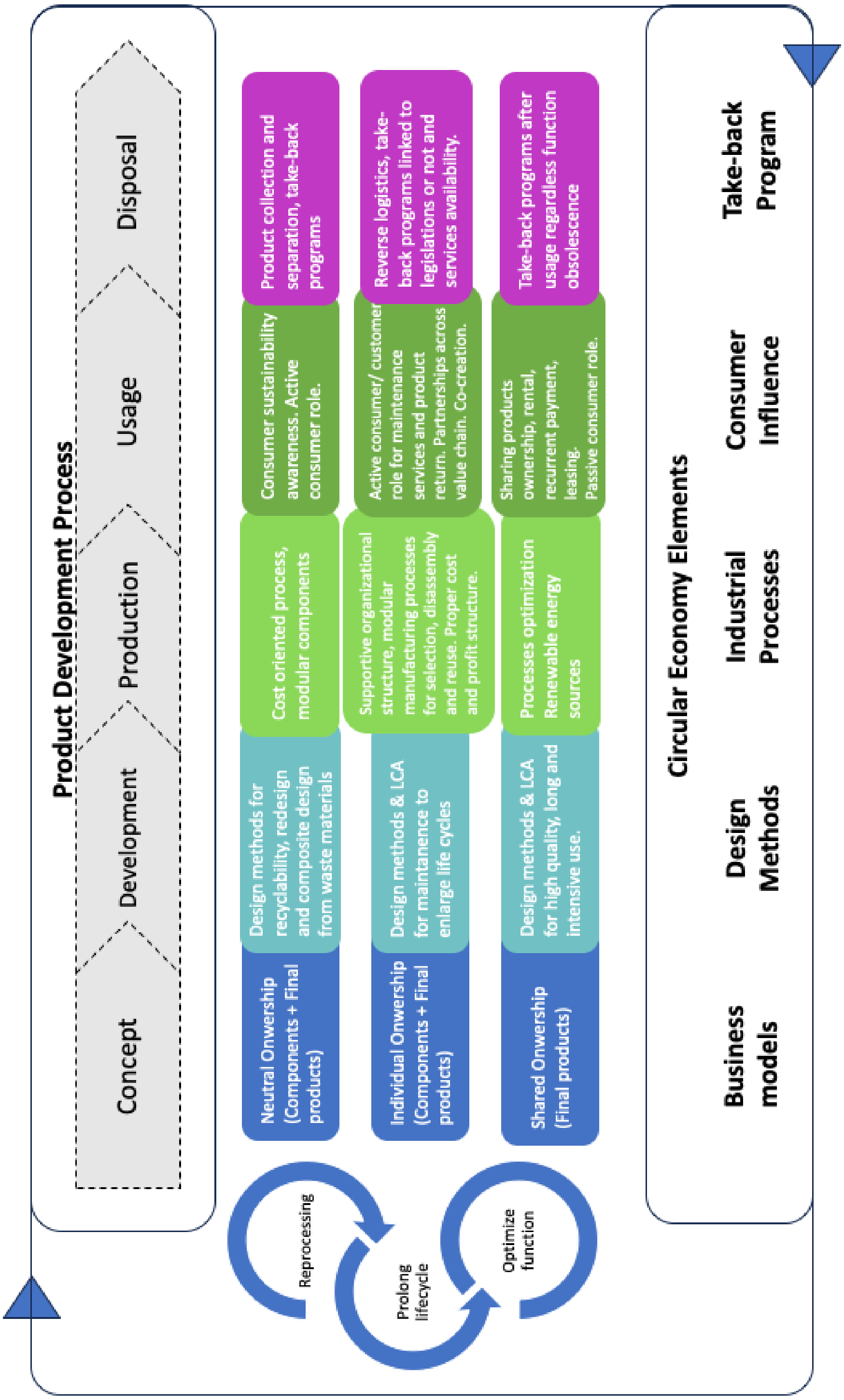
In the development stage, the proposed elements are aligned with the design methods and requirements essential for the PDP. This alignment underlines the critical importance of designing products with circularity in mind, necessitating adherence to specific design methodologies tailored to meet the demands of circular product development. By integrating these suggested elements, it is a reinforcement of the imperative for product designs to be oriented towards circularity, ensuring that they can meet the necessary requirements for sustainability and resource efficiency throughout their lifecycle. This emphasis on circular product design not only addresses environmental concerns but also aligns with evolving consumer preferences. Ultimately, incorporating these elements into the development stage serves to promote the adoption of circular principles within the broader context of product design and development processes.

In the production and usage stages, the literature findings are validated, affirming the consistency of the preliminary framework without significant alterations. Both stages align with the established framework, reinforcing its conceptual underpinnings. In the Production stage, the focus remains on the centrality of processes, corroborating the framework's emphasis on efficient production methods and practices. Meanwhile, in the Usage stage, there is an emphasis on maintenance as a complementary perspective, supporting the framework's holistic approach to product lifecycle management. These confirmations underscore the robustness and reliability of the preliminary framework, demonstrating its ability to accurately capture and reflect the key dynamics and considerations across different stages of product development and usage.

In the disposal stage, particular emphasis was placed on two key aspects: the recycling rate and recycling activities, along with the significance of establishing standards to define product types, such as remanufacturing. The focus on recycling rate and activities underscores the critical role of recycling in managing end-of-life products, highlighting the importance of efficient and effective recycling processes to minimize waste and maximize resource recovery. Additionally, the recognition of standards for defining product types, particularly in the context of remanufacturing, speaks to the need for clear guidelines and criteria to facilitate the remanufacturing process. Standardization ensures consistency and quality in remanufactured products, promoting their acceptance and integration into the market while also contributing to environmental sustainability by prolonging the useful life of materials and reducing the need for virgin resources. Overall, these considerations underscore the importance of robust recycling infrastructure and standardized practices in achieving sustainable disposal practices within the CE framework.

The CPDF provides a clear roadmap for integrating CE strategies with various stages of the PDP, based on findings pertaining to product composition and its implications for CE elements. Within this framework, different CE strategies are applied selectively depending on the product's composition and ownership principles. The strategy of Optimize function, for instance, is deemed applicable only to complete and final products, particularly in scenarios where the principle of shared ownership is emphasized. Conversely, strategies such as reprocessing and Prolong lifecycle are deemed suitable for both final products and individual components, particularly in cases where ownership is more neutral or individualized. However, what emerges as a key consideration is that, for components, the concept of ownership becomes less relevant compared to the significance of product composition. This shift in focus underscores the importance of understanding the material of components and their potential for reuse, recycling, or other circular practices, thus highlighting the pivotal role of product composition in shaping CE strategies within the CPDF.

Figure 14: Circular Product Development Framework



Source: The author, 2024

4.3. DISCUSSION

In the discussion section, the study observes into the intricacies of integrating theoretical foundations with practical considerations, revealing how these elements converge or diverge to form a robust framework. Through an analysis, the section explains the blending of theoretical concepts with real-world applications, demonstrating how theoretical insights are translated into practical activities, strategies, and methodologies. The discussion offers valuable insights regarding the CPDF that effectively addresses the complexities and challenges inherent in the study's objectives.

The preliminary framework, serving as intellectual guide, finds its manifestation in a set of practical tools, methodologies, and strategies. This nuanced interplay between the conceptual and practical frameworks not only enhances the relevance and applicability of this research but also empowers to navigate the complexities of the research landscape with a pragmatic and informed perspective. The findings about the CE elements and their integration between CE strategies and PDP stages reveals a new perspective of circular product development in a systematic approach. These elements have been also confirmed by experts in the Delphi survey and supported to create the final CPDF.

The strategy of Optimize function in the preliminary framework presents the idea of sharing ownership as a CE element for business model in the starting point for concept stage of the PDP, however this element has presented divergencies in the second round of Delphi survey which reveals the practical aspect of CE element applicability. This highlights the final product development versus components and sub-components development. Final products are possible to share by consumers, however components and sub-components are possible to be reused or remanufactured, which leads to a different CE strategy for PDP.

Development and production stages presented an alignment between both frameworks about CE elements of design methods and industrial processes. In the design methods there was a suggestion of additional element about the design for easy disassembled which supports the design for reuse in the EOL strategy. Both methods are associated in the design for environment (DfE). In this strategy the focus of design methods is in enlarging the lifecycle of a certain product, however balancing the energy and resources requirements, in other hands in the terms of embodied exergy involved (Almeida et al. 2017). For industrial processes the efficiency is given as the most common element related to resources in use and renewable energy sources, processes optimization is also considered a path for efficiency resources usage (Urbinati et al. 2019).

Sharing products ownership in usage stage is the element which presents less alignment in the consumer influence CE element, however recurrent payment, rental, and leasing are in alignment in both frameworks. Product sharing is related to a Product/service-system (PSS) and Product-system substitution (Kjær et al., 2019). The PSS is composed by three types according to Tukker (2015): i. Product-oriented PSS (product sold to users with additional to services), ii. Use-oriented PSS (function is sold to user, but product ownership remains at PSS provider, as well as maintenance costs), and iii. Result-oriented PSS (pure service sold to user, no product is involved) and this is only possible in final products category, leading the CE Optimize function to final products in direct contact with consumers.

Disposal stage in the Optimize function strategy is interrelated to the take-back program element. In this point the highlight is about what to do after taking back useless products to be aligned with CE principles. The take-back program is an enabler for creating CE alternatives to enlarge product lifecycles such as durability upgrading and repairing solutions (Albæk et al., 2020). As additional elements, the suggestion was related to recycling alternatives such as recycling rate and stringent recycling activities, these two elements interconnected the Optimize function strategy with the reprocessing strategy after CE alternatives to enlarge product life cycles are depleted. This interconnection between CE strategies to achieve CE principles is an outcome from expert’s Delphi panel.

In the strategy of Prolong lifecycle there is an alignment between both frameworks in the concept stage towards the CE element of business case. The product ownership plays an important role, as well as the final product and components category due to highlight other CE alternatives related to the application and type of usage. PSS is possible to be implemented with Aftermarket strategy perspective, co-creation with users is an ally to enable value-added services such as repairing (van Dam et al., 2020). Respondents in the first round raised as main challenges for the integration of CE and PDP are in the initial phases and internal company mindset, reinforced that CE principles must be considered since the creation and in product concept.

Development stage confirms the design methods CE element in both frameworks and in the Prolong lifecycle strategy, the design possibilities is considered the final product, components, and sub-components categories, including design changes possibilities and re-design (de Fazio et al., 2021). In this strategy, the element design method is focusing in allowing more than one lifecycle after usage, for instance, it can be via remanufacturing or repairing. The idea is to reuse, so design for disassembly, timeless design, the application of LCA and waste management tools are confirmed by experts' panel. Remanufacturing alternative should be incorporate in the early phase of the design due to its complexity, it involves company strategy (Boorsma et al., 2021). The reuse and modularity concepts for components and sub-components is fostering in the product development as an EOL strategy alternative. Design optimization especially for remanufacturing is a path for meeting change requirements during product life cycle (Al Handawi, et al., 2021).

The CE elements regarding industrial processes are determined by alternative models. To implement reuse alternatives the manufacture infra-structure and related organization should be involved. Crucial factors enabling the remanufacturing is the integration of feedback in the product design process and feedback channels with a supportive organizational structure into the manufacturing. All stages such as design, production, service, reuse, remanufacturing and disposal should be involved in a circular information flow (Haziri et al., 2019). In the first round of qualitative questions, respondents highlighted technical changes during product lifecycle management (PLCM) creates issues, production processes and the layout for OE products are designed for highest efficiency and reliability so installing different concepts is a challenge, this reinforces the importance of the involvement of the whole organization in a multiple life-cycle product strategy.

The usage and disposal stages are essentially connected in this CE strategy due to the importance of the feedback flow in this stage and the presence of partnerships between the stakeholders i.e. manufactures, retailers, customers and third parties, all members in the value chain for the value creation of reverse logistics in the EoL (Berssaneti et al., 2019). Reverse logistics is fundamental for allowing the reuse, repair and remanufacture as alternative in EOL strategy. Regarding to market requirements, respondents highlighted i) remanufactured product must be competitive against the new product in terms of margin, lead-time, and handling in all chain' steps; ii) product appearance must be like new. All products should be remanufacturable (one core = one reman product) with same fit, form, function, and same quality as a new product, easy to handle and cost neutrality. For the achievement of the best outcomes the supply chain design should be considered in the early stage (Wu et al., 2017).

In terms of EOL possibilities beyond, respondents have underscored a critical challenge: the seamless exchange and utilization of information among different sectors and teams involved not only in the PDP, but also in the conception and execution of CE strategies. This challenge is multifaceted, encompassing the need for effective communication channels, shared understanding, and collaborative efforts. Without robust information sharing mechanisms, the integration of these areas becomes jeopardized, potentially impeding progress toward sustainable practices. Moreover, integrating consumers into the cycle presents its own set of hurdles, requiring clear communication and active engagement strategies to ensure their participation and buy-in. This can avoid the cannibalization of sales of new products (Berssaneti et al., 2019).

Remanufacturing products offers multifaceted benefits that extend beyond waste reduction, including energy and material savings. Comparative analyses have revealed that remanufacturing can often outperform new manufacturing or EOL treatments, such as material recycling, from various sustainability perspectives. It offers a potential growth for the remanufacturing business in Europe by 2030, estimated at €100 billion (Haziri et al., 2019).

Furthermore, the integration of PSS into passive products has been shown to significantly diminish environmental impact, as measured by global warming potential over the product's life cycle. This integration results in a remarkable environmental impacts reduction ranging from 45% to 72%, primarily attributable to the increased number of product reuses and extended product lifetimes. Additionally, this approach is associated with cost savings, with decreases ranging from 8% to 37%. These findings underscore the considerable environmental and economic advantages of remanufacturing and the integration of PSS, highlighting their potential to drive sustainable innovation and practices across industries (Kaddoura et al., 2019).

The strategy of reprocessing in the preliminary framework presents an alignment between both frameworks in the concept stage towards the CE element of business case. In this strategy the ownership become less relevant due to the focus in the possibilities of reprocessing a final product or a component after other CE strategies are depleted. In this case the importance is to find the alternative beyond disposal to reduce waste generation, the EOL strategy definition plays an important role in the early phase based on the materials and design selection. In the concept and development stages, business model and previous CE strategy definition are fundamentals for the elaboration of design methods, materials decision, recyclability, and waste reduction. In this CE strategy, the focus is in developing new materials and technologies from waste to be use as alternative in producing raw materials for new products development. For instance, packaging replacement or substitution of previous material applications, the Design for Recycling strategy can be broader applied in the method CE elements (Ragaert et al., 2020).

In the reprocessing the cost orientation process is base for the production stage. Where the CE element of industrial process relies in operational efficiency due to the pressure of large-scale requirements and competitiveness. Sustainable practices should be focus on lower energy usage and environmental practices standards like ISO 14001 (Jungend et al., 2020). The choice of renewable or natural materials to produce components and subcomponents is important to minimize the dependence of fossil materials. Respondents has raised the pressure for cost reduction that leads to cheaper manufacturing bolding methods consequently products cannot be disassembled, so as alternative modular designs linked to the modular production is capable to create as many products as possible just combining the components. This is aligned with the necessity of efficiency (He et al., 2021).

In this strategy, the utilization stage encompasses a wide range of possibilities beyond its conventional interpretation. These possibilities include utilizing of reprocessed raw materials in sub-components, using recycled sub-components in larger components, integrating these components into finished new products, and ultimately, the consumption of these final products by consumers. A complete chain of usage considering the alternative materials. Each of these stages presents opportunities for sustainable practices and reflects a shift in consumer awareness and mindset, influenced by designers. This represents a significant structural change in how sustainability is perceived and prioritized (Jungend et al., 2020). Respondents raised in the first qualitative round the importance of customers be informed about the circularity and sustainability level behind a certain product.

Take-back programs, followed by product collection and separation are fundamentals to realize the CE principle in the PDP completely to avoid as maximum the incineration or discard in the EOL stage. Post-consumer scrap is also considered raw material commodity and they can be traded at global level like the aluminum scrap (Niero et al., 2016). This highlights the importance of a specific market creation for the trading of scrap materials, a structured collection and separation process is helpful in making this market running. For final products such as clothes for instance, creation of textile-textile recycling system including proper technology development. The necessity of understanding the complexity of supply-chain, customer behavior and establish a new standard in the designer's mindset are key drivers for the materials reprocessing in the EOL (Sandvik et al., 2019).

The transition from the conceptual CPD (Circular Product Design) framework to its final iteration marks a crucial turning point, notably influenced by two key factors: the principle of product composition and ownership, and the intricate definition of business models. This transition involves navigating complexities such as material types, process optimization, regulatory requirements, and customer preferences. Across industries, the level of complexity varies significantly, with each presenting unique challenges and considerations. For instance, in the automotive sector—highlighted by the expert panel—the complexity manifests in the diverse array of product variations. This complexity extends to the final product, encompassing the composition of various components and sub-components, and their integration throughout the PDP within different levels of CE strategy implementation. This underscores the need for tailored approaches and strategies to effectively address the specific challenges inherent in each industry context.

5. CONCLUSION

In this study, it has been explored the concepts, theories, and gaps available in the literature regarding the relationship between PDP and CE, the main findings were the CE elements of integration between CE strategies and PDP stages, i.e. business models, design methods, industrial processes, consumer influence and take-back programs. In additional the adaptation of CE strategies in 3 main categories, Reprocessing, prolong lifecycle and Prevention of Obsolescence based on the R framework from Potting et al. (2017). Regarding the PDP the product ownership characteristics such as Neutral ownership and Individual ownership, which is related to the components and final products, share ownership related only for final products

The interrelation between the CE and PDP highlights the implications for sustainable development and its relationship with the SDGs. Some areas, such as responsible consumption and production, are especially significant due to the need for decisions regarding raw material and energy use in new product development. This aligns with the SDG focus on responsible consumption and production, as well as affordable and clean energy. While these areas are more prominent, other areas offer significant potential for further exploration, such as decent work and economic growth, industry, innovation, and infrastructure, which are key enablers for a practical transition to sustainability.

According to the micro-level proposed by Ghisellini et al. (2016) with the focus on a company and consumer domains, the main concepts identified in this study is about the transition from linear to CE based on regenerative system which resources input, waste, emission, and energy leakage can be minimized by slowing, closing, and narrowing materials and energy loops (Geissdoerfer, 2017) in
industrial processes via CE strategies of Optimize function, prolong lifecycle and Reprocessing, and their interconnection based on final product, components, and subcomponents. The differentiation between these strategies is by product function, value perception, and configuration.

The Optimize function strategy lies in the lack of product ownership. Function utilization optimization, only applicable for final products which function can be sold via product-service-system, its maintenance, lifetime extension is connected to the Prolong lifecycle CE strategy or reprocessing CE strategy. Prolong lifecycle strategy is related to stable performance and product ownership. It is about possibilities for product lifetime extension, such as repairing, refurbishing, and remanufacturing Focus is to increase efficiency and minimize usage of resources (Bocken et al, 2016). Reprocessing strategy is about the reusability of product subcomponents via upcycling and downcycling possibilities. In this strategy the focus is to recover materials after lifetime, new materials development out of discarded products and considering energy efficiency. The value definition in this case is based on commercial value, material quality or the use-related value (Singh et al., 2016).

The relationship between CE strategies and PDP stages, as proposed by the literature, is founded on two primary pillars: the initial design phase and the final end-of-life (EOL) processes. These stages are crucial as they determine the CE strategy and the subsequent PDP elements to be implemented. However, gaps have been identified, particularly in the production and usage stages of the PDP. These stages, which involve the company's infrastructure and the product's lifecycle, have been less thoroughly investigated. There is also a need for better integration of each PDP stage into the broader CE concepts. In this context, the research highlights the significant connections within these areas and identifies key elements that facilitate integration. Specifically, the research points to the necessity of a comprehensive understanding of how production and usage stages can be aligned with CE principles. This alignment includes optimizing infrastructure, enhancing sustainable practices during production, and promoting consumer awareness, efficient usage to extend product life.

It has been explored the context of integration between CE strategies and PDP stages. Key connections facilitating this integration are found in business models, such as leasing or product-as-a-service, which support sustained product use and maintenance. In design methods to ensure products are durable, repairable, upgradeable, easier to reprocess, maintainable, and environmentally friendly materials. Industrial processes to enable the remanufacturing, refurbishment, alternative materials (i.e. raw materials from discarded products), and energy efficient (considering renewable energy sources) essential for CE practices. Consumer influence towards sustainable consumption, products lifetime extension, maintenance and returning in EOL stage, finally robust take-back programs that enable the discarded product is back in the value chain, in other words to close the loop via possibilities of CE strategies. Together, these elements create a comprehensive framework for embedding CE principles throughout the PDP, enhancing sustainability from design to end-of-life.

In the preliminary CPDF, it has been revealed the dimensions and the elements which interconnected the CE and PDP fields. In the early stages of CPDF, the proposed business model’s element is to explore new possibilities about value delivery to the customers via physical ownership or function usage, followed by aftersales services such as maintenance and proper cost and profit structures in the company. This aspect is relevant for the CE transition due to the fact of current business orientation is based on value delivery in physical products, this changes the business environment and companies’ processes.

The proposed element of design methods emphasizes that creating circular products necessitates a holistic approach that goes far beyond traditional product design. It requires organizations to undergo significant transformations, which include implementing changes in processes, adopting a circular mindset throughout the company culture, and potentially restructuring infrastructure to support circularity initiatives. This comprehensive approach ensures that circular principles are embedded at every stage, from initial conception and material selection to manufacturing, distribution, use, and end-of-life management. By fostering a culture that prioritizes sustainability and circularity, companies can better align their operations with environmental goals, enhance resource efficiency, and drive innovation towards more sustainable practices. This transformation is crucial for developing products that not only meet consumer needs but also contribute to the broader goals of sustainability and resource conservation.

This entails reevaluating traditional linear production models and embracing circular principles throughout the entire value chain. In this context, the proposed element of industrial processes requires a shift beyond mere cost-oriented approaches. It necessitates the adoption of modular manufacturing processes that incorporate areas specifically designed for disassembling used components, as well as the expertise for ensuring cleanliness, thorough inspection, and accurate selection of these components. Implementing these changes leads to the creation of a supportive organizational structure that promotes process optimization and the integration of renewable energy sources. These steps are essential for achieving CE principles, as they enable the efficient reuse of materials, reduce waste, and enhance the sustainability of manufacturing operations. By fostering an environment that supports modularity, cleanliness, and the reuse of components, organizations can more effectively align with CE objectives across the entire value chain.

The proposed element of consumer influence is shedding a light in the active consumer role via sustainable consumption, in the product lifetime extension via aftersales services i.e. maintenance and product return after EOL, it is also highlighted the passive consumer role changing the value perception though sharing products, rental and recurrent payments in return to delivery product function.

To facilitate the closure of the loop within CE frameworks, it is essential to establish efficient take-back and reverse logistic programs. This proposed element serves as a fundamental cornerstone shared among the three presented CE strategies. Indeed, it represents the prerequisite for enabling the closed-loop cycle, wherein products and materials are effectively reintegrated into the production process following their initial use. By planning robust take-back and reverse logistic systems, organizations can systematically retrieve EOL products, thereby fostering their reintegration into the value chain. This holistic approach not only promotes resource conservation and waste reduction but also underscores the pivotal role of circularity in achieving sustainable resource management practices.

By integrating these circular elements into every phase of product development—concept, development, production, usage, and disposal—companies can effectively transition towards more sustainable and resilient business practices. At the conceptual stage, products are designed for longevity, reparability, and recyclability. During development, sustainable materials and modular designs are prioritized. In the production phase, processes are optimized to minimize waste and energy consumption, often utilizing renewable energy sources. In the usage stage, companies encourage practices that extend product life, such as maintenance and product-service systems (PSS). At the disposal stage, robust take-back schemes and reverse logistics ensure products are reclaimed and reprocessed, reintegrating materials into the production cycle. This holistic integration reduces environmental impact, enhances resource efficiency, creates new business opportunities, and fosters a sustainability-focused corporate culture, thereby positioning companies as leaders in the transition towards a CE.

From the dimension of CE strategies, the integration occurs in the Optimize function by addressing the issue of product obsolescence by focusing on factors such as the lack of product ownership and optimizing functional utilization. This approach is particularly relevant for final products that can be offered through a product-service-system, where maintenance and life extension play pivotal roles. Furthermore, these efforts are intricately connected to the others CE strategies, such as the Prolong lifecycle approach or reprocessing. By understanding the nuances of each strategy and their interplay, organizations can effectively align their PDP efforts with CE principles, fostering sustainability and innovation throughout the product lifecycle.

In the Prolong lifecycle connection, the emphasis is on revitalizing products by refurbishing, remanufacturing, repair and restoring them to their original function condition. This approach is geared towards prolonging product lifespans and minimizing waste. By conducting a thorough case study analysis, it becomes clear that employing remanufacturing practices yields benefits beyond just environmental conservation. Indeed, it presents significant economic opportunities by optimizing resources and retaining the value of products. For instance, remanufacturing allows companies to utilize existing materials and components more efficiently, reducing the need for raw materials and lowering production costs. Moreover, repair and refurbish products often retain a considerable portion of their original value, thereby generating additional revenue streams for businesses. This dual benefit of environmental sustainability and economic viability underscores the importance of remanufacturing as a key strategy in advancing CE principles.

Similarly, in the reprocessing strategy, where materials are recycled or converted into new products, the emphasis shifts towards closing material loops and promoting resource efficiency. By exploring real-world examples and case studies within each strategy, we gain valuable insights into their practical implementation, challenges, and potential benefits. By conducting a detailed examination of these strategies, we can achieve a nuanced understanding of their integration into PDP. This deeper understanding enables to identify synergies and opportunities for alignment, thereby fostering sustainability and driving innovation across industries.

In the test of preliminary framework via Delphi panel, the dimensions of CE strategies were presented, followed by the stages of the PDP and their connection to CE elements, which act as enablers for circular product development. The proposed Circular Product Development (CPD) framework is guided by this connection, utilizing the CE elements identified in the literature. The integration of CE strategies is structured according to the level of the product's architecture—sub-components, components, and final products. Specifically, the CE strategy to Optimize function is applicable to final products, ensuring their longevity and creating possibilities for business models. Meanwhile, the CE strategy for multiple lifecycles applies to both components and final products, enabling them to be reused, repaired, or remanufactured through successive cycles. Finally, the CE strategy for reprocessing is relevant across all levels—sub-components, components, and final products—facilitating the recovery, repurposed or reintegration of materials and parts into the production process. This structured approach ensures that each level of the product's architecture is aligned with the most suitable CE strategy, thereby fostering comprehensive circularity throughout PDP.

From the CE implementation viewpoint there are two main pillars, design methods and take-back programs. The design methodologies offer a framework through which designers and engineers can navigate these complexities, integrating principles of sustainability, resource efficiency, and circularity into the very fabric of product design. By employing such methodologies, organizations can streamline the development process, optimize resource utilization, minimize waste generation, and ultimately create products that are not only functional and aesthetically pleasing but also environmentally responsible and economically viable. Thus, design methods play a pivotal role in realizing the transformative potential of CE strategies within the realm of product development.

The implementation of take-back programs is essential as a foundational step for establishing a closed-loop process. Reverse logistics systems are already operational in many industries and, in some cases, on a large scale, such as with aluminum beverage cans. However, there is significant potential to expand these programs into other sectors. Forming partnerships with retailers and distributors can greatly enhance the effectiveness of take-back initiatives, leading to higher return rates. Additionally, educating customers and consumers about the importance and benefits of participating in take-back programs is crucial. By increasing awareness and understanding, companies can foster greater participation and ensure the success of closed-loop processes. This comprehensive approach not only promotes sustainability but also strengthens the collaboration between various stakeholders in the supply chain, ultimately contributing to more efficient and environmentally responsible business practices.

The adaptation of the production stage represents a challenge for the CPDF, given the entrenched nature of existing infrastructural setups and the substantial energy consumption inherent within this stage. Consequently, the primary focus lies in initiating transformative measures at transitioning towards renewable energy sources. Simultaneously, there is a pressing need to reassess prevailing production processes, thereby facilitating the incorporation of novel methodologies conducive to the integration of reuse and recycling principles. By strategically implementing these changes, companies can not only mitigate their environmental footprint but also engender a paradigm shift towards sustainable resource utilization within the production domain.

Regarding the ownership principle in the usage stage in Optimize function is feasible for final products, industries that are supplier of components needs to rethink about business models thinking about the final user and the intermediate company. Notably, the aftermarket services emerge as a necessary aspect across all CE strategies, particularly within the maintenance and usage stage. This stage has a broader meaning in the reprocessing strategy due to the multiple use possibilities such as raw material use in sub-components application, sub-component utilized in a component, components utilized in products and final products usage by consumers. All these possibilities permeate the consumer influence and mindset from the designers, this is a structural change of awareness about sustainability.

Additionally, there's a pressing need for product development professionals to deepen their understanding of CE principles, particularly concerning their responsibilities for products beyond their initial creation. This includes exploring diverse EOL possibilities beyond conventional recycling or scrapping methods, such as refurbishment, remanufacturing, or repurposing. By broadening their knowledge and embracing innovative approaches, organizations can navigate these challenges more effectively, paving the way for a more circular and sustainable future.

5.1. LIMITATIONS & FUTURE RESEARCH

Conducting the Delphi Panel within a single company has certain implications that should be carefully considered. While this approach enables a focused, in-depth analysis tailored to the specific context, processes, and strategic priorities of the organization, it inherently restricts the diversity of perspectives. The insights gathered are deeply aligned with the company's operational environment, which may be shaped by unique market conditions, organizational culture, or industry practices. As a result, the framework developed through this process is highly relevant for this particular company but may not be fully transferable or applicable to others without adaptation.

This limitation also affects the generalizability of the findings. By concentrating on a single company, the framework might overlook industry-specific nuances, regional differences, or varied business models that could influence how CE strategies and PDP are implemented elsewhere. Moreover, certain challenges or opportunities that arise in different sectors or organizational scales might not be captured in this focused study. To enhance the robustness and applicability of the framework, it would be essential to extend the research to include multiple organizations across different industries, geographies, and scales. This would allow for comparative analysis and a more comprehensive understanding of how the framework can be adapted to diverse business contexts.

The final framework is a culmination of insights gathered from experts within the automotive industry, representing a critical starting point for the integration of PDP and CE strategies to establish the CPDF. However, it's important to recognize that other industry segments may offer distinct perspectives and considerations that could enrich the framework further. Future research endeavors can delve into these alternative industries to explore their unique challenges, opportunities, and best practices, as well as the development of software and their influence in hardware for sustainable practices purpose. The social aspect of this study is not much in the focus, as well as the SDGs, this is a limitation from the perspective of ESG baseline.

While the production and disposal stages can be shared among CE strategies, there exists the potential to elevate them to a higher level that emphasizes increased energy efficiency and more sustainable material usage in future studies. This evolution involves reimagining these stages to not only minimize waste but also optimize resource utilization throughout the entire product lifecycle. By implementing innovative technologies, adopting circular design principles, and fostering collaboration across sectors, companies can strive towards a more efficient and environmentally conscious approach to production and disposal. This shift not only aligns with the core principles of the CE but also drives continuous improvement towards more sustainable practices.

In the context of the reprocessing CE strategy, there is a notable scarcity of studies that specifically investigate the influence of consumers on the integration of PDP and CE. This gap highlights a significant area for further exploration and analysis. Understanding how consumer behavior, preferences, and perceptions intersect with PDP and CE integration is crucial for developing effective strategies and initiatives that resonate with end-users. By conducting more focused studies in this area, researchers can uncover valuable insights that inform the development of consumer-centric approaches within the reprocessing CE strategy, ultimately driving more sustainable consumption patterns and behaviors.

The application of the CPDF in future studies and case studies, particularly those employing a quantitative approach is highly recommended to test and refine the CE elements, and framework dimensions. Conducting empirical research and collecting quantitative data will allow for a rigorous evaluation of the framework's effectiveness and its practical implications. This approach can provide valuable insights into the strengths and weaknesses of the current framework, enabling researchers to identify areas for improvement and to develop more robust strategies for integrating CE principles into product development. Moreover, quantitative studies can help establish measurable benchmarks and performance indicators, facilitating the comparison of outcomes across different industries and contexts. By continuously testing and enhancing the CPDF, researchers and practitioners can contribute to the advancement of sustainable product development practices and the broader adoption of CE strategies.

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APPENDICES

DELPHI QUESTIONNAIRE WITH EXPERTS

Round 1 (qualitative questions) understanding the topic:

a) What, in your opinion are the main challenges for the integration of circular economy and product development processes?

b) What is common customer and/or market requirements related to circular products development?

Round 2 (Elements Agreement test):

Do you agree with the identified elements within PDP stage Concept and CE Optimize function, or do you like to add other elements to support Circular Economy transition?

	Concept	
	Agree	Disagree
Circularity as strategic focus	○	○
Product/Service system	○	○
Business model transformation	○	○
Shared ownership	○	○
Resource reduction	○	○
Exergy awareness	○	○
Reuse & materials efficiency	○	○

Do you agree with the identified elements within PDP stage Concept and CE Prolong lifecycle, or do you like to add other elements to support Circular Economy transition?

	Concept	
	Agree	Disagree
End of Life Strategy	○	○
Business models for services	○	○
Product platform consideration	○	○
Passive products category	○	○
User requirements changes management	○	○
Polution prevention	○	○
Internal awareness & knowledge for remanufacturing	○	○
High quality products	○	○

Do you agree with the identified elements within PDP stage Concept and CE Reprocessing, or do you like to add other elements to support Circular Economy transition?

	Concept	
	Agree	Disagree
Function unit	○	○
Consumer behavior understand	○	○
Energy conservation and emission reduction targets for development	○	○
Recycling End of Life strategy	○	○
Products from waste	○	○

Do you agree with the identified elements within PDP stage Development and CE Optimize function, or do you like to add other elements to support Circular Economy transition?

	Development	
	Agree	Disagree
Product usage/ substitution	○	○
Long Life-time	○	○
Design for Environment	○	○
End of Life strategy	○	○
Selection of non-toxic, biodegradable materials	○	○
Life Cycle Assessment application	○	○
High quality products	○	○

Do you agree with the identified elements within PDP stage Development and CE Prolong lifecycle, or do you like to add other elements to support Circular Economy transition?

	Development	
	Agree	Disagree
Circular composites design methods , waste management tools	○	○
Multiple life-cycles	○	○
Design methods: for Disassembly , for Environment, for Reman/ repair, for X.	○	○
Design changes possibilities incl. cost analysis, Re-design incl. spare parts, design with recovered materials, timeless design	○	○
Co-creation with users	○	○
Function unit thinking	○	○
Life cycle assessment (LCA) application	○	○

Do you agree with the identified elements within PDP stage Development and CE Reprocessing, or do you like to add other elements to support Circular Economy transition?

	Development	
	Agree	Disagree
Designer mindset and knowledge	○	○
Design for dismantling possibility	○	○
Life-time and durability requirements	○	○
Cloud-based architecture: recyclability level of components mapping	○	○
Selection of materials easy to recycle, materials properties, strength, durability, material composition	○	○

Do you agree with the identified elements within PDP stage Production and CE Optimize function, or do you like to add other elements to support Circular Economy transition?

	Production	
	Agree	Disagree
Processes optimization	○	○
Energy efficiency	○	○
Renewable sources of energy	○	○

Do you agree with the identified elements within PDP stage Production and CE Prolong lifecycle, or do you like to add other elements to support Circular Economy transition?

	Production	
	Agree	Disagree
Alternatives production models	◯	◯
Solid residues reduction	◯	◯
Supplier payoff, minimizing manufacturing total cost	◯	◯
Upgrading process	◯	◯
Supportive organizational structure	◯	◯
Additive manufacture (AM)	◯	◯
Closed-loop production	◯	◯
Quality and safety of products that serve multiple use-cycles	◯	◯

Do you agree with the identified elements within PDP stage Production and CE Reprocessing, or do you like to add other elements to support Circular Economy transition?

	Development	
	Agree	Disagree
Large scale	◯	◯
Cost of products	◯	◯
Modular components	◯	◯

Do you agree with the identified elements within PDP stage Utilization and CE Optimize function, or do you like to add other elements to support Circular Economy transition?

	Utilization	
	Agree	Disagree
Sharing products ownership	○	○
Recurrent payment (Rental, leasing)	○	○

Do you agree with the identified elements within PDP stage Utilization and CE Prolong lifecycle, or do you like to add other elements to support Circular Economy transition?

	Utilization	
	Agree	Disagree
Value creation solution	○	○
Usage information, feedback flow	○	○
Usage change requirements	○	○
Profit management vs new products (cost & price)	○	○
Maintenance services, upgrades	○	○
Availability of remanufacture and recycled products partnership with retailers	○	○

Do you agree with the identified elements within PDP stage Utilization and CE Reprocessing, or do you like to add other elements to support Circular Economy transition?

	Utilization	
	Agree	Disagree
Consumer satisfaction	○	○
Awareness of consumer about sustainability	○	○

Do you agree with the identified elements within PDP stage Disposal and CE Optimize function, or do you like to add other elements to support Circular Economy transition?

	Disposal	
	Agree	Disagree
Take-back programs	○	○
Durability upgrading and repair	○	○

Do you agree with the identified elements within PDP stage Disposal and CE Prolong lifecycle, or do you like to add other elements to support Circular Economy transition?

	Disposal	
	Agree	Disagree
Life-time extension, structural reuse, material recycle, product recovery	○	○
Reverse channel structure, Cost of return	○	○
Repair and take-back services	○	○
Value creation for reverse logistics	○	○
Information exchange by industries	○	○
Compliant with legislations	○	○

Do you agree with the identified elements within PDP stage Disposal and CE Reprocessing, or do you like to add other elements to support Circular Economy transition?

	Disposal	
	Agree	Disagree
Reverse logistic program	○	○
Specific markets for waste materials	○	○
Reprocess, downcycling	○	○
Alternatives use	○	○
Collection, Separation	○	○
Post consumer waste, incinertion	○	○

Round 3 (Elements Agreement test):

How likely are you to consider relevant and applicable the CE elements below in the PDP in the concept phase?

	Not at all likely		Neutral		Extremely likely
	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Avoid schedule obsolescence	○	○	○	○	○
Shared ownership	○	○	○	○	○
Passive products	○	○	○	○	○

How likely are you to consider relevant and applicable the CE elements below in the PDP in the development phase?

	Not at all likely		Neutral		Extremely likely
	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Avoid schedule obsolescence	○	○	○	○	○
Shared ownership	○	○	○	○	○
Passive products	○	○	○	○	○

How likely are you to consider relevant and applicable the CE elements below in the PDP in the production phase?

	Not at all likely		Neutral		Extremely likely
	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Upgrading process	○	○	○	○	○
Large scale	○	○	○	○	○

How likely are you to consider relevant and applicable the CE elements below in the PDP in the utilization phase?

	Not at all likely		Neutral		Extremely likely
	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Upgrading process	○	○	○	○	○
Large scale	○	○	○	○	○

How likely are you to consider relevant and applicable the CE elements below in the PDP in the disposal phase?

	Not at all likely		Neutral		Extremely likely
	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Recycling rate	○	○	○	○	○
Stringent recycling activities	○	○	○	○	○
Common remanufacturing standards and its definition	○	○	○	○	○