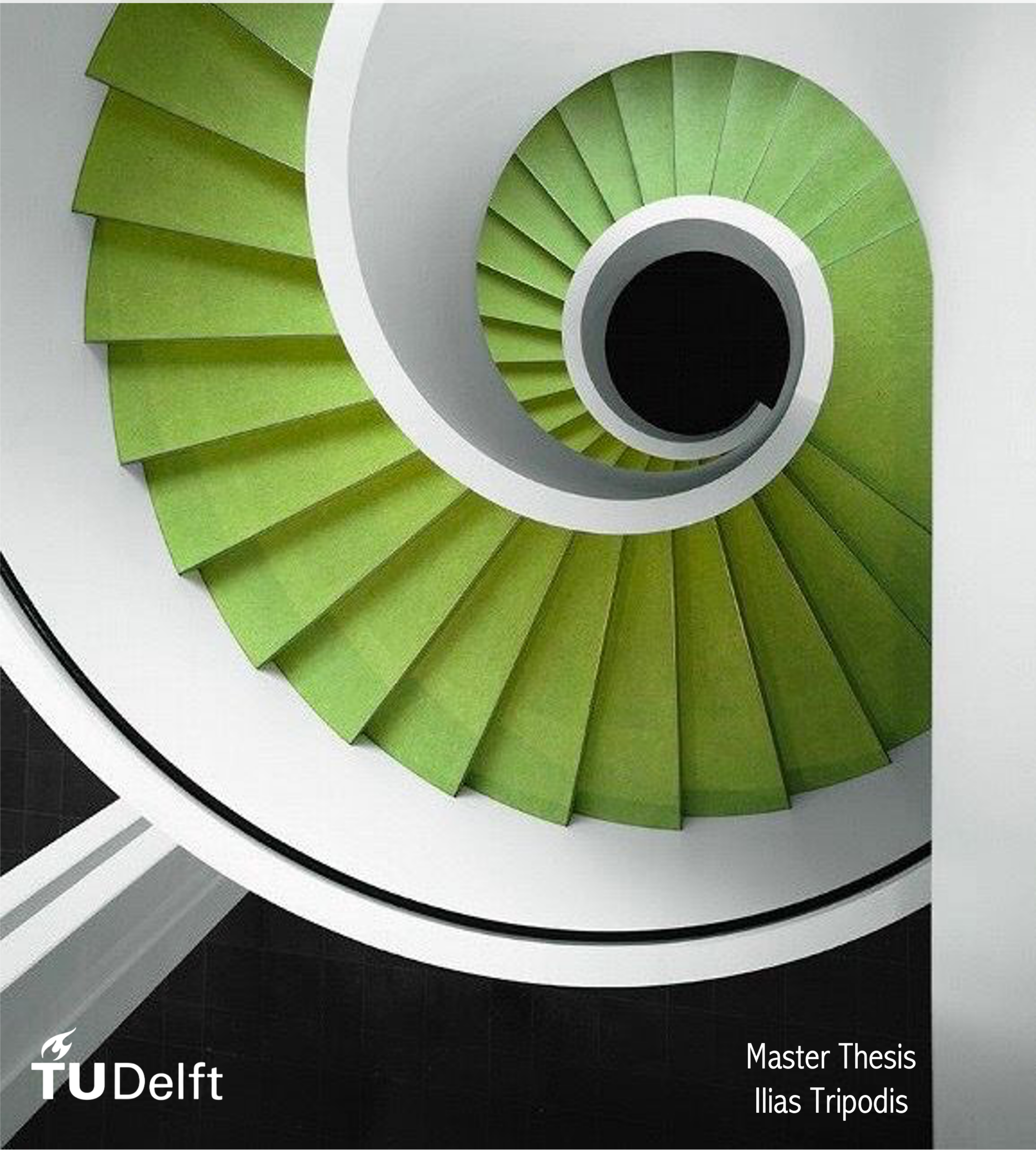
Integrating Circular Strategies and Industry 4.0 Technologies to assist Manufacturing Firms in the transition towards Circular Business Models



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Integrating Circular Strategies and Industry 4.0 Technologies to assist Manufacturing Firms in the transition towards Circular Business Models

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"Circularity represents the profound wisdom of nature, where every end is a new beginning, and what we perceive as waste becomes the catalyst for regeneration and renewal."

- Dr. Leyla Acaroglu

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As the journey of my master studies comes to an end point, I stand in awe of the knowledge gained and the experiences acquired along the way. During this path, numerous individuals have contributed to my growth and the realization of my academic milestones, therefore I would like to express my heartfelt appreciation to each and every one.

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Executive Summary

In today's society, the emerging need for resources efficiency and energy conservation has become a prominent and widely discussed topic among businesses, countries and territories. As the environmental challenges intensify, the concept of circularity has gained significant momentum due to its potential on addressing these concerns and driving sustainability. By designing business models that prioritize the preservation of the resources, companies can significantly reduce their ecological footprint while creating additional economic value compared to a traditional linear business model. A key enabling force in this transition comes from the side of technologies which are booming within the Industry 4.0 era, a revolution characterized by automation, connectivity, and data-driven processes. By harnessing the power of digitalization and innovative technologies, companies can achieve greater sustainability, reduced waste generation, improved resources efficiency, and enhanced competitiveness.

However, despite the plethora of circular strategies and Industry 4.0 technologies available, companies face challenges and confusion in selecting the most effective approach to achieve circularity within their business models. This issue is particularly relevant in the manufacturing sector, which accounts for substantial resource and energy consumption and calls for immediate solutions within the circularity mandate. The implementation of circular business models is still limited and scarcely observed in this sector, despite the high demand for resource reduction and loop-closing. Existing research on the circular economy often focuses on individual businesses and products, lacking a comprehensive conceptualization of circular business models and their interactions with the external environment. Furthermore, the transformative potential of Industry 4.0 technologies in facilitating circularity is not yet fully understood and calls for further investigation. Connecting the various perspectives and understanding their interconnections can unlock ample potential for building knowledge and facilitating manufacturing firms to enter a circular future.

The purpose of this study is to investigate how circular strategies and Industry 4.0 technologies can facilitate the transition of manufacturing companies towards circular business models. By developing a deeper understanding of the interconnections between circular strategies, business model elements, and novel technological advancements, this research aims to provide clarity and structure the knowledge around those literature streams. This is purposed through the development of an all-encompassing framework which theoretically conceptualizes how the circular business models should be structured from the perspectives of the company, the value chain and the technologies. Based on this tool the aim is to provide practical guidance for manufacturing entities seeking to embrace circularity. The ultimate goal is to drive sustainability, resource efficiency, and competitiveness within the manufacturing sector while paving the way for further research and exploration in this interdisciplinary domain.

To reach the research objectives a methodology of three steps has been employed. Firstly a structured literature review provided with a comprehensive understanding of the various concepts and how those have been applied in relevant circularity frameworks. Through a three-step approach which includes literature data collection, relevance evaluation and reporting it was possible to identify and define the circularity principles as well as the capabilities of the Industry 4.0 technologies. The framework development serves as a second stage where the concepts from the literature are categorised and integrated into a structured framework. This framework serves as a practical tool for analyzing and designing circular business models combining the contexts of Industry 4.0 technologies and value chain for a more holistic perspective. To validate the framework and evaluate its applicability case studies were structured. This performed through the implementation of the developed framework into real businesses in order to align theoretical reasoning with practical insights. The cases involve engaging with industry practitioners to gather qualitative data on their experiences, building a conceptual circular business model and refining the framework based on qualitative analysis. Overall, this methodology aims to provide a comprehensive understanding of the circular economy concept and its application in developing business models that promote the "loop closing" trend. By combining rigorous academic research methods with practical insights, further contributes in advancing this holistic understanding.

Through the literature five core circular strategies were identified, the greening, narrowing, cycling, extending and intensifying. Under those strategies several circular actions were mapped as enabling practices leading to a clear understanding how the different concepts are defined and connected. The strategies were further studied from the perspective of their contribution in the circular value where connections emerged with the three components of a business model, the value proposition, creation, delivery and capture. Additionally, the capabilities of the Industry 4.0 technologies were identified and divided based on their contribution for enabling the various circular strategies. The concept of circular value chain was also comprehended from academic and secondary practical resources leading to the identification of the stages and the practices implemented along them for closing the resources and energy loops.

Based on these, the Hybrid Circular Business Model - Tech framework was constructed with three perspectives, namely the circular business model elements, the strategies along the value chain and the Industry 4.0 technologies. The circular strategies were connected to the circular business model elements through the practices and the circular value. Those elements are defined in a dynamic way, representing its potential structuring for enabling circular business models implementation. The strategies were further linked along the circular value chain through the identified and clustered practices in the literature. Finally, the dimension of the Industry 4.0 technologies was connected to the circular business models through the circular value components. Digital data technologies, for instance, the Internet of Things, big data and artificial intelligence technologies as well as additive manufacturing seem to have the greatest contribution in the circular value proposition, creation and delivery (customization, data collection and information management) while the blockchain technology in the value capture (transparent circular transactions).

The case studies (four Dutch manufacturing companies from different industries) have shown that the manufacturing sector is keen on implementing circular business models due to the need for immediate resources and energy minimization. Additional key drivers for circularity among the cases were its potential for competitive advantage as well as financial benefits through additional revenue streams. On the other hand the challenges towards circularity concern more the lack of knowledge on the topic, customers motivation and trust but also cost-related barriers. The studies identified two critical aspects on the side of the value chain concerning circularity, one emphasizing the need for a reverse logistics stage and the second highlighting the greening strategy as the one able to be implemented along all stages. Additionally, the cases showcased different circular business models structuring and technological requirements according to the context of each firm which were all covered by the proposed framework. As revealed, the framework is an all-encompassing tool for the ideation and guidance towards circular business model structuring. Based on the expert's insights the elements of the framework have been refined so it can effectively support further implementations in manufacturing firms aiming to transition towards circularity.

In conclusion, this study has made significant contributions to the understanding of circularity by directly linking the elements of the business model with circular strategies and practices. The categorization process and analysis presented in this research provide a novel perspective on the landscape of circular economy around businesses which not only relates to the internal environment but also incorporates the value chain view encompassing also the network perspective. Additionally, the study highlights the role of Industry 4.0 technologies as drivers for circularity and their connection to circular business models through the value proposition, creation, delivery, and capture. The framework developed in this study enriches the theoretical intersection between circular economy business models, Industry 4.0 technologies, and the circular value chain while paving the way for integrative approaches in future research. Further, it has been successfully implemented in real cases, demonstrating its potential on the practical side while allowing practitioners to ideate and build potential circular business models. As a whole, the Hybrid Circular Business Model - Tech framework serves as a valuable starting point for manufacturing firms to make informed decisions in their transition from a linear to an integrated circular alternative. It provides practical guidance and empowers practitioners to embrace circularity and foster sustainable practices within their organizations.

List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
BM	Business Model
BMI	Business Model Innovation
CBM	Circular Business Model
CE	Circular Economy
CPS	Cyber-Physical System
EMF	Ellen MacArthur Foundation
HCBMT	Hybrid Circular Business Model Tech
I4.0	Industry 4.0
IoT	Internet of Things
MECE	Mutually Exclusive, Collectively Exhaustive
ML	Machine Learning
MoT	Management of Technology
PaaS	Product-as-a-service
R&D	Research and Development
RFID	Radio Frequency Identification
RQ	Research Question
SBM	Sustainable Business Model

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1 Introduction

This introductory chapter provides an overview of the research area and information highlighting the current status of circularity. Additionally, this chapter outlines the problem statement, research scope, research objectives, and research questions, focusing on the role of technologies in facilitating the transition towards circular business models.

1.1 Background

One of the most debated and discussed terms of the last decade concerns the Circular Economy (CE) in the manufacturing sector which is heavily pushed by regulations and initiatives to become greener and embrace sustainability. This trend has been recognized as an action towards sustainable manufacturing and production processes with the aim to minimize the resources consumed (Velenturf & Purnell, 2021). More specifically, the focus of a circular economy is to develop closed-loop supply chains based on CE strategies which suggest the reduction, reuse and recycling of materials or products (Heshmati, 2017). This approach allows the manufacturing sector to adopt sustainable production methods and re-design its business models in order to enable efficient use of resources and effective value delivery and capture (Han et al., 2020).

The CE is a model which supports the re-generation of materials and products at the end of their life while in parallel allowing for economic returns and additional revenue streams for companies which adopt relevant actions (Piscitelli et al., 2020). The CE has been studied from the perspective of alternative actions with regard to the product's life cycle improvement and lengthening. Those actions range from efficient use of resources to product life extension, remanufacturing and reuse of materials or products (Bakker et al., 2021). According to Potting et al. (2017) the CE extends beyond recycling with a framework presenting 10R strategies (recover, recycle, repurpose, remanufacture, refurbish, repair, re-use, reduce, rethink and refuse) that has been developed to showcase the various approaches that could be aimed for circularity.

To adopt those CE practices, firms have to alter their linear business models to circular ones in order to follow the sustainability trends, satisfy their customers and achieve the economic benefits the circular economy entails (Abdul Rehman Khan et al., 2022). Those business models differ from the linear business models since the relationship between the customer and the manufacturer is not ending when a product is sold but rather continues in a circular way to maximize product life and minimize waste (N. M. Bocken et al., 2016). The circular business models (CBM) are key enablers of circular practices and targeting in resources efficiency without discounting the value for both the customer and the firm (Lahti et al., 2018). Based on the various CE principles, different CBMs emerge which can be applied throughout the product's life cycle, providing circular value before the product reaches its end-of-life (Muller et al., 2022).

Nowadays, there are big efforts from the manufacturing sector trying to implement circular business models rendering, in that way, the linear business models obsolete. However, only a few manufacturers have successfully adopted CBMs since internal and external barriers hindering its implementation are still present (Hina et al., 2022). Overcoming those barriers is critical for companies which aim to accelerate their transition to CE and enhance their position within the market. Challenges are being recognised both in the internal and the external environment of a company considering in that way processes, stakeholders, policy frames, actions, resources and incentives. To start with, the lack of collaboration between organizations has been stressed as a significant hindering factor for the adoption of CBMs since companies belong to a broader supply chain network where interrelationships are necessary for closing the resources loop (Guldmann & Huulgaard, 2020). Notwithstanding, are also the technological barriers mentioned especially in the product design for circularity, the supply chain information exchange and the quality assurance at the end of products life (Vermunt et al., 2019). An additional barrier blocking the implementation of CE within a business setting is related to a lack of knowledge and incentives. This knowledge dissemination among firms is necessary for building CBMs, designing new offerings for the customers and achieving faster the sustainability goals (Salvioni et al., 2021).

A potential enabling factor for CBMs and a supporting tool in the agenda of manufacturers have proven to be a trend which refers to the booming of Industry 4.0 (I4.0) technologies (Neligan et al., 2022). This trend concerns the transition of traditional manufacturing to more advanced and technologically oriented processes and production techniques which allow for more efficient results and products (Rosin et al., 2019). This transition is progressing within a greater sustainability mandate calling for synergistic circular economy and technological applications in order to further reduce resource consumption and ecological impact (Kumar et al., 2020). The role of the technologies in the CE era can be seen in terms of capabilities for the manufacturing sector to enhance resources efficiency, cut on waste and create value from recycled and refurbished materials and components. For instance, I4.0 technologies such as blockchain and the Internet of Things (IoT) can increase customer trust, support networking with suppliers through data collection, and enhance quality control of the products in a transparent and secure way (Neligan et al., 2022).

The digitalization of the industrial sector extends further with the implementation of cyber-physical systems and digital technologies aiming to optimize processes, enhance production efficiency and increase the options for scalability (Zheng et al., 2020). Additionally, big Data and Additive Manufacturing (AM) can be used in recycling and material reuse processes while IoT technology can be an enhancing force for remanufacturing and services development. Application of such technologies can reduce barriers towards circularity and sustainability and assist CBM development (Rosa et al., 2020). The main problem in this transition is that the interface between the I4.0 technologies and the CE is not entirely covered since the adoption of CBMs is not widely implemented by the manufacturing sector. In that way the capabilities of the Industry 4.0 technologies within the circular value share have not entirely been covered which opens paths for further research (Hennemann Hilario da Silva & Sehnem, 2022). In addition, it is still fading how the I4.0 technologies can support the business model elements and add value to companies aiming to transition towards circular activities. Managing of the technological advancements to enhance CBM adoption is a topic that is receiving a lot of academic and business attention and therefore it is wise to touch upon this topic, for paving the way towards a sustainable future.

1.2 Problem Statement

The sustainability mandate is calling for immediate actions for resources and energy minimization in order to achieve the climate goals being set for 2030 (United Nations, 2022). Those objectives can be admitted via circular economy strategies that can close the resources loop and enhance the value landscape of the business in a broader sense. Up until now, only a few initiatives have been taken by companies which implement practices in order to optimize resources consumption and yield the economic benefit it may entail. This phenomenon is especially problematic when considering the manufacturing sector which is responsible for the major share in resources and energy utilization due to the constant production processes. Therefore, the adoption of circularity in this sector is necessary to reach a certain level of sustainability.

Different approaches and business models have been created to support the transition of the manufacturing sector from a linear consumption to a more closed-loop approach. With that means, various circular business models have been developed and discussed in a conceptual level but have rarely been tested in practice to admit their economic and ecological benefits. One of the main reasons for this scarcely observed adoption by the manufacturing sector is the lack of structured knowledge behind the circular principles and their implementation in a product or a service. For manufacturing firms, it is still blaring what are the various circular strategies and how those can be applied in a sense that will provide value not only to the firm but also to the potential customers and the environment. A well-recognised practice among manufacturers is the recycling of materials and parts but a plethora of different options needs to be exploited in order to admit value that is currently being wasted.

Since the climate urge is forcing firms to become more circular, the need for accelerating the adoption of CBMs is undeniably a top priority for firms and policy makers. Industry 4.0 technologies can play a significant role in increasing the speed towards circular actions but how those technologies can be leveraged remains open for further exploration (Hennemann Hilario da Silva & Sehnem, 2022). Knowledge dissemination is therefore needed on the capabilities of the technologies and how those can serve an enabling factor role in the introduction of circular practices within a business frame. The identified gaps that need to be explored and filled in this thesis are summarized in the following sentences.

- There is a lack of understanding of how circular strategies can structure the elements of a circular business model and create value in a closed-loop manner. In addition, understanding how I4.0 technologies can enable the aimed value is seen as a missing dimension from circular approaches.
- Knowledge is missing on which circular strategies can be applied along a firm's value chain to change it from a linear to a circular perspective.
- There is a need for a tool that could assist manufacturing companies in ideating on how they could implement circular business models and I4.0 technologies in order to enhance their value proposition, value creation, delivery and value capture landscape. In addition to that, the practical use of this tool in a real-life setting is also a missing point that needs to be considered in order to align academic and business philosophies.

1.3 Research Objective

The topic of circular economy is broad and can be applied in different business settings that include resource-intensive processes and energy consumption. As discussed, one of the most relevant sectors to conduct research regarding strategies towards circularity is the manufacturing and especially the technological cluster due to its flexibility and innovation-oriented mindset. The same applies to alternative manufacturing business entities in the Netherlands which allow for broadening the scope of the research in multiple industrial clusters that actually implement or plan to implement a circular perspective in their business models.

The main objective of this study is to assist manufacturing firms accelerate their transition towards circularity. To achieve this, a deep understanding of the various strategies used in the literature is aimed in order to build a structure for implementing them in business settings. An additional objective of this research is to connect the various strategies with the components and elements of a circular business model in order to introduce suggestive options for manufacturers which embrace the benefits of circular economy in a broader sense. A connection will be also aimed between the value chain stages and the circular strategies in order to make the former be structured in a closed-loop view. Including the value chain perspective is highly relevant since the companies are not sovereign and act in a network, therefore insights in that matter will be key for a holistic view of circularity. To accelerate the adoption of CBMs, in this thesis, it is also intended to link the technological aspect with the concept of circularity through the capabilities that can be offered for enabling CBM and innovation.

Successfully obtaining the aforementioned objectives and exploring how circularity can be admitted from a business model, technological and value chain perspective, will lead to the final aim of this thesis. This includes the development and practical application of a business circularity tool which will allow companies to envision different circular strategies and structure a business model to embrace the circularity benefits. With this tool, the manufacturing firms will be also able to structure their knowledge around the potential strategies that can be applied in a circular value chain as well as ideate on the potential technologies that could assist them advance their circular outcome and their offerings to the customers.

1.4 Research Questions

This study is initiated based on the structured knowledge missing in the literature as well as on the lack of a comprehensive tool to assist companies with their circular economy objectives. To achieve a level of directionality, research questions have been formulated for guiding the study and the objectives. The research questions serve as an exploration point which revolves around the concept of circular economy business models and the technologies of the Industry 4.0 era. The main research question of this study is presented as follows.

How can circular strategies in relation to Industry 4.0 technologies contribute to the transition of manufacturing companies towards circular business models?

To further guide the objectives of the study, individual questions have been formulated aiming to build up knowledge towards answering the main research question. Those questions are answered throughout the thesis in order to give an understanding of the different concepts that have been analytically studied. Bellow a list is presented with the necessary to answer questions leading to the main research question.

- RQ1: What circular strategies can lead to circular business models?
- RQ2: How do Industry 4.0 technologies contribute to the implementation of circular strategies and circular business models?
- RQ3: How do circular strategies in relation to Industry 4.0 technologies assist Dutch manufacturing companies on the transition towards circular business models?

The purpose of the research questions is to create a logical narrative in the field of Industry 4.0 technologies, circular strategies and circular business models which will provide information for building a comprehensive framework for manufacturing companies. In that sense, the various research questions will be answered in order to retrieve information which will assist in defining the building blocks for constructing a framework and answering the main research question.

2 Literature Review

This chapter is dedicated to the study of the literature in a sense that provides a clear understanding of the circular business model concept, the various circular strategies as well as the capabilities Industry 4.0 technologies can offer to support the transition towards those models. In an effort to follow a narrative, the section describes every concept in terms of literature found and comprehended accordingly. This structure extends throughout the section that follows bellow.

2.1 Business Models

Each firm is characterised by specific strategies and aspects related to its products or services that need to be communicated both to its internal and external environment in order to give a direction and purpose. Therefore, the concept of business model was developed as a "messenger" of the firms' strategies and processes. This concept revolves around value that a company creates and delivers to its customers along with the mechanism involved to allow those elements (Teece, 2010). As a conceptual framework, the business model targets into bridging the offerings of the company (value created) with the needs of its customers in order to provide them novel solutions (value delivery) which will purchase to receive the benefit (value capture). This indicates that the major elements of the business models relate to mechanism and tactics used by firms along with its directions and activities in an organizational as well as a stakeholders' level. Approaching the business model as a company logic based on value, the key components that can be identified refer to the value proposition, the mechanism for creating value, the delivery of that value to the customers and thereafter the capture of the economic benefit through revenue structures (Shakeel et al., 2020).

Those key components of a business model serve a different role within a firm and are dedicated to its objectives, its purpose and the relationships with its customers, financial and non-financial. To be more specific, the roles of each component and its purpose in the business model have been recently defined by Shakeel et al. (2020) and are listed as follows.

Value Proposition
This component of the business model refers to the value that can be offered by the firm to the customers and is the unique shelling point which distinguishes the company from its competitors. With its capabilities, the firm is aiming at providing to the customers a product or a service which could be of benefit for the targeted customer group. Along with the product/service offered, the company indicates how this provision can be valuable and how it will benefit the customer in any manner, organizational, functional or financial. The value proposition is therefore a message to the customers which highlights the capabilities of the offering and the potential results it can entail to the customer if purchased.

Value Creation
An additional component of the business model is the way the company creates the value promised to the customers through the value proposition. This component includes not only the processes and the internal aspects which create the value of the final offering but also external relationships and decision making strategies. Therefore, the value created and offered to the customers is based on an ecosystem approach with each factor to have a shared contribution.

Value Delivery
The value created should be delivered to the customers through channels and networking. This aspect in the business model is captured by the component named after value delivery. The role of this side of the business model is to indicate how the value will be transferred from the company to the customer. This includes the partnerships in the supply chain, the methods to be employed and the activities which will serve as delivery options, for instance order processing, customer support, fulfillment/satisfaction, etc.

Value Capture
The last and one of the most important components of a business model is the value capture which defines how the customer will pay for the product or service delivered. The value capture refers to the financial

models employed by the firm in order to generate revenue streams from the value created and delivered. This also includes the cost structure, the pricing and the financing tools which are purposed to make the customer pay for the value delivered to them.

The key components of a business model are not only limited to the three aspects mentioned but can be further divided into specific elements. Each element relates to a specific section and activity within a business and describes how value is admitted and recognized. A tool which conceptualizes the various elements of a business model and is widely used due to its practical aspects, is the business model canvas as developed and presented by (Osterwalder & Pigneur, 2010). This framework consists of nine elements which are positioned under the three primary value components, value proposition, creation & delivery and capture. The value proposition component relates to the offering of the product or service, the customer segments and relationships, while the value creation and delivery considers the partners, the resources and the activities as well as the channels to connect with the customers and deliver the offering. The remaining elements considers more the financial side and consists of the cost structures and the revenue streams as mechanisms for capturing the value.

A more comprehensive approach categorizes the business model elements in three main components which take into consideration the customers and market, the value creation dimension and the strategy of the firm (Wirtz, 2020). Each component consists of three sub-components which in total structure a business model with nine core elements. The two approaches mentioned above have commonalities in terms of elements framing the business model which are presented in Table 1. Through the table the nine most commonly used business model elements are being highlighted for further use in the framework to be developed within the scope of this thesis.

Table 1: Overview of business model elements.

Retrieved from: (Osterwalder & Pigneur, 2010)			Retrieved from: (Wirtz, 2020)
Value Proposition	Product/Service Offering	**Value Offering (product/service)**	**Customers & Market**
	Customer Segments	Target Group	
	Customer Relationships	**Customer Relationships**	
Value Creation & Delivery	Channels	**Channels**	
	Key Partners	**Network & Partners**	**Value Creation**
	Key Resources	Core Competences & Assets	
	Key Activities	Manufacturing & Procurement	
Value Capture	Cost Structures	**Cost Structure**	**Value Creation**
	Revenue Streams	Financing Model	

2.2 Business Model Innovation

To keep its competitive position in the market, a firm needs to continuously innovate and differentiate from its counterparts. In that sense, companies need to redefine its core objectives and modify its activity system in order to introduce new practices which will sustain its overall position and performance. The innovation could be aimed in the products or processes, but business model (BM) related innovations have proved to be more effective for the firms who initiates a change of that type (Geissdoerfer et al., 2018a). Innovating the business model is based on developing additional capabilities which will assist the company adapt to changing customer needs and arising competition (Shakeel et al., 2020).

The change of the business models in terms of innovation is focused on repurposing the value that have been previously offered to the customers as well as the ways the new value will be delivered and captured. In that sense, the business model is newly structured to serve demanding customers and markets. Therefore, companies are constantly searching for new ways of satisfying the customers and generating profit in parallel. This is performed through sensing opportunities that have been neglected or left unexploited (Blomsma et al., 2019). Thereafter, through business model innovation (BMI), businesses try to develop new business models aiming to make use of the identified opportunities, in different combinations and ways, reframe the value offerings and develop new capture mechanisms.

To structure a business model which will bring additional value to the company or change the existing one, companies have to undergo an innovation process (N. Bocken et al., 2019). BMI is an iterative process with four distinct phases which starts from the initiation of the change, followed by the ideation and the integration phase while ending with an actual implementation of the innovative business model within an organization (Frankenberger et al., 2013). The ideation phase is usually the focal point of a firm where an opportunity in the market or the surrounding ecosystem is translated into a valuable business idea. This can be considered as the foundation for an innovative business model which will give the firm the opportunity to differentiate from its competitors and seize strategic opportunities (Pieroni et al., 2019).

2.3 Sustainable Business Models

Apart from the firm itself, BMI considers also aspects which relate to social and climate-oriented mega-trends. The last decades the increased competition and the changing market demands have brought sustainability on top of the list as a point of awareness. Within its BMs, firms are trying to innovate in a way that considers both the value aspect (for the firm and the customer) as well as the sustainability dimension as longevity target. This type of BMI is aimed at changing the currently used traditional/linear BMs with models which bridge the firms' value with that of the various stakeholders and generate a long-term sustainable solution (Geissdoerfer et al., 2018b). With a sustainable business model (SBM), the firm can aim for sustained competitive advantage while changing its value to a sustainable value.

As a product of innovating within the BM terrains, the SBM is a model which aims at integrating multi-stakeholders views and creating long-term and sustaining monetary and non-monetary value (Shakeel et al., 2020). In that sense, the SBM entails the alignment of the classical business model elements of value proposition, creation, delivery and capture with the concept of sustainability which surpasses the nexus of financial benefits and aims at a wider range of value acquisition through various stakeholders (N. M. Bocken et al., 2016). Based on the review of (Nosratabadi et al., 2019) an additional perspective is included in the definition of the SBMs which relates to the consumption by the end-users in a sustainable and incentive-based manner. Taking into consideration all the aspects mentioned in the literature from the various definitions, it is clear that the SBM are encouraging stakeholders' interaction aiming for an ecosystem-based longevity. With that means, the sustainability principle is integrated within the organizations value logic elements but also extends to stakeholder management for prolonged value co-creation (Geissdoerfer et al., 2018a).

The term sustainability is also relevant to the preservation of the natural environment, a topic which has recently started to pose obligations for the companies to act responsibly. Since the environmental issues are growing due to depleting raw material resources and the climate change, companies should also incorporate the aspect of environmental sustainability in their activities. This calls for reinvention of the BM components in order to incorporate both financial, social and environmental value (Geissdoerfer et al., 2018a). For that purpose, sustainable BMI focuses on creating, delivering and capturing economic, societal as well as ecological value in one all-encompassing business model. Based on this triple-line perspective, sustainable business models development or implementation is highly aimed by companies as a strategic action for creating sustainable value and a resilient face towards environment (Comin et al., 2020). At that point it is worth mentioning for clarity purposes that the concepts of BMI and sustainable BM are interconnected with the former to set the foundations required in order to develop various BMs which incorporate all the aspects discussed. The relationship of moving from a linear business model configuration to a sustainable BM and thereafter to a circular business model can be illustratively explained as shown in Figure 1.

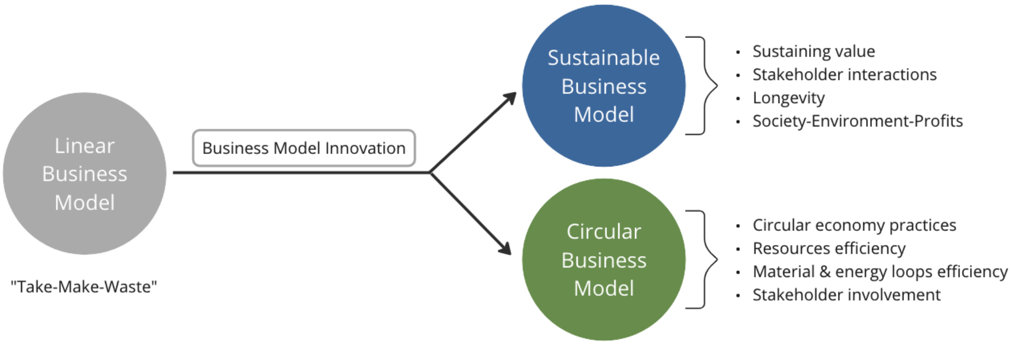

Figure 1: Logical sequence of steps from a liner business model to a sustainable and circular business model. (own interpretation)

2.4 Circular Business Models

A result of the sustainable BMI is the development of models which embrace the environmental consideration and set circularity in the core of the company practices. Those models are named after circular business models which prioritize resources efficiency and waste minimization. Based on the paradigm of circular economy the CBM are defined as models which aim to reduce resources flows and closing the loop of material usage by integrating circular practices within the components of a BM (Oghazi & Mostaghel, 2018). The circular economy practices are known as R strategies which represent the actions performed in order to enhance circularity. Those R practices are ranked from low to high initiation of circularity based on the threefold categorization presented by Potting et al.(2017). The three main categories relate to i) the product use and manufacturing which includes practices such as refuse, rethink and reduce, ii) the product lifespan extension which incorporates practices such as reuse, repair, refurbish, remanufacture and repurpose, and iii) the materials applications which consider the recycling and recovery aspects.

In that term, the CBM entails a combined environmental and economic benefit which derives from the different circular practices for resources efficiency. More specifically, this benefit is translated into minimal environmental impact and cost reduction due to resources efficiency and can be captured from both the company and the customers. Under the umbrella of BMI, several CBM have been developed with different perspectives of what value means and how it is entirely leveraged. According to Bigliardi and Filippelli (2021) CBM integrate the circular economy practices within the business model components in order to generate additional value through recycling, repurposing and reuse of materials or products. In that way, the initial value created can be further utilized even at the end of the life cycle of the product. Value can also be created before the product reaches its end of life ensuring in that way resources minimization and energy efficiency. The CBM are therefore models which focus on creating, capturing and delivering value of products or materials throughout the whole life cycle (Bigliardi & Filippelli, 2021). By implementing a CBM, companies are not only showing its ecological consideration but also strive for additional value through multiple non-waste loop.

The additional value to be created, calls for interaction and collaborations between the various stakeholders along with its willingness to change into a closed loop scheme. While changing its BM to more circular practices, the firm should also consider the effect this change might have on the entire actors' network. Therefore, the CBMs which support the closed-loop philosophy are highly related to network collaboration in order to create value for all the actors involved (Bigliardi & Filippelli, 2021).

Based on the findings in the literature, the CBM are considering multiple aspects ranging from value attributes to actors/stakeholders, sustainable development and circular strategies. All those aspects should be considered in an all-encompassing definition which clearly explains the aims, objectives and characteristics of a CBM. To do so, multiple definitions from the literature (most cited) have been extracted and summarized in Table 2.

Table 2: Summary of circular business model definitions.

Definition	Comment	Publication
A CBM is based on using the economic value that remains after the use of a product for the creation of new offerings. This assumes that the users will return the product to the producer via closed-loop supply chains. Those chains relate with circular practices, for instance recycling, remanufacturing, refurbish, renovation, repair etc.	Only the term closing is mentioned. The value in retained after the use of the product with R practices. The definition is missing the aspect of the stakeholders in the loop closing.	(Lieder & Rashid, 2016)
CBM is defined as the way a firm exploits innovation in order to create, deliver and capture value by applying circular practices, allowing re-alignment of stakeholders to achieve social, ecological and financial benefits.	Innovation is the main driving force for integrating stakeholders, environment and profit. Definition more relevant to the SBM.	(Lahti et al., 2018)
CBM is a mean through which a company redefines its value creation while implementing circular economy practices.	The term “redefine” is mentioned without additional explanation.	(Lüdeke-Freund et al., 2019)
A CBM is a holistic system of collaborative managerial actions for collective value creation, delivery and capture which lead to sustainable solutions.	Assumes sustainable development through managerial practices. More relevant to SBM definition.	(Ünal et al., 2019)
A CBM is a BM which considers cycling, extending, dematerializing and intensifying of resources loops (energy and materials) as a mean to reduce input and output losses to and from an organizational system.	Includes circular strategies of slowing, closing, dematerializing and intensifying. Covers the range of circular practices. Mentions organisational systems as an actor's system.	(Geissdoerfer et al., 2020)
A CBM is based on four logics for efficient and effective value creation which are, material-technical loops, product-service loops, social-collaborative loops and symbiotic ecosystems.	Focuses on efficiency and effectiveness in resources loops. The energy recovery aspect is not clearly stated.	(Fehrer & Wieland, 2021)

According to the summary Table 2 the definition that incorporates the circular economy strategies, the value logic as defined by (Zott et al., 2011), the aspects of the stakeholders and the ecosystem as well as the business model dimension with its broader financial objectives, is the one proposed by Geissdoerfer et al. (2020). This definition will be the one that will accompany the present work where required.

2.4.1 Circular Strategies

As mentioned in the definition of a CBM, circular practices are being implemented via circular strategies. Companies that decide to move towards a CBM are based on those strategies which allow them to build the new model and efficiently use the resources loops in a circular manner. Circular strategies have been existing for long, but as stressed by Brendzel-Skowera (2021), its implementation is scarce among industrial clusters which lack awareness of their characteristics and how those could affect the elements of a business model.

Resources efficiency can be achieved not only by recycling products but also by changing the material/energy loops and the way the company creates, delivers and captures value. According to N. M. Bocken et al. (2016), resources efficiency can also be aimed via product life extension practices as well as by changing the way products are exploited by customers (narrowing practices). Each strategy has different characteristics and purposes with their common goal to be value creation and resources minimization. The closing, narrowing and slowing strategies are mainly purposed for products or materials already in use aiming to extend their value. However, circular economy practices can be exploited even before that stage without the product being introduced in the market. According to Geissdoerfer et al. (2020), product dematerialization can be considered an additional circular strategy aiming at substituting the product with a service which can offer the same benefits and value.

Additional circular strategies could be linked to the product's design in a sense that slowing and extending its use and cascading for different purposes (Moreno et al., 2016). In addition, the upgradability concept is stressed by Khan et al.(2018) as a potential circular strategy. This strategy is purposed at designing a product with the aim to carry upgrades in order to expand its life span. In a broader sense, the upgradability concept fits under the extending strategy as described by N. M. Bocken et al. (2016). Further studies on the circular strategies revealed that circularity is not achieved only by resources efficiency but also through incentivizing the customers to reduce consumption (Nußholz, 2017). Demand reduction can fall under the narrowing concept in the sense that the need for a product can be substituted with an alternative component or service (Geissdoerfer et al., 2020).

Since the products are being offered to customers and distributed through a network of suppliers, circular strategies are also applied in an ecosystem perspective. According to Geissdoerfer et al. (2020), an additional circular strategy considers the use of the product by multiple users. Intensifying product use adds to the circular economy since fewer products need to be manufactured. With that matters, the products are being used in a collaborative manner which increases the overall value offered and lengthens the duration of its life cycle (Planing, 2018). Besides the customer aspect, circularity also entails a sustainability dimension which is usually neglected from the strategies perspective. With regards to Konietzko et al. (2020), a strategy identified to be important for achieving circularity is that of regenerate which is related to the physical ecosystem sustaining and the use of renewable energy. This strategy is added in the agenda of circular strategies as an action to promote green development and incentives to use clean energy for operations, production and distribution of products.

Throughout the literature, different naming is used to describe the strategies mentioned therefore aligning the names would give a clear view on the different taxonomies. Based on their characteristics the closing strategy can be also referred as cycling, while the slowing of resources loops can be also named after extending strategy. The intensifying strategy is not given any additional naming in the literature since it is considered as unique circular economy practice with a specific purpose. The narrowing approach is considered as a separate strategy which promotes dematerialization and resources reduction. However, according to Geissdoerfer et al. (2020), the dematerializing could be considered as part of the narrowing approach since transforming a product into a service automatically reduces resources used. Finally, the greening (regenerate) strategy is mainly focused on sustainable processes and natural ecosystems which can be also a distinct strategy in the circular economy sphere.

With this new perspective, the strategies which can be considered as pillars for the circular business models are extending within five aspects, the characteristics of which are summarised in the following Table 3. Knowing the characteristics of each strategy is crucial in order to understand how business models are defined and how those can be applied later along the value chain.

Table 3: Summary of description and characteristics for the circular strategies.

Circular Strategy	**Description**	**Characteristics**
Greening (regenerate)	Using of renewable energy and regenerating the natural ecosystem.	The greening strategy is purposed for businesses which relate on natural resources and need to sustain ecosystems for both a financial and environmental perspective. It also promotes the use of sustainably produced energy for production, logistics as well as product use.
Narrowing	Reducing the usage of resources and the demand for product. Where applicable, dematerializing the product with the provision of a service.	This circular strategy aims to reduce the use of materials by designing products that require fewer materials, using alternative materials, and digitizing products and services. It promotes a demand reduction and service vs. product, which reduce resources usage and environmental impact.
Cycling (closing)	Creating a circular flow of resources where materials are recovered, recycled, and returned to the production process.	This circular strategy aims to keep products and materials in use for as long as possible, by designing products for durability, facilitating repairs, and reusing or recycling materials. It promotes a circular economy that minimizes waste and conserves resources.
Extending (slowing)	Reducing the rate at which resources are consumed and waste is generated by increasing the useful life of the product.	This circular strategy aims to extend the useful life of products and materials, by providing repair and maintenance services, remanufacturing, reselling or donating products, and upcycling materials. It promotes a circular economy that reduces waste and conserves resources.
Intensifying	The strategy of maximizing the value obtained from resources by increasing their overall utilization, efficiency, and productivity.	This circular strategy aims to maximize the value derived from products and materials, by optimizing their use, improving their performance, and creating value-added services. It promotes a circular economy that increases economic value while reducing resource use.

2.4.2 Circular Strategies & CBM Value Components

Since the circular strategies of greening, narrowing, cycling, extending and intensifying are in the core of a CBM definition, its relations with the elements of a business model (value proposition, creation, delivery and capture) are direct and intertwined. According to Geissdoerfer et al. (2020) the circular strategies directly affect the business model elements in a way that different configurations can lead to different business models and a different value logic. The interconnection between the business model value elements and the circular strategies is based on the circular practices each strategy entails. When a CBM is being designed, firstly the circular strategy is chosen which consists of various circular practices. Based on those practices, which are actions enabling circularity (e.g., recycling, refurbishing, sharing, design for longer, etc.), the BM value components are reconfigured in order to perform those actions (Geissdoerfer et al., 2020). Therefore, recognising the practices linked to each circular strategy among the published studies is the first step in order to understand how CBMs are being structured. The following subsections briefly introduce the connection of CBM elements with the circular strategies and therefore a comprehensive overview of the literature that has been studied, is listed in the Appendix B.

Greening Strategy and Circular Value

The regenerate or greening strategy has not been studied extensively from the perspective of circularity but it is referenced since it contributes to an all-encompassing approach of the sustainability topic. This strategy entails practices which refer to the local ecosystem regeneration and the use of renewable energy for production, usage and transportation (Konietzko et al., 2020). When considering the value proposition aspect, the scholar argues that the products can be produced based on renewable resources and living materials which make them sustainable. When developing a CBM based on this strategy, the value creation and delivery activities for a company is achieved through building-up of renewables capacity, conducting creative partnerships which promote circularity, restoring polluted ecosystems and offering a product which functions with sustainable energy (Konietzko et al., 2020). The value creates is captured through increased reputation based on the sustainable actions and through savings from using renewable energy.

Cycling Strategy and Circular Value

The cycling strategy entails practices which relate to the material recycling, the cascading usage, the energy recovery and the resources sharing loops within a system (industrial symbiosis) (N. M. Bocken et al., 2016), (Lüdeke-Freund et al., 2019), (Nußholz, 2017). In addition this loop closing strategy is linked with the actions of repurposing, reusing and reselling of the products (Geissdoerfer et al., 2020). To achieve a CBM, the value proposition for the product or service offering is focused on products which reuse materials, driving in that way the cost and resources waste risk down (N. M. Bocken et al., 2016). According to Nußholz (2017) companies incorporating cycling actions in their business model can offer buy-back schemes which intend to close the loop between old products recycling and new products purchasing.

On the value creation and delivery side, implementing a cycling strategy requires take back systems as a way to collect the used products in order to recycle or repurpose them (Lewandowski, 2016). This also includes actions which promote the reverse logistics aspect through customer incentivization and collection points (Lüdeke-Freund et al., 2019). According to N. Bocken and Ritala (2022), creating and delivering value with the cycling strategy can be also aimed through open and close innovation. More specifically, open innovation considers the creation of value through network collaborations while the close innovation refers more to the internal system of creating value through take-back systems. Those network collaborations are key actions for upgrading circularity either in an upstream (internal) or a downstream (supply chain) level (Urbinati et al., 2017).

Capturing the value in CBM which focus on cycling the resources loops is based on savings from resources which are being recycled and reused (N. M. Bocken et al., 2016), (Nußholz, 2017). Within a take-back setting, the value is captured through collection, credit schemes, reselling and waste exploitation (Lüdeke-Freund et al., 2019). The cycling strategy, as mentioned, includes also material trading through industries which can further increase revenue from waste through transaction or trading fees (Whalen, 2019). In addition, the lower price offerings (from repurposed products) and the recycling incentives could increase the customer base and generate further revenue streams. Based on N. Bocken and Ritala (2022), capturing this non-financial value is also important in a CBM for building a strong brand image and reputation in the market.

Narrowing Strategy and Circular Value

Within the concept of narrowing the resources loop, various practices can be employed in order to embrace circularity in a broader sense. From the definition of the term narrowing, the products should be designed in a way that the minimum possible resources are being utilized (N. M. Bocken et al., 2016). Such designs make use of eco-friendly materials (Konietzko et al., 2020) or substitute materials to reduce the input resources and the environmental impact (Nußholz, 2017). An additional activity which can be positioned under the scope of the narrowing strategy is the dematerialization of a product and its offering via a service able to serve the same functionalities (Geissdoerfer et al., 2020).

By applying the narrowing strategy in their CBM, companies offerings revolve around products with reduced material input for environmentally aware customers (Konietzko et al., 2020). Since the narrowing strategy also involves the dematerializing approach, the value proposition is also related to the provision of a service instead of a product which leads to waste reduction and resources saving that could have been otherwise used as hardware components (Geissdoerfer et al., 2020; N. M. Bocken et al., 2016). By reducing the materials used during the production process, the product could be offered in lower prices, reducing in that way the total cost of ownership and the up-front investments.

To create and deliver the intended value proposed in a CBM following the narrowing strategy, scholars argue that customer rationalization for demand reduction is key for resources reduction (Geissdoerfer et al., 2020). In addition, the need for processes optimization is stresses as a key activity for using fewer resources per product and reducing in parallel the footprint on the natural environment where the resources are being extracted (Konietzko et al., 2020). On the other hand, on a service offering aspect, designing a product-service system, implementing technology and enhancing network collaborations are necessary for creating and delivering the intended value (N. M. Bocken et al., 2016), (Geissdoerfer et al., 2020). This value is being created for instance with the offering of a software package which can substitute the functionality of a hardware-based product and provide identical performance while no natural resources and energy waste is required.

Implementing a CBM emerging from the narrowing circular strategy can further create savings and value to a manufacturing firm. This is obtained through cost saving mechanisms since less resources are consumed and utilized during production (N. M. Bocken et al., 2016), (Nußholz, 2017). In such business models, the customer increase is also a mechanism for capturing value through eco-friendly offerings for environmentally concerned consumers (Konietzko et al., 2020). Considering the service provision, Geissdoerfer et al. argues that revenues can be admitted through pricing schemes per service provided or result obtained. In that sense, the value capture mechanism in a product-service system could be implemented in a use-base or result-oriented manner (Urbinati et al., 2017). Customers pay for the service instead of purchasing a hardware-based product which could save resources to the manufacturer and allow for dynamic pricing based on the results or the perceived performance (N. M. Bocken et al., 2016).

Extending Strategy and Circular Value

Circular business models that are based on the extending strategy, reflect on the resources minimization through product utilization for longer period. The life cycle extension strategy is based on practices which tend to repair, refurbish, remanufacture and upgrade the product so it can be used again without wasting its total value (den Hollander et al., 2017). As stressed by Moreno et al. (2016), extending the product life cycle allows for slowing the rate resources are being disposed as waste. This slowing approach in business model allows a company to exploit the residual value of a product after its use and through a maintenance or an after-sale service, introduce the product back in the market (Planing, 2018). Additionally, this strategy is not only referring to the extension of a product's life but also on the designing for longer use and ease for maintenance (M. A. Khan et al., 2018).

The proposition offered from CBM incorporating the extending as a circular strategy is with regards to services for maintenance and performance control (Lüdeke-Freund et al., 2019). Since products are refurbished and recontextualized, its price is reduced without that meaning a discount on the quality and the overall functionality. Therefore, with CBMs that embrace the extending as a strategy, long-lasting and high quality products are being offered, with always-in-style designs (Geissdoerfer et al., 2020). Additionally, Khan et al. (2018), upgradability options is also part of product life extension which allow for adaptability according to the customer needs (adaptable value offering).

In CBMs emerging from the extending strategy, value is being created from the begging of product life where the product are designed to promote durability and longevity (N. M. Bocken et al., 2016). To last longer, products in that stage should also be designed to facilitate maintenance and upgrades in later stages of the life cycle (M. A. Khan et al., 2018). According to Planing (2018), transforming a product into an alternative to serve a different purpose is also a way of value creation and extension in a CBM. From the perspective of value delivery, the extending strategy involves after-sale services and maintenance provisions based on a plan that the manufacturer suggests (Lüdeke-Freund et al., 2019; N. M. Bocken et al., 2016). To enable a high quality maintenance service, companies should build a network which allows them to perform the required repairing and deliver to the customers, a fully functioning as new, product (Geissdoerfer et al., 2020). This network can have multiple roles for instance facilitating recontextualization, redistribution and product remedial, with each stakeholder following a separate life cycle extending business model (Whalen, 2019). Extending the life cycle is not only maintaining and upgrading the products but also knowing when a product needs to be returned and repurposed. As mentioned by N. M. Bocken et al. (2016), using technological capabilities for predicting an making a maintenance plan is a key element for retrieving product value and deliver it to the customers via a long-lasting product.

The value created in a BM which is based on the extending circular strategy is being captured in two ways, either through resources savings and therefore cost savings, or through additional profit streams based on the offered maintenance services. Capturing the extension mattered value of products belonging in a high-quality class is being admitted based on premium pricing, warranties and customer loyalty (N. M. Bocken et al., 2016). Those products fall in the scheme of high-price for high-life and therefore can yield additional profits while saving resources as the product is used for longer (Nußholz, 2017). For lower-value products, maintenance services can lead to resources efficiency, since no new products are being manufactured, and no additional energy is required, which both allow for profit margins in the longer term (N. M. Bocken et al., 2016). On the service provision side, the profit can be obtained through fees for service use or charges for maintenance (as an additional service) (Lüdeke-Freund et al., 2019). Moreover, according to Khan et al. (2018), an additional revenue stream can be created based on upgrading schemes and new features options, which allow the product to be used for longer and the firm to charge for the upgrades.

Intensifying Strategy and Circular Value

Further CBMs can emerge to support the circular economy and its benefit focusing on the use of a product. The intensifying strategy revolves around product utilization by multiple users in a sharing economy setting (Geissdoerfer et al., 2018a). The practices for promoting circularity in that kind of CBM are mostly related to leasing and pooling models instead of full ownership after the product's purchase. The identified intensifying business models are purposed for collaborative consumption among customers while the company retains ownership of the product (Planing, 2018). Since one product is purposed for multiple users, resources are minimized while the customers continue to acquire the value that could have been otherwise purchased (Urbinati et al., 2017).

The value proposition of CBMs structured around resources sharing is based on products being offered as services to the intended customers (N. M. Bocken et al., 2016). The difference between the value proposition discussed in the narrowing strategy and that of the intensifying is that in the former the product is substituted by a service, whereas in the latter the product is offered as hardware for multiple users in a sense of a service. Products being offered in a collaborative aspect besides the resources efficiency can be offered to customers for lower price reducing the investment cost required for ownership (Geissdoerfer et al., 2020). With an open access model, customers can exploit the constant availability of products for temporary use either by manufacturers or users through a platform (Planing, 2018).

Sharing the value among the customers is achieved through capacity building and logistics management since the products should be monitored for delivering the required performance (N. M. Bocken et al., 2016). Intensifying value creation is not only a matter of the product shared but also based on customers education to share as well as on suppliers or service providers orchestration (Geissdoerfer et al., 2020). Since products are shared in a broader network, the created value is assisted via enabling technologies and platforms for tracking and monitoring purposes (Konietzko et al., 2020). Those platforms serve also as value delivery channels with the users accessing shared products (M. A. Khan et al., 2018) or trading their own as second-hand allowing for additional value creation (N. Bocken & Ritala, 2022). Besides products, managing customer relationships is among the capabilities the company has to possess to ensure that the value is created and delivered in a satisfying way to the customers or users (N. M. Bocken et al., 2016).

Capturing the value in a CBM in which the intensifying strategy is being applied, is directly obtained through temporary contracts and use-based charges, for instance by leasing products (Geissdoerfer et al., 2020). When considering the product offerings through platforms, profits can also be streamed through subscription and transaction fees by the service provider (Whalen, 2019). According to N. Bocken and Ritala (2022), in a rental model, profits can be also increased in terms of customer loyalty through pricing for leading non-ownership offerings. It is also argued that value can be indirectly captured based on resources and energy saving due to multi-usage.

2.5 Circular Value Chain

Until today, firms based on linear practices are following the philosophy of take, make and use of products which is structured based on the value chain framework. As described by Porter (1985), the linear value chain is a framework consisting of consecutive steps in each of which value is added. The cumulative value is thereafter transferred to the customers with the firm receiving the benefits of this transaction. The value chain framework consists of certain activities that the firm is necessary to follow in order to create and deliver with success the intended value. The value chain activities are divided into five primary and four secondary which are clearly displayed in Figure 2.

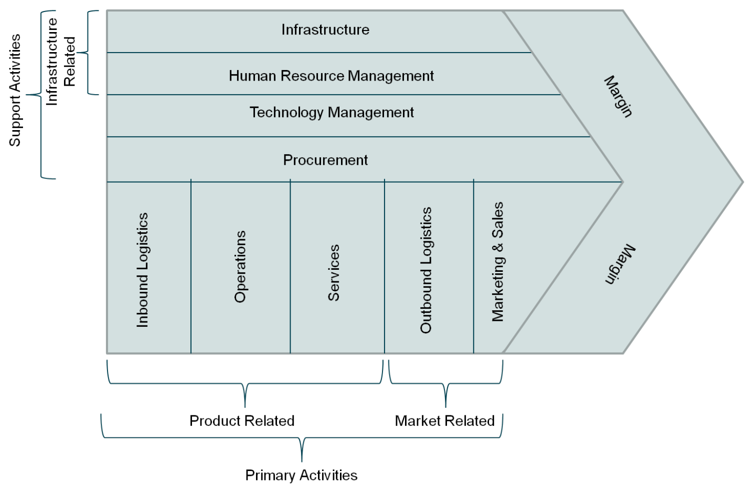

Figure 2: Porter's Value Chain. Retrieved from (Porter, 1985).

With the introduction of circular economy practices, the philosophy of just using the product has altered towards a more cyclical aspect which also includes the disposal dimension at the end of the life cycle. This change in the way products and materials are treated brought about additions in the value chain of firms to allow them seize opportunities and sustain their competitive advantage. To embrace circularity and practices aimed at reusing, repurposing and reintroducing value, the linear value chain as presented has changed to its circular value chain alternative in order to close the resources loop. According to Fehrer and Wieland (2021) the traditional view on the value chain needs to be changed in order to direct businesses as well as people towards sustainability and circularity.

The circular value chain is a restructuring of the Porter's linear value chain since the implementation of circular practices affects both the primary and the secondary activities a firm performs. In that sense, the linear perspective cannot be sufficient and capable to support circularity and therefore the circular value chain is being proposed (Eisenreich et al., 2022). The elements of a circular value chain are closely related to the ones proposed by Porter (1985) with additions at the end of the chain after the service phase. This addition is the reverse logistics and disposal dimension at the end of the value chain as an element which aims to retain the value of the product even after its full utilization by the customers (Eisenreich et al., 2022).

A more comprehensive approach of the circular value chain as an all-encompassing framework has been proposed by (Hennemann Hilario da Silva & Sehnem, 2022) which extends the primary activities in order to capture the whole life of the product. The primary activities start with the procurement and the use of input and continue with the circular product or service design and development. Afterwards, the clean production phase starts where additional value is added. The produced outcome is being delivered to the customer in a circular logistics manner supported by the next primary activity which involves the communication and marketing. Within the marketing domain, the sales and after-sales (service) activities follow to increase the value creating along the life cycle. When the product reaches its end-of-life, the next activity in the value chain relates to the waste management and the recovery, or else called reverse logistics (Hennemann Hilario da Silva & Sehnem, 2022).

Incorporating the reverse logistics and the recover dimensions in the value chain, the Porterian model turns into a closed loop alternative to highlight that the primary value retention activities are being performed in a cyclical manner.

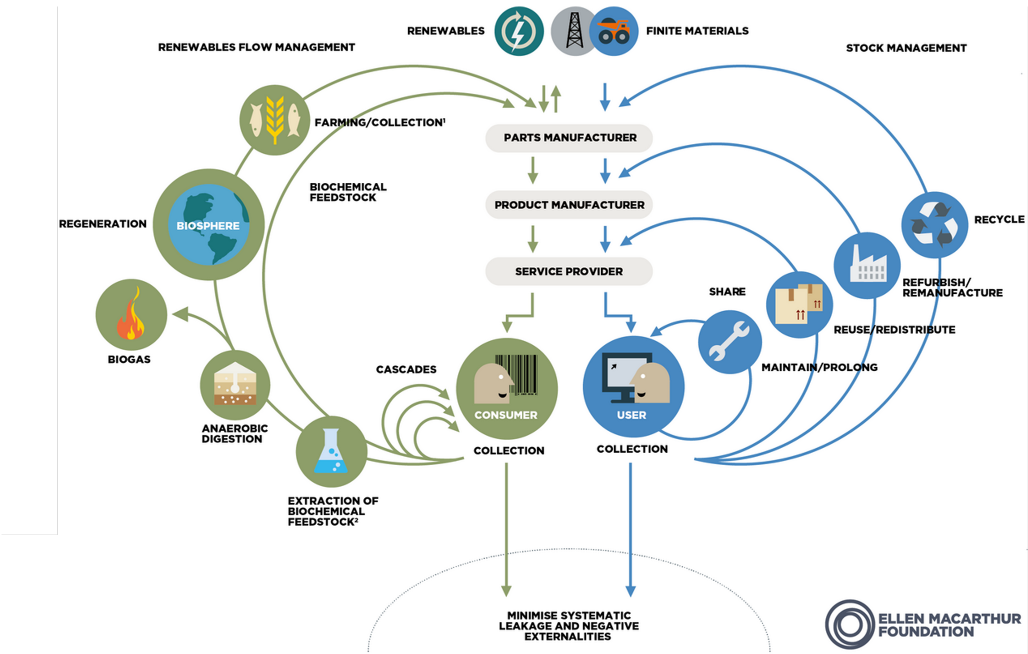

Figure 3: Representation of circular practices along the value chain. Retrieved from (EMF, 2023).

Each activity in the value chain is dedicated to a specific value creation mechanism and therefore a different strategy is followed when considering the implementation of circular practices (Eisenreich et al., 2022). This indicated that along the value chain, several circular business models can be applied based on its characteristics and the purpose they serve. The application of different business models across the value chain is highly related to the value proposition of each business model and how this proposition fits within the value intended by each chain activity. Only a few studies have been identified in the literature to position the circular strategies along the value chain.

2.6 Circular Practices along the Value Chain

According to (Moreno et al., 2016) which takes into consideration the closing, intensifying, dematerializing and extending loops practices, five distinct archetypes of CBMs are being positioned across the value chain indicating how value flows are being satisfied. The resources stage can be served by practices such as cascaded uses which are more intended for resource's minimization or reuse after being recycled. On the other hand, the manufacturing activities can be supported by business models relevant to designing products for extending their value across their life cycle. When considering distribution, use and maintaining activities in the value chain, the strategies that suggested as good fits, relate to value extension as well as the availability of resources which could be achieved through sharing platforms. Finally, closing the loop activities, for instance end of product life, strategies are purposed for material recycling, upcycling and energy recovery are being applied (Moreno et al., 2016).

Based on the study of Pavel (2018), the circular value chain consists of six distinct stages with circular practices such as reuse, rethink and reduce to be applied in all, besides the evaluation of materials stage. In the manufacturing, distribution and marketing value chain phase practices such as reuse, repair and refurbish can be applied. In the same context, Reike et. al. (2018) positions the 9-R practices along a seven stage value chain which consists of material production, components production, end-product manufacturing, retail, consumption, collection and land fill. Practices related to recycling, elements remining and energy recovery are being performed in the first and last stages of the value chain where the components are being manufactured or the complete product is being returned through a collection point. On the other hand, circular activities with regards to remanufacturing, refurbishing, repair and repurpose are applied in the middle stages during the manufacturing, the retail and the use of the product.

A different taxonomy is used by Kalmykova et al. (2018) who position forty five potential circular practices along ten stages in the value chain. In this study, remanufacturing, material sourcing and circular inputs are considered as separate value adding mechanisms through which recycled inputs, materials from waste, elements extracted and refurbished or upgraded products are being looped back in the starting point of the value chain or introduced again in the market. Circular activities performed for a product-as-a-service (PaaS) offering are being applied throughout the whole value chain since the ownership remains with the company which possibly undertakes responsibility of all the stages (Kalmykova et al., 2018).

A direct connection of the slowing, narrowing and loops creating strategies with the stages of the value chain have been performed by Preston et al. (2019). The authors present a circular chain which consists of four stages considering the material input, the design and manufacturing of the product, the distribution and use, and finally the end-of-fist-life. This circle is repeated by applying narrowing and loop creation strategies at the two last stage, through business models which tend to retrieve materials or component's value and bring the product back for further use. For the first two stages of the value chain, the slowing and closing (loop creation) strategies are stressed to be more applicable through design for longer, remanufacture, recycle and replace practices (Preston et al., 2019).

Following the approach of Reike et al. (2018) on the circular value chain, Bianchini et al. (2019) adds maintenance as a separate chain stage where products are being disassembled, repaired and fed back to the use stage. The same study also connects the flows of resources from one stage backwards to the previous stage for creating additional value that could have been otherwise wasted. In that sense, from the distribution and use phase materials for new components or components for new products are looped back to the manufacturing an assembly stage respectively. The recovered resources or damaged components are being repaired, maintained or recycled and fed again to the market without value or energy being wasted (Bianchini et al., 2019). Lastly, the products ending in the maintenance stage in a circular value chain are assessed and thereafter being looped back to all the previous stages as regenerated products (distribution and use), good parts (for assembly phase) or as recycled materials (for components manufacturing).

2.7 Industry 4.0 Technologies & Capabilities

Since the transition from a linear to a circular and closed-loop philosophy has become a first order priority as a social initiative, firms have to adjust their business strategies in order to embrace the new sustainable era. To achieve a smooth transition, several factors have been encountered as enablers with the most promising one to be the technological applications (Kumar et al., 2020). With the emerging digital technology along with the Industry 4.0 (I4.0) technological booming, circular economy practices can be supported throughout the extension of the value chain activities, with efficient resources management and loops tracking (Kristoffersen et al., 2020).

The I4.0 technologies are ranging from digital technologies to edge computing, additive manufacturing (3D printing), wireless sensors, cyber-physical systems (robotics and virtual reality) as well as autonomous systems. According to (Romero et al., 2021) the technologies constantly change and therefore new additions can be encountered in the I4.0 agenda. However, the current state-of-the-art technologies which can be considered as the major circular practice's enablers are listed as follows. A description of the technologies, their capabilities as well as their characteristics can be found in background information referenced in the Appendix A.

Table 4: Overview of Industry 4.0 Technologies.

Emerging Industry 4.0 Technologies		
- Internet of Things (IoT)	- Cloud Computing	- Blockchain
- Big Data	- Artificial Intelligence (AI)	- Sensor Technology
- Data Analytics	- Cyber-Physical Systems (Robotics)	- Simulations – Digital Twins
- Machine Learning (ML)	- Augmented Reality (AR)	- Additive Manufacturing (AM)

The aforementioned technologies have some unique capabilities which can be applied throughout the entire life-cycle of a product or combined in a service offering, enabling circularity and to an extend the implementation of CBMs (Neligan et al., 2022). As a result, the role of digital and data technologies on CBMs is apparent since digitalization and automation can reduce resources consumption, increase data sharing and trust among parties and ensure the quality of the products near its end-of-life. In that terms, knowledge capabilities are enhanced and customer resistance can be effectively reduced (Neligan et al., 2022). Although the review is extensive and refers to the adoption of CBMs by the manufacturing sector, only the aspect of digital technologies is stressed, excluding additional I4.0 technologies which can lead to alternative CBMs.

A more comprehensive and focused to the business models approach suggests that different I4.0 technologies can be applied throughout the product life cycle and embrace the implementation of CBMs. According to Rosa et al. (2020), technologies which relate to AM, Big Data and IoT can have a supporting role in the life cycle management. Additionally, Big Data and additive manufacturing (AM) can be used in recycling and material reuse processes while IoT technology can be an enhancing force for re-manufacturing and services development. Application of such technologies can reduce barriers towards circularity and sustainability and assist CBMs development (Rosa et al., 2020). However, since the synergy between I4.0 technologies and CBMs is relatively new the author suggests further research for understanding the concepts in more practical aspects.

The advancements of the I4.0 era and the relation of each technology to the practices of circular economy have been also reviewed recently from the perspective of stakeholder's. I4.0 technologies can also contribute to CE advancements in terms of manufacturing, supply chain management and production (Hennemann Hilario da Silva & Sehnem, 2022). More specifically, IoT technologies facilitate data generation, ensuring long-term product quality by enabling the retrieval of production information. In addition, AI technology can support traceability of the products even after sold to the customer and predict its life expectancy or recyclability. On the other hand, Blockchain can assure encryption and support information transparency which increase customer trust and stakeholders' involvement. In parallel the adoption of AM processes can support BMs which are dedicated to products re-manufacturing and refurbishing as well as to new recycling practices and material re-use (Hennemann Hilario da Silva & Sehnem, 2022).

Although the aforementioned studies are highlighting the support of I4.0 on circular practices, they are mostly based on the data technologies. As Romero et. al. (2021) mentions, circularity can be enhanced also by the capabilities of AM, simulation and cyber-physical systems. With AM, new production processes can be introduced by utilizing the material from the recycling loops. In that way waste is reduced and no more sustainable products are manufactured. This is supported due to automated solution offered by cyber-physical systems (CPS), which enable the human-machine interaction. This can increase speed of production and minimize the chances of errors which can be interpreted in excess resources use. The process can be further optimized with the development of digital twins which translate the physical process in the digital world. This allow firms to enable system behavior understanding, experiment with various CBMs, and perform resource-efficient interaction with the ecosystem (Romero et al., 2021).

Technological capabilities are also applied along a circular value chain to solve deficiencies and enhance circular practices. Data technologies are applied in different stages on a circular resources flow in order to remove barriers and enable circular design, flow transparency, processes optimization in shorting, disassembly and reverse collection as well as product reuse (WEF, 2019). As can be seen from Figure 4 IoT and big data technologies allow data collection and analysis with regards to product's condition, blockchain technology ensures transparency of that condition and AI technologies offer optimized solutions for product design, material shorting and reverse collection activities.

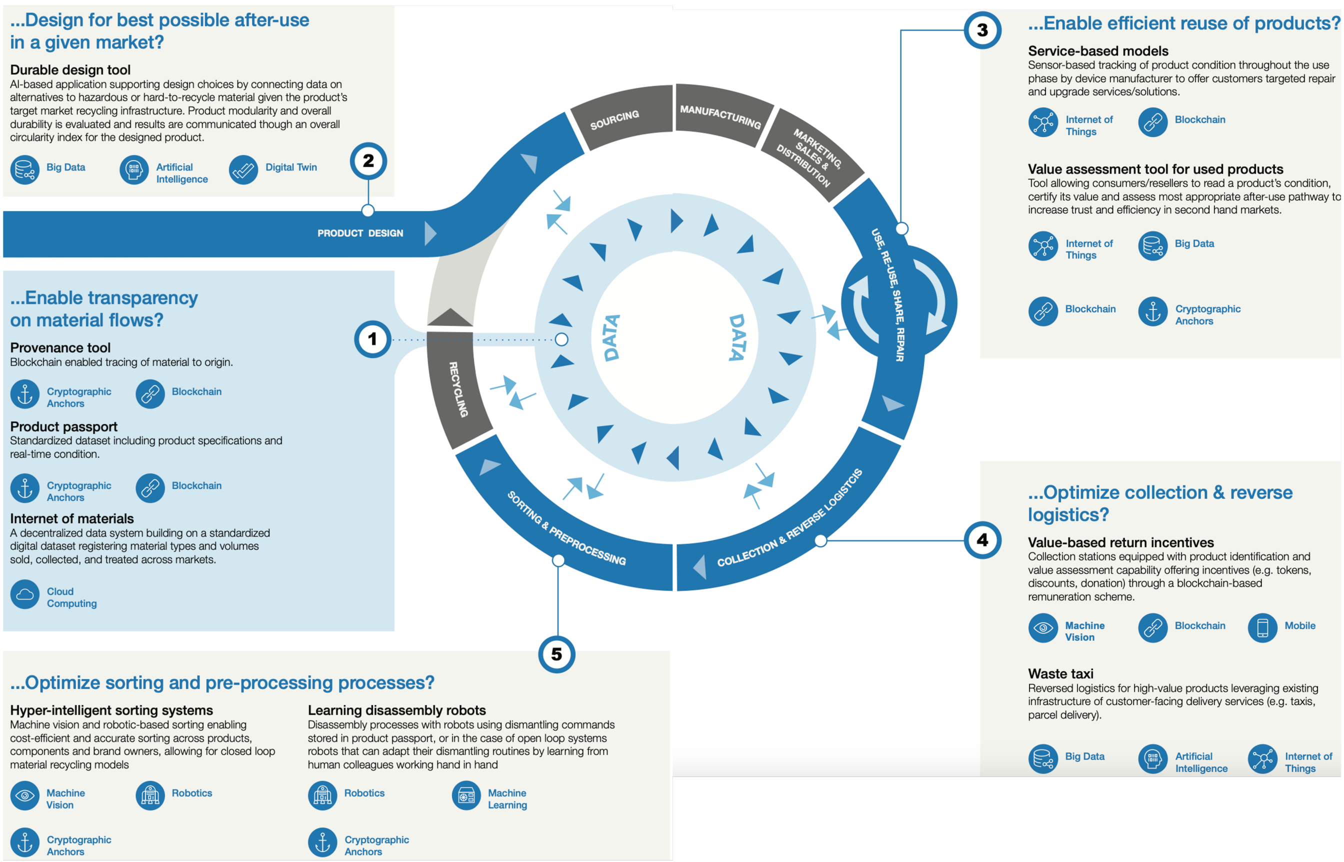

Figure 4: Technological capabilities along the value chain. Retrieved from (WEF, 2019).

2.8 Industry 4.0 Technologies and Circular Value

The capabilities of the I4.0 technology are linked to the circular strategies as presented in the previous sections via the circular practices. The literature studied with the most recent work which links the technologies with the circular practices is summarised in the third table in the Appendix B. Based on their capabilities, the I4.0 technologies have also a unique role on the business model components as they could enable circular value proposition, creation, delivery and capture (Awan et al., 2021). In a broader sense, the technologies that have been studied can enhance business opportunities and allow companies to implement circular strategies in an effective and open way. To do so it is necessary first to understand how the capabilities of those technologies correspond to the different components of a potential circular business model.

2.8.1 Industry 4.0 Technologies and Value Proposition

The role of I4.0 technologies is critical in order to introduce circular value proposition offerings into the market. With its data collection capabilities, IoT technology can promote efficient resources utilization and minimize waste while allowing for efficient product life cycle management (Rosa et al., 2019). Since data are being collected for the products in use, the customers can constantly monitor the quality of the materials and its overall condition. This offering can be enhanced by big data technologies which support the development of digital documents containing useful information about the products, namely "product passports" (Pagoropoulos et al., 2017). By leveraging data and analytics, businesses can make informed decisions that align with circular principles, improving resource efficiency and minimizing environmental impact (Toth-Peter et al., 2023). Smart technologies, for instance artificial intelligence (AI), machine learning (ML) and augmented reality (AR) can be valuable for the proposition of a product or service since they enhance customer experience, offer performance prediction and enhance resources/energy efficiency, reducing in that way the environmental footprint (Toth-Peter et al., 2023; Pagoropoulos et al., 2017). On the transactions side, blockchain technology enables value proposition through reliable and verifiable product information exchange, facilitating efficient supply chain management and fostering a transparent ecosystem (I. S. Khan et al., 2021).

The value proposition is further enhanced through CPS and AM which enable product customization and efficient maintenance or repair processes (Lopes de Sousa Jabbour et al., 2018; Nascimento et al., 2019). In addition the automation of manufacturing processes allows customers to quick repair and remanufacture products in an efficient and energy saving way (Rosa et al., 2019). From a service point of view, customers can be in close proximity to production and exploit the capabilities of a CPS to customize their product (Nascimento et al., 2019; Toth-Peter et al., 2023). Automation is further supported by real time data collection which can allow manufacturers track performance and take decisions for advancing their offerings (Lopes de Sousa Jabbour et al., 2018). With cloud computing, the manufacturer has the ability to monitor product use, understand customer needs and facilitate platform offering in order to support upgradability as a value proposition dimension (Lopes de Sousa Jabbour et al., 2018; Toth-Peter et al., 2023). Finally, touching upon the customisability offering, Rosa et al. supports that allowing customers to be involved in the design/prototyping process through simulation offerings can both satisfy their needs and reduce waste or valuable resources.

2.8.2 Industry 4.0 Technologies and Value Creation & Delivery

Manufacturing companies can also leverage the capabilities of I4.0 technologies for creating and delivering the intended circular value to customers. The IoT technology facilitated data collection throughout the whole value chain through radio frequency identification (RFID), sensors and barcodes (Pagoropoulos et al., 2017; Lopes de Sousa Jabbour et al., 2018). Those data are analysed with the support of big data in order to optimize resources use and energy consumption while creating in that way circular value (Toth-Peter et al., 2023). As I. S. Khan et al. mentions, data security, transparency and accuracy is necessary when considering value creation from data collection, highlighting the ability of blockchain technology to support this aspect. Furthermore, the value creation and specifically the extension of product life for additional value exploitation can be supported by ML and AI technologies which allow for efficient maintenance planning through useful life predictions (Rosa et al., 2019).

Additional technologies that can support value creation are the cyber-physical systems and the AM which can facilitate the automation of processes during production and to an extend the resources/energy reduction (Lopes de Sousa Jabbour et al., 2018). With recycled materials as feedstock for 3D printing, the value from resources can be used for delivering new product offerings to customers reducing in parallel the need for excessive and additional material, parts or components (Nascimento et al., 2019). Efficient resources usage for value creation can be also admitted through balancing the supply and demand in order to always deliver offerings to customers. This aspect can be supported by cloud computing technologies which allow for live-data collection related to customer needs and preferences (Lopes de Sousa Jabbour et al., 2018). Data collected, can be also fed into simulations to optimize offerings, test design and processes scenarios and maximize resources efficiency. In that way, digital value can be delivered to customers through trials, refined and finally created as offering which respects waste minimization and enhances customer experience through conceptualization (Toth-Peter et al., 2023; Rosa et al., 2019).

2.8.3 Industry 4.0 Technologies and Value Capture

Technologies can also contribute to capturing the created value that relates to the circular actions and practices. As an enabling force, I4.0 technologies can map revenue streams and reduce overall manufacturing cost due to optimized processes and resources reduction (Toth-Peter et al., 2023). More specifically, scholars argue that IoT and big data can facilitate product data access through platforms or apps enhancing in that way resources trading and allowing for new revenue streams creation (Lopes de Sousa Jabbour et al., 2018; Rosa et al., 2019). With the use of cloud computing, data can be stored online reducing the need and cost for storing capacity (Pagoropoulos et al., 2017). Additionally, technologies related to AI and ML can be used for financial predictions and process optimization which will allow for value capture through cost reduction (Toth-Peter et al., 2023).

In a circular setting, value can be captured also through resources trading and sharing in a network of customers, manufacturers and suppliers (Toth-Peter et al., 2023). The blockchain technology can facilitate this value capturing mechanism by securing trustworthy contracts and supporting transparent transactions (resources, financial) (I. S. Khan et al., 2021). From a service perspective, manufacturing firms can also admit the capabilities of CPS and AM to capture value from customization and manufacturing-as-a-service offerings through service pricing (Rosa et al., 2019). In addition, robotic technologies can minimize the cost for prototyping with the use of by-materials and allow for customized pricing, enhancing both financial savings and new revenue opportunities (Toth-Peter et al., 2023).

3 Methodology

This section is purposed for providing a clear overview of the methodology to be followed throughout the thesis including the literature analysis as well as the intended cases with subject matter experts. The methodology is designed in a way that all the research questions are thoroughly answered and discussed based on academic research methods performed in qualitative studies. This section is structured as follows, first, the methodology for the literature review conducted is presented. Thereafter, in the interviews subsection, the methodology for collecting and analysing data is discussed while briefly explaining the purpose and the objectives aimed at. Finally, for clarification and illustration purposes, a road mapping schematic will be presented, which will serve as an overview of the research steps followed for answering the research questions and structuring the thesis layout. As will be analysed, the methodology followed consists of three distinct stages, the theoretical review, the framework development and the case study stage. The goal of following an academic and a practical path is to reach parsimony on the topic of circular economy and understand how business models can be developed to further enhance the "loop closing" trend.

3.1 Stage 1: Theoretical Review

The purpose of the literature review is to retrieve relevant academic knowledge regarding the research topics of circular business models, circular strategies, circular value chain and enabling Industry 4.0 technologies. Since the study is characterised as exploratory and descriptive qualitative research, a structured literature review is followed to identify relevant work that has been previously conducted in an academic manner. The literature review, as a core part of the current thesis, is based on a three-step approach, data collection, research relevance evaluation and reporting. Literature data have been collected from journal articles based on keywords which are summarized in Table 5. The articles collected were evaluated based on the number of citations and the relevance of the research perspective (title and abstract). While focusing more on knowledge regarding CBM design, business model elements and Industry 4.0 technologies supporting the circular economy, articles with extensive and generic literature reviews as well as those with mathematical models were excluded. To ensure that all relevant information where retrieved, the backward snowballing method has been employed to identify additional articles in the relevant field (Wohlin, 2014). For consistency purposes, the same inclusion and exclusion evaluation was followed based on the title and the abstract information.

Table 5: Overview of literature review data collection terms.

Core Sources	**Key Themes**	**Keywords**
	Business model frameworks	*business model definition, business model innovation, sustainable business models*
ScienceDirect	Business model elements	*value proposition, value creation, value delivery, value capture, business model canvas*
TU Delft Library	Circular economy	*circular strategies, circular practices, resources minimization, energy minimization, product-as-a-service*
Scopus	Circular economy and business models	*circular business model (CBM) definition, archetypes, CBM components, CBM frameworks, CBM in manufacturing sector*
Whiley Online Library	Circular value chain	*Porter value chain, value chain and circular economy, closing the loop, reverse logistics, circular supply chain*
Google Scholar	Industry 4.0 technologies and capabilities	*data technologies, additive manufacturing, industry 4.0 and innovative technologies, enabling industrial technologies, capabilities and characteristics*
	Industry 4.0 and circular business models	*resources tracking, technologies and circularity, technological enabling factors and circular economy*

Based on the principles of the structured literature review as described by Sekaran and Bougie (2016) additional information is gathered from secondary sources to supplement the required knowledge regarding the CBM and the circular strategies applied. Those sources are well-known and reputable organizations (e.g., Ellen MacArthur Foundation (EMF), Holland Circular Hotspot, etc.) that conduct research on circular economy and how to unlock its potential.

After the screening process, the relevant information was reported as presented in section 2. Overall, the literature review is aimed at studying the work that has been performed among various scholars and that of organizational approaches to reach a level of full understanding of the concepts. Navigating through the existing reviews allows for building perspective knowledge which is further used for constructing a circularity-based framework.

3.2 Stage 2: Framework Development

The second stage of the research design includes the framework development which integrates the concepts studied in the theoretical review. Building a framework allows to collect, structure and codify the knowledge that has been discussed in the literature. To proceed with this, key publications of the concepts related to circular strategies, CBM elements, value chain practices and I4.0 technologies were collected from the previous stage and analysed. To structure the conceptual framework the study of Aminoff et al. (2017) was employed. This research presented the requirements for building a conceptual framework around the concept of circular economy. The proposed method consists of three phases (i) the understanding of the concepts through literature, (ii) the identification of the key components through the categorization of the initial literature findings and (iii) the synthesis of the findings into a structured framework.

The first phase has already been analysed in stage one, which considers the theoretical review. In this stage, phases (ii) and (iii) are employed to build the conceptual framework with the studied concepts. By following this method and starting with phase two of the framework development, the identified frameworks constructed by various scholars are being categorized, analysed and compared. Performing cross-comparisons allows for mapping the various CBMs along with their elements under the circular strategies as have been defined in the previous stage. Exploring the different frameworks will also allow for identifying the components that are required for building an all-encompassing framework in this study. The same comparison approach applies also for the concepts of circular practices, the value chain and technologies. In that way, it is possible to understand further the concepts and identify the information that will be useful for the framework structuring.

The third phase concerns the actual connection of the concepts into an all-encompassing framework which is purposed at providing a spherical view on the CBM and its support by the I4.0 technologies. The links between the concepts are performed based on the findings of the second phase where the literature is compared and categorised accordingly. As already discussed, the framework is focused on the circular strategies, the CBM elements, the value chain perspective (since companies belong into a network) and the I4.0 technologies as enabling factors for the CBM transition. Based on those views an integrated framework is built ready to be used in the next stage of the research design.

3.3 Stage 3: Case Study

The third stage of the study relates to the application of the framework in real business settings in order to align theoretical reasoning with practical insights. With the purpose of further exploring how companies implement circular business practices and develop their CBMs, cases were structured to test and enrich the framework also from the lenses of industry experts in the relevant research fields. The data collection and analysis is based on the principles of qualitative research which is employed for this study due to its advantages for concepts that require in-depth understanding before actual application. To be more specific, the reason of choosing a qualitative case study is based on the advantages that such a study can offer in complex phenomena where more in-depth analysis is required. The case studies were structured based on the research work of (Yin, 2009) which comprehensively describes how data should be collected, analysed and exploited. In addition to that, the process of qualitative research followed is thoroughly reported with regards to the principles as discussed by Tong et. al. (2007). Based on this work the study design, the sampling method, the data collection process and the data analysis are exhaustively discussed in the following sections to allow researchers with relevant expertise (regarding circular economy) to replicate this study (Tong et al., 2007).

For the current research, an exploratory case study was chosen in order to test the functionality of the framework proposed. The reasoning behind this choice, as also mentioned before, is based on the need for understanding the multi-faceted topic of circular strategies and I4.0 technologies also from a practical perspective. By implementing the framework developed in a real business setting it was possible to collect data about how companies proceed with the implementation of CBMs, extract information about the strategies and the technologies applied for transitioning towards CBMs and supplement the academic findings, closing to an extend the gap between theory and practice. Besides the theoretical contribution, the framework was also evaluated based on its clarity, content and ease of use, which allowed for its revision in order to make it a handy tool for assisting practitioners with their decisions. Details about the structuring of the cases are analysed in the following sections.

Unit of Analysis

The unit of analysis in this study comprises firms in the manufacturing sector represented by key top-level management experts. To scope down the range and due to proximity reasons, companies identified to be good fit for the research are entities that are well-established in the Dutch manufacturing sector. The selection of that industrial cluster aligns with the objectives of the study to investigate how those companies can be assisted into reducing their resources and energy consumption. An overview of the targeted companies can be summarized in the following table.

Table 6: Overview of the focal companies.

Case No.	Company	Expert Function	Manufacturing Sector	Circular Actions
1	Philips	Innovation & Sustainability Manager	Appliances	Recycling
2	Royal Ahrend	Sustainability & Circularity Manager	Furniture	Recycling & Circular Design
3	Sif Group	Strategy Director	Steel structures	Renewables-based Production
4	Additive Industries	Sales Engineer & Business Developer	Industrial 3D printers	Material recycling

To be more specific, the manufacturing firms selected as units of analysis are particularly noteworthy due to several distinguishing factors. Firstly, these companies stand out for their proactive stance towards sustainability, demonstrating a genuine commitment to transitioning from linear to circular business models. Their active engagement in adopting environmentally conscious practices sets them apart in the manufacturing sector. The chosen firms represent a diverse range of industries, allowing for a comprehensive exploration of circular business models across different manufacturing contexts. Moreover, their geographical location in the Netherlands offers an advantage, given the country's emphasis on sustainable development and innovative approaches to circular economy principles. Finally, the selected firms showcase a readiness to explore and adopt technologies that facilitate the transition to circularity. Their willingness to identify and integrate suitable technologies aligns with the research focus on technological solutions for circular business models. Overall, these special characteristics of the selected manufacturing firms enhance the case study's ability to provide valuable insights into the strategies, technologies and outcomes associated with the transition to circular business models within the Dutch manufacturing sector.

Sampling

The criteria for choosing the experts being employed as participants in the research are related to the experience they have on the topic of interest, their contribution in the application of circular business models as well as their seniority level within the target company. The exclusion criteria are with regards to candidates that lack practical experience on the I4.0 and circular economy transition within their organization. Additionally, candidates that have joined the company recently and are not familiar with the processes that have been performed in the past are not considered as good fit for the research. The goal of the interviews was to approach people from various companies in order to have a diverse panel of experiences and expertise. The approach was performed through personal contacts and online professional platforms (Linkedin) in order to increase the chances of attendance. In addition, contacts were aimed through snowballing, where personal contacts were employed as the intermediate point for reaching out to the subject-relevant experts.

Data Collection

The method used for collecting data is semi-structured interviews with the experts as defined in the sampling section. During the course of the interviews, both prepared as well as ad hoc questions were asked to the experts and data were collected which have been later analysed. In a sense, the semi-structured interview method adds flexibility to the data collection and increases the chances that all the aspects are covered. In contrast, a survey-based approach would be broadly shared to an organization of interest ending up in a long and time-consuming process with a lack of focus on the specific topic which would reduce the research control.

Building a plan for preparing for the interviews includes the formation of the questions and the approach of the interviewees from the companies of interest. To avoid chances of delay, the preparation for the interviews was performed in parallel to contacting the relevant participants. As soon as the objective was set and the literature study was at its final stage, a draft script of questions was provided to the supervisor for feedback purposes and to ensure that the range of themes to be discussed is covered. The re-worked questions were provided to the participants in advance of the interview for preparation purposes. A flow diagram of the process followed is presented in Figure 5.

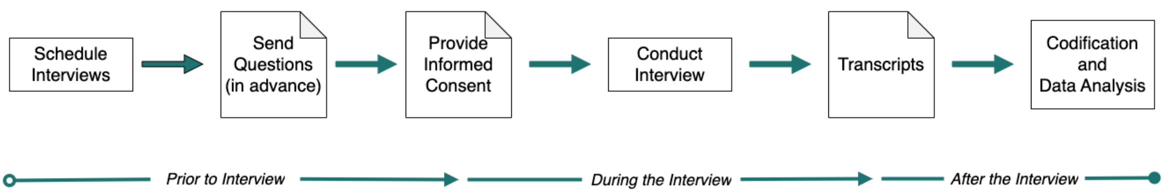

Figure 5: Steps overview throughout the expert interviews process.

The interviews were structured in three parts. A more detailed analysis of the interview structuring as well as a sample of the topics that have been covered is presented as follows in the *interview structuring*. To ensure the ability to analyse the data after the interviews were conducted and extract prominent to the study information, the discussions with the experts were recorded and transcripted via MS Teams while also some notes were taken for personal assistance. The interviews were mostly kept short due to the busy schedule of the experts and therefore the duration varied between 30 and 45 minutes, sufficient to gather all the required information.

Interviews Structuring

The interviews were conducted on a semi-structured principle with open questions in order to retrieve insight about the circular actions performed or planned to be performed in a practical business setting. The interview agenda is divided in three distinct parts, the open discussion, the circular business model formulation and the validation/evaluation of the developed framework respectively. The objective of the open discussion about the circular economy was to gain insights and capture knowledge regarding the key drivers towards circularity as well as the challenges encountered blocking this transition, from the lenses of the practitioners. Since the interviews are dynamic and the content constantly changes the questions were adapted based on the flow of the discussion. The topics for discussion in the first place are listed below:

- Circular activities and strategies performed by the company
- Importance of circularity and circular actions
- Challenges in implementing circularity from a practical perspective
- Positioning in the value chain and business model

- Plans for moving towards circular economy

The second part of the interviews was dedicated to the developed framework. After a brief introduction and presentation of its components, the framework was shared with the interviewee for testing and implementation. The participant was given a moment to navigate through the circular strategies and how those can structure the elements of a business model promoting resource circularity. Getting confident with the dimensions of the framework allowed for discussion and zoom-in questions on how a circular business model could be structured for a product or service offered by the company the expert belongs to. Firstly, the participant was asked to provide his/her insights about the potential strategies that could be applied along the value chain of the firm. Based on the choices, the participant could spot which practices promoting circularity can potentially be applied in the specific stages of the value chain while also building knowledge that was not thought in advance. In that phase, more specific questions could be asked which relate to the following listed topics:

- Circular strategies along the company's value chains
- Actions to embrace circularity along the value chain

Since the value chain part was covered, the participants were asked to move further to the business model aspect of the framework. With those matters, the participants were asked to choose a strategy that could be applied to one of the products or services of the company. Along with this strategy, the nine elements of the business model are discussed and analysed. Through the framework dimensions, the participant could structure how value can be proposed, created, delivered and captured while applying the intended circular strategy. In every case, the framework was used in a form of a clickable tool for the expert to think of ways for introducing the product/service in the market in a more circular manner. While structuring the elements of a circular business model, the discussion was formed around the choices and how those could be applied in the setting and the provisions of the company in question. In parallel to the framework navigation, each participant was also asked questions on the following topics:

- Overview of applicable circular strategies based on the product or service discussed
- Stakeholders, partners and customers related to the company
- Activities that could be considered as circular and required resources
- Circular actions and connection with cost structures and revenue streams

The interview continued with the I4.0 technologies dimension. At that stage, the participant was asked to ideate on the potential technologies that could be assisting the implementation of the CBM structured in the previous stage. Although hard to justify for non-technological companies, the framework suggests how each technology can be applied and therefore each participant could give his/her insight on that dimension. Based on the product or service of the manufacturer, multiple technologies could be applicable in ways to support the value aspects of a CBM, therefore the participants were asked to highlight all the possible fits for their setting. In parallel, questions were asked on how the technologies mentioned in the framework can be applied in the company of interest and if plans are in place to introduce them for a transition towards circular economy.

For validation and verification purposes, the final step of the expert interviews includes questions regarding the functionality of the framework, the ease of use and the appropriability for building circular business models. In that step, each participant was asked to provide an overview of the parts that are missing from the framework and need revision. In addition, each expert was called to envision the implementation of the developed framework in his/her business, the setting of this implementation as well as the potential it would bring if applied. The aim of the last step in the interview round is to gain insights about the completeness of the framework and its potential as a bridge between the academic and the practical world. Based on the feedback received from the experts the framework can be refined to supplement the theories and principles of circular strategies and increase its potential as an all-encompassing tool during business ideation series.

Ethical Consideration

The process of expert interviews considers also the ethical aspect which is related to the consent of the participants for collecting and analysing the data as well as disclosing the results at the end of the thesis in the university repository. Therefore, an *informed consent* was provided to the interviewees informing them about the purpose and scope of the interview as well as about their right for recalling their participation in the interview. Additionally, actions securing the data anonymity and confidentiality were mentioned in the form, in order to ensure that the participants will not experience any privacy concerns. The data transcript was used for further analysis therefore the participant's consent was important and requested in the beginning of each interview. To further ensure the confidentiality of data collection and analysis, while in parallel complying with the regulations of TU Delft about the participant's protection and the data risks, an application with an overview of the ethical considerations and the data protection practices was submitted to the Human Research Ethics Committee (HREC) and has been approved. As suggested, the recordings and transcripts were deleted after the end of the research study for confidentiality purposes.

Data Analysis

The data that were collected from the interviews through transcription were analysed in a way to extract experiences and perspectives on the circular business models and the role of I4.0 technologies in the overall business. To analyse the data based on the requirement of the qualitative research, a coding methodology mentioned in the literature as the thematic analysis was followed in order to extract the relevant information from the interviews (Crowe et al., 2011).

The thematic analysis started with an initial coding which aimed at identifying potential patterns among the data or implicit meanings which were useful for the thesis research and the developed framework (Braun & Clarke, 2013). Firstly, codes that serve as ideas, experiences or perspectives of the experts on the central concepts were formulated and studied in order to familiarize with the data sets. Thereafter, the codes were clustered in greater code families which are used for structuring the data. An additional overarching level of coding has been added to provide a generic view of the themes clusters and give a general direction of what can be found under those specific terms.

Once the data were clustered in families, the focus was scoped on identifying patterns or commonalities and differences among the manufacturing sectors based on the answers of the various interviewees. This assisted into enriching the research of the thesis and the elements of the framework. This also allowed to recognise if some themes or codes are widely stressed and if more attention is paid in particular areas. To summarize, the methodology that is followed and the methods employed in the cases, are illustratively presented under Table 7.

Table 7: Summary of research methodology and data collection/analysis approach.

Data Collection Method	**Risk of Attendance**	**Mitigation Activities**	**No. of Interviews**	**Duration**	**Analysis Method**	**Sampling**
Expert Interviews	Low / Medium	- Use of Personal Contacts - Snowballing (reach out experts through personal contacts)	1-2 per company	30 - 45 min	Thematic Analysis (TA) -Coding of Data (themes extraction)	Homogenous (experts from the same field of expertise)

Research Quality

The qualitative research performed in this thesis has been also tested for its quality and importance both in the academic and the managerial terrains. To ensure a certain quality level, the validity of the research should be thoroughly considered. As with every qualitative approach, the thesis research might lack generalizability since there is no standard or single answer when conducting interviews. This can pose a risk in the overall study and reduce the academic relevance of the findings at its final version. Identifying this risk in advance helped to build a proper mitigation plan which will increase generalizability and make the findings valid for future studies.

Since the range of I4.0 technologies is great and the CBMs have been applied in different ways between the companies of interest, collecting data by multiple sectors and resources ensures that the themes are broadly covered. This allows for different perspectives on the same central topic by providing a helicopter view in various levels from the manufacturing companies in question. An assisting approach which has been employed is the interview saturation where the interviewers were asked questions on pre-discussed topics in order to understand if new themes are coming into light or no additional information is generated. This method is used to increase the research rigor and ad a sense of confidence on the findings to be presented.

3.4 Methodology Overview

An illustrative representation of the methodology that is followed in the thesis is given in Figure 6.

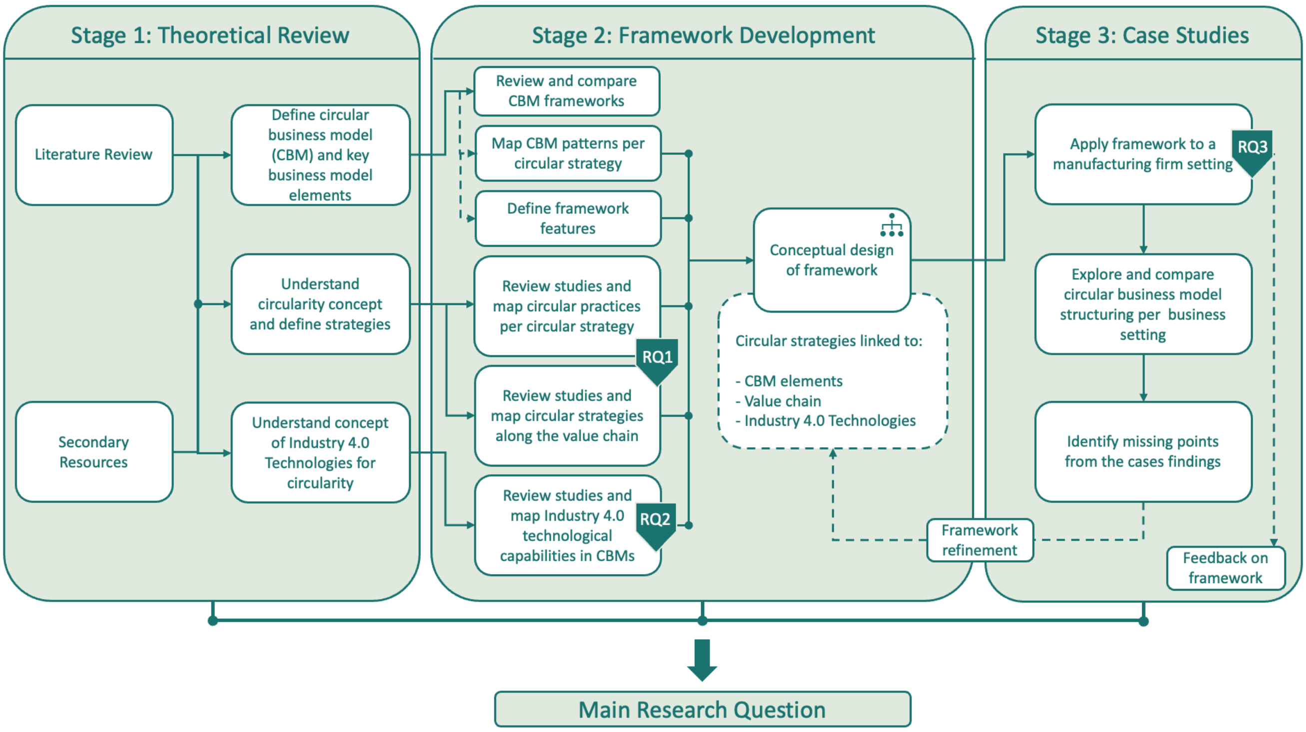

Figure 6: Schematic representation of research methodology.

4 Framework Development

In this chapter the information gathered from the literature review chapter with regards to the concepts of circular value chain, circular strategies, CBM elements as well as I4.0 technologies are brought together for synthesizing an all-encompassing tool which will be afterwards implemented in manufacturing companies for testing and evaluation. Firstly, based on the literature overview which is summarized in table 3, the various circular practices are being categorised within the circular strategies clusters. When the strategies are well defined and comprehended, they are being positioned along the circular value chain in accordance with the literature summary as presented in the second table in appendix B.

Thereafter, the circular strategies are linked to the CBM elements, as presented by the literature in section 2.1. The effect of each circular strategy on the specific BM elements will be structured based on their connection with the value-based components of the BM, namely the value proposition, creation and delivery, and capture. Connecting the CBM elements with the circular strategies through the value logic presents how a CBM should be structured and defined (Pieroni et al., 2019). The connection is based on the literature review being performed and summarized on the first table in appendix B. After the CBM elements are being defined in a way that promote the circular strategies, an additional connection is being applied. This concerns the I4.0 technologies with regards to their capabilities for enhancing the various circular strategies and the value components of a CBM. This connection is based on the literature in section 2.8 and the third summary table in appendix B.

To ensure that the components selected to be part of the framework have an exclusive meaning and are not repeated either directly or indirectly, the MECE principle was employed. This principle stands for Mutually Exclusive and Collectively Exhaustive (MECE) and is purposed at eliminating information, codes, components and meanings that are redundant and repeatable among the studies (Lee & Chen, 2018). Using this principle also assisted in preventing gaps in the analysis based on the studies collected and endorsed clear, well defined and exhaustive data to fill in the parts for developing an all-encompasing framework. This helped into increasing the credibility and rigour of the framework since a systematic approach was used for the analysis performed.

Combining the various concepts leads to the composition of the Hybrid CBM-Tech framework (HCBMT) as will be presented further. A complete view of the HCBMT framework with all the connections and the data collected is hard to present for visual reasons. Therefore, a more generic illustration of the composition of the framework highlighting the connections of the various concepts is given in figure 7. A detailed view is developed with the support of the Miro software which is given under appendix D.

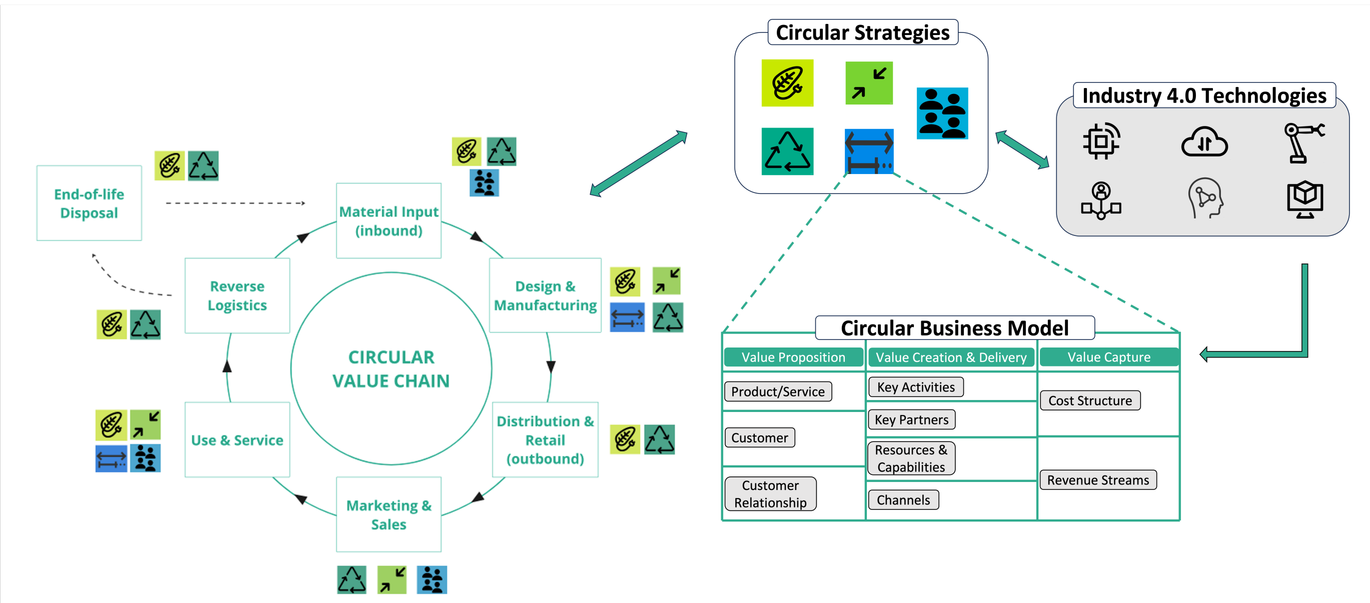

Figure 7: Illustrative representation of the HCBMT framework.

4.1 Clustering Circular Practices under Circular Strategies

The circular strategies that have been identified in the literature as the most common among the scholars are the greening, narrowing, cycling, extending and intensifying. Each strategy represents a specific role in the circular economy which is related to the resources and energy efficiency, processes optimization, loop closing and product life cycle lengthening. Implementing each strategy required the exploitation of circular practices that are linked with those roles and could lead to the intended circular outcome. Firstly, the greening strategy, based on the description presented in the literature, is purposed at sustainability either from the side of energy or the natural ecosystem. Therefore, practices that could be applied in such setting relate to green initiatives for products production, transportation and powering as well as green-based partnerships with suppliers and customers. The ultimate circular practice included in this strategy is the natural ecosystem recovery for long term perseverance of resources which could be used for material production during manufacturing.

On the other hand, narrowing means reducing resources and energy where possible without discounting the offerings quality or availability to the customers. Applying this strategy in a circular setting is achieved through actions which substitute materials with alternative eco-friendly or with enhanced properties and introduce alternative designs with less resources consumed. For resources reduction, an additional practice that could be performed is named after on demand production which entails a balance between supply and demand avoiding products in stock. The demand could be further reduced by incentivizing people on altering their needs in a resource-saving manner. Energy reduction can be achieved through local initiatives and localization of market boarders which could also strengthen the local community besides the circular aspect. A combination of resources and energy narrowing can be achieved by removing the materialistic dimension from the product and offering a service instead with equal performance outcome.

The cycling strategy as the name suggests, is directly linked to loop closing and circulation of resources back in the system for exploitation of the value that could have been otherwise wasted. Applying the cycling as a concept is performed through recovering of nutrients, materials, components and energy at the end of the life cycle of a product. Those resources are being reused and thereafter sold again in the market as a completely new offering. Reselling can also be achieved through redistribution of products in the form of useless resources for one business side but valuable inputs for another manufacturing firm (industrial symbiosis). Within the cycling concept is also included the cascading of products which were serving a purpose and can be altered to serve a different action. For closing the loop, products, components or parts are being collected via take-back systems which could be otherwise characterised as reverse logistics practices. Achieving this return of resources at the end-of-life is highly contributed by customers who should be incentivised to bring the products back closing in that way the loop.

Another circular strategy that can be aimed through a CBM is the extension of the life expectancy of products. Extending includes practices that relate with the design of a product to last longer which in sense reduces the need for resources in order to produce a new one. Therefore, products are being designed in a way that their style hardly becomes obsolete despite the constantly changing tastes of the customers. The extending strategy also includes designs of premium quality products aimed at cycling for longer and being durable throughout the years. Additionally, a practice that have been discussed in the literature is the design of products for ease of maintenance after being used. The life extension can be also obtained through after-sales services which support the product repair and maintenance while products that cannot be repaired are remanufactured or refurbished before they are introduced again in the market. Finally, a circular practice under the umbrella of extending is the upgradability which can renew the product, its performance and its features while also make the customers willing to use for longer.

Approaching the circular economy from the sharing perspective leads to the intensifying strategy which represents the multiplication of the value of a product or service when this is utilized by multiple users. Performing this strategy for circularity includes practices which are purposed for making the offerings available to users through leasing, renting and pooling schemes. As discussed among scholars, intensifying is being applied via collaborative consumption and product sharing among users or companies while the manufacturing firm retains the ownership. Within this matter, the product is not being purchased by the customers but the performance or the results from the use of it are being offered as a service. The intensifying strategy includes also practices for educating customers or network partners (suppliers, providers) to share product and trade resources for increasing the potential value and closing the loop. Though limited practices have been identified to fall in the intensifying cluster, its contribution in the resources and energy saving is significant when considering implementing CBMs based on sharing value.

The findings on the practices clustering among the five distinct circular strategies are being illustratively presented in figure 8.

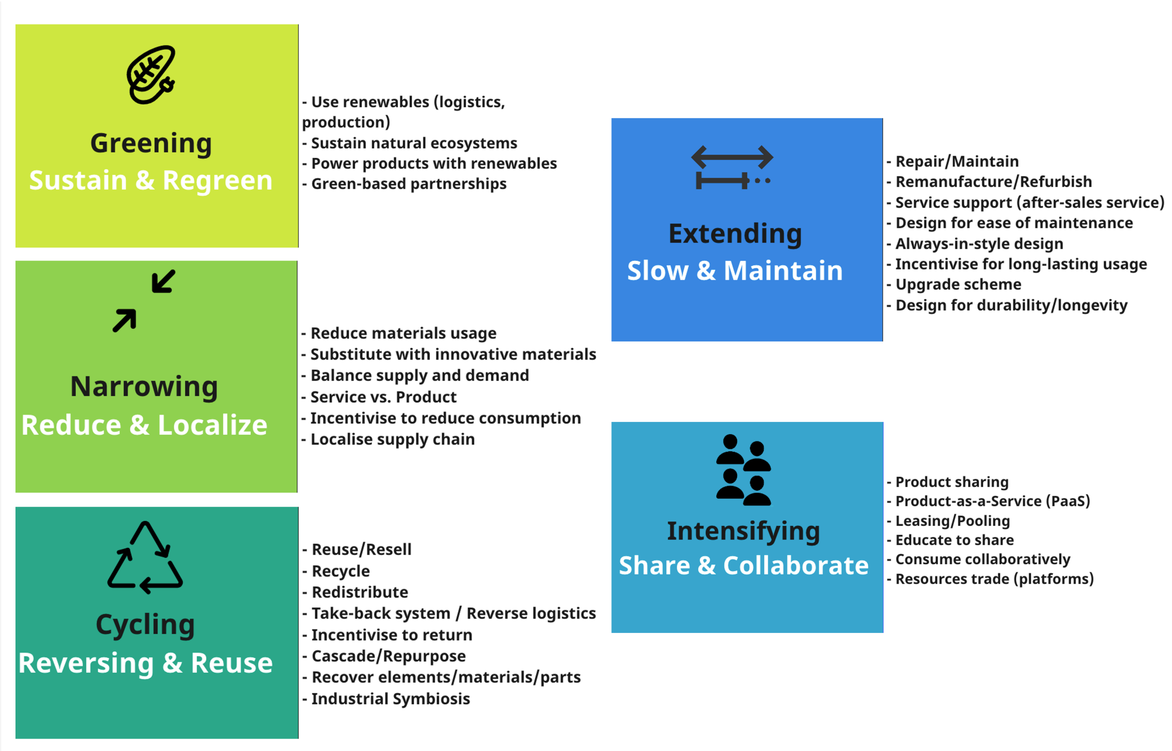

Figure 8: Clustering of circular practices under circular strategies.

4.2 Positioning Circular Strategies along the Value Chain

The second step in the framework development is related to the application of the circular strategies along the different stages of the value chain. To achieve this, the most relevant and highly cited studies have been analysed in the literature review. The information collected was related to the stages that define a "circular value chain" and the circular practices that could be applied along it. Thereafter, based on the clustering performed in the previous section, the circular practices are replaced with circular strategies along the value chain. This provides a simplified perspective and allows decision makers to navigate through five distinct strategies instead of multiple circular practices that are mixed within a value chain. On the academic side, placing the circular strategies along the value chain can be seen as a way of structuring the collected knowledge and disseminating it in a simplified and direct way.

The positioning of the circular strategies along the value chain is based on the literature findings in section 2.6 which are thoroughly mapped in the second table of appendix B. Based on the information collected the following table 8 was constructed which represents the different stages of the value chain and the circular strategies that could be applied. As an intersection point between the two concepts, the various circular practices per value chain stage are also displayed and clustered to provide an organized understanding of the interconnections performed.

Table 8: Mapping of the circular strategies along the value chain.

Value Chain Stage	Circular strategy	Circular Practice
Material Sourcing (inbound logistics)	Greening	- Green-based partnerships
	Cycling	- Reuse - Industrial Symbiosis
	Intensifying	- Resources trade (via platform)
Design & Manufacturing	Greening	- Use renewables for production
	Narrowing	- Reduce material use - Substitute with innovative materials - Balance supply & demand
	Cycling	- Cascade/Repurpose
	Extending	- Design for ease of maintenance - Always-in-style design - Design for durability/longevity - Remanufacture/Refurbish
Distribution & Retail (outbound logistics)	Greening	- Use renewables for logistics
	Cycling	- Redistribute
Marketing & Sales	Narrowing	- Service vs. product
	Cycling	- Resell
	Intensifying	- Educate to share - Product-as-a-Service (PaaS)
Use & Service	Greening	- Power products with renewables
	Narrowing	- Incentivise to reduce consumption - Service vs. product
	Extending	- Repair/Maintain - Service support (after-sales service) - Incentivise for long-lasting usage - Upgrade scheme
	Intensifying	- Product sharing - Leasing/Pooling - Product-as-a-Service (PaaS) - Educate to share - Consume collaboratively
Reverse Logistics	Greening	- Use renewables (reverse logistics)
	Cycling	- Recycle - Take-back system - Incentivise to return
End-of-Life Disposal	Greening	- Sustain natural ecosystems
	Cycling	- Recover elements/materials/parts - Recover energy

From table 8 it is clear that for each stage of the value chain multiple circular strategies can be applied accompanied by the relevant actions for circularity. In the same matter, some circular practices can be applied in multiple stages of the value chain serving a different purpose. For instance, the intensifying strategy can be admitted in marketing and sales stage as well as in the use and service stage by applying the same circular practice, namely the PaaS. In the first place, the practice is targeting into convincing the customer about the benefits of non-ownership while also promoting circularity. On the other hand, the PaaS practice makes the use phase more circular by allowing the firm to provide the performance and not the product itself to the customer. The same applies for the service vs. product proposition which is aimed at reducing offerings from hardware and replace them with a software provision. The application of this circular practice can be seen in the marketing phase for attracting customers as well as in the use phase where the service value is being utilized and exploited.

4.3 Connecting Circular Strategies with Business Model Elements

The third step of the framework development considers the connection between the circular strategies and the business model elements. This is a way to understand how the BM elements should be structured in order to embrace circular activities and how the different strategies are affecting those elements. Based on section , The business model elements that are used are explicitly denoted in section 2.1. To achieve a connection and map all the possible relationships between the CBM elements and the circular strategies, highly cited studies have been chosen which relate to CBM reference models and taxonomies. The selected publications are discussed under section 2.4.2 a summary of which can be found in the first summary table in appendix B. Through this it was possible to highlight the various CBMs and how the value proposition, creation, delivery and capture are structured. From the information gathered, patterns have been also identified which denote the CBMs in relation to the five distinct circular strategies. This pattern clustering was utilized to link the various strategies with the BM elements. It is worth mentioning that for the CBM clustering again the MECE principle was exploited in order to avoid overlapping among studies.

CBM Elements for Greening

The greening strategy relates to offerings which either being produced by renewable resources or being powered as such in order to reduce the environmental footprint. Companies offering green products or services target incentivised customers with high environmental awareness, The customer relationships for supporting a greening based CBM are based on collaborative initiatives which promote green energy and ecosystem protection. On the value creation side, those CBMs require customer education and incentivization and partners who enable green production, delivery and utilization of goods. To apply the greening strategy, manufacturing companies require to build-up renewable energy capacity and enhance green-oriented marketing through human resources. The communication and value delivery channels can be formed via social media initiatives as well as direct product delivery always in green manners. Finally, the application of a green-based CBM can yield savings from the use of sustainable energy and green-mobility and generate additional revenue streams based on ”green-reputation”.

Table 9: Proposed structure of CBM elements when implementing the ”greening” strategy.

CBM Elements	Proposed Formation in Greening
Product/Service	- Processes use renewable energy to transform materials into green products. - Products have low environmental footprint while being powered by renewable resources (solar panels, scalable wind turbines).
Customer	- Incentivised customers which purchase only green-powered products. - Customers with high environmental awareness.
Customer Relationships	- Transportation is initiated based on renewably powered means (electric-based mobility, bikes, etc.). - Collaborative initiatives to sustain or regreen natural reserves and ecosystems. - Collaboration only with suppliers which support green initiatives.
Key Activities	- Educate customers to use only green products. - Create awareness about green actions and incentivise customers.
Key Partners	- Collaborative initiatives to restore and regreen natural ecosystems. - Delivery of supplies with the utilisation of renewable resources and non-fossil mean.
Resources & Capabilities	- Build-up renewables capacity and use it in production and by-processes. - Delivery of products in a sustainable way. - Make creative partnerships which embrace green energy. - Human resources to support green marketing and promote sustainability.
Channels	- Sustainable transportation and delivery. - Sustainable insights promotion through social media for customer and stakeholder education.
Cost Structure	- Savings from renewable energy consumption. - Savings on transportation costs.
Revenue Stream	- Reputation due to green initiatives, can attract incentivised customers with high environmental awareness.

CBM Elements for Narrowing

Applying the narrowing strategy can form different CBMs since the actions followed are focusing on reducing the material, resources and energy even before a product is produced. The products proposed in narrowing-based CBMs are built with the leat possible materials consumed or from innovative materials that can substitute the conventional ones. The value proposition in those models can be also formed around services which aim at providing the same functionalities as the physical product would do. An additional unique proposition in this strategy is the provision of products based on the demand to keep resources to the minimum possible levels by reducing stocks. In this CBM the customers are incentivised and willing to reduce consumption and the relationship between them and the manufacturing firm is ensured via guarantees for the product or service functioning. The key activities required in such CBMs relate to the education of customers to reduce consumption, creation of software which can substitute hardware and keep customers satisfied as well as initiation of reuse and recycling habits.

In CBMs which are based on the narrowing strategy, local supply chain partners are suggested and inter-industrial collaborations for material innovations. On the resources side, the management capacity is necessary to supervise demand and keep supply in a balance. Additionally, in case of a software offering instead of a physical product, technological capabilities are required to support the digital functionalities. The channels that can support the aforementioned offerings can either be direct sales, online tools or software offering platforms that can deliver the value to the customers. From an economic point of view, the narrowing-based cost structure can be benefited from savings on stock reduction and efficient material use as well as by exploitation of local suppliers and partners. Nonetheless, in narrowing CBMs, additional revenues can be introduced by fees or subscriptions-based pricing from platforms supporting service/software exploitation.

Table 10: Proposed structure of CBM elements when implementing the "narrowing" strategy.

CBM Elements	Proposed Formation in Narrowing
Product/Service	- Products offered are build based on the minimum possible material consumption. - Service offering which completely substitutes the functionalities and capabilities of a physical product. - Products are being produced based on the demand, supply-demand ratio is balanced. - Products made of innovative materials which are purposed at reducing the consumption of conventional materials.
Customer	- Proactive customers willing to reduce consumption.
Customer Relationships	- Exploitation of local suppliers and partners in order to reduce energy consumed from transportation and materials trading. - Ensure product functionality besides the reduced materials utilisation during production (product guarantees). - Ensure service performance besides the lack of a physical product (service guarantees).
Key Activities	- Educate customers to reduce consumption where possible. - Reduce product consumption with service offerings. - Reassure that the service offered can cover customer needs. - Reduce resources utilisation by initiating recycling and reuse actions.
Key Partners	- Supply resources in local basis. - Innovate materials with advanced properties along with institutes which can substitute the traditional non-ecological materials.
Resources & Capabilities	- Substitute product with an equal service which can serve the same functionalities. - Capacity management in order to have an equilibrium between supply and demand. - Technological capabilities which can assist with service offerings and demand prediction.
Channels	- Software delivery instead of product via performance/functionality provision. - Social media and online channels for offerings delivery. - Apps and online tools for service delivery (product virtualisation). - Direct sales of non-ownership products.
Cost Structure	- Savings from on demand production and efficiency due to innovative materials. - Savings from transportation cost reduction due to local supplies.
Revenue Stream	- Revenue from new non-ownership contracts. - Profit from subscription schemes for software utilisation.

CBM Elements for Cycling

A CBM based on the cycling strategy is focused on closing the resources loop by reusing and recycling the materials, parts or components of products that have been in use. This BM involves offerings of recycled or second-hand products, including those cascaded for different uses. When a manufacturing firm is applying this CBM should target incentivized customers who are willing to purchase previously used products. The customer relationship in this CBM is also continuing after sales in a reverse logistics manner where facilitating collectors play a crucial role for crating take back systems. The activities required to support a cycling-based BM revolve around accessing the end-of-life products in order to retrieve the useful resources, ensure the quality of products through life cycle management and educate customers to return products back.

Further, key partners are required to facilitate product returns, circulation and by-product exchange through cooperatives and redistribution relationships. The resources required for cycling relate to take-back systems and collection points as well as reversing processes and supply chains. In addition, the technological input is necessary in order to support product tracking and enable inter-industrial value exchange. As from the channels side, direct and online channels can be used in order to allow for second-hand product resell and resources exchange between stakeholders. In addition, reverse flow infrastructure is needed as a channel for facilitating take-back systems. Capturing the value in CBMs where the cycling strategy is applied, is based on cost structure savings from material inputs and joint production lines. Finally, new revenue streams can be aimed through lower price product offerings, reputation gains from sustainable offerings, transaction fees for by-product trading/reselling as well as through buy-back service fees and trade credits.

Table 11: Proposed structure of CBM elements when implementing the "cycling" strategy.

CBM Elements	Proposed Formation in Cycling
Product/Service	- Products made of recycled elements/materials/components. - Second-hand/second-chance products which are being redistributed to market for reselling and reuse. - Value from biomass is returned to the ecosystem, cascading.
Customer	- Incentivised customers willing to purchase redistributed goods. - Customer segments with high environmental awareness.
Customer Relationships	- Facilitating suppliers and collectors which support reverse logistics activities. - Material/parts trade among industries to cover needs without additional resources input to the system.
Key Activities	- Incentivise customers to return products for reuse and redistribution. - Reassure that recycled or second-life products have good quality and can serve the intended functionalities and purpose. - Access end-of-life products and retrieve useful resources from waste.
Key Partners	- Reverse logistics partners which are purposed for product return and resources circulation. - Cooperation with facilitators and redistributors for product collection, inspection and direct selling. - Resources trading through cooperatives and by-products exchange.
Resources & Capabilities	- Take-back systems and products/materials return point. - Recycling processes and reverse supply chains. - By-products exchanging with industries, waste from a manufacturer can be used as a valuable input. - Mange product traceability with IoT and cloud technology.
Channels	- Direct channels for resell either through retailers or online means. - Social media and apps to communicate recycling value to customers. - Virtual channels (media, platforms) for resources trading. - Reverse flow infrastructure as a channel for recycling.
Cost Structure	- Savings from reduced production costs. - Savings in material inputs with the exploitation of by-products. - Joint (customer, manufacturer) cost reduction and new production lines.
Revenue Stream	- Revenue from product offerings in lower price, reselling revenue streams. - Revenue from resources trading. - Reputation gains in "green" customer segments. - Direct and indirect sales (transaction fees) and revenue streams from reselling. - Additional profit from buy-back scheme, take-back service fee and trade-in credit.

CBM Elements for Extending

Additional CBMs can emerge by applying the extending strategy to achieve product life cycle extension. The value proposition of these models include products with timeless design, durable structure and easiness for remanufacture and repair. In addition services can be offered aiming to upgrade the product in use or take the product back for maintenance and repurposing. The targeted customer base in extending-based circular models concerns those willing to reuse refurbished products as well as segments which aim to save on capital costs by using for longer. The customer relationships are continuing after sales through third parties and network of actors offering maintenance services. To support life cycle extension, activities related to repair and upgrade plans should be initiated. These are designed for either individual customers or businesses, aiming to ensure the proper operation of the product. Key in this CBMs is the customer education in order to use in a way that promotes longevity.

The BM element related to partners suggest network collaborations to support remanufacturing and external partners for outsourcing maintenance and repair activities. To support the extending based CBMs key technological and labour resources are required supporting upgradability services and design for long lasting products. In addition, technological capabilities are necessary to predict life expectancy and guarantee product performance. To deliver the created value, direct channels can be exploited with additional after-sales support through virtual means. On the economic side, the extending CBMs offer cost structure savings from material minimization during remanufacturing while revenue can be yielded through service fees. Additional revenues can be aimed through premium charging for durable products or subscription fees for maintenance service plans. Non-financial profit can be also admitted through customer lock-in which allows for trust building and long term relationships eventually leading to economic benefit.

Table 12: Proposed structure of CBM elements when implementing the ”extending” strategy.

CBM Elements	Proposed Formation in Extending
Product/Service	- Product is designed in a durable way to last longer. - Product is based on timeless design (does not fade out of style). - Defected or damaged products are being repaired to retrieve their capabilitied without resources waste. - Upgrade to new modes (product or service) with additional features and high quality. - Product design is easy to maintain, disassembly, remanufacture and refurbish.
Customer	- Conscious customers willing to use the product for longer. - Customers segments which lengthen consumption to save on capital costs.
Customer Relationships	- Suppliers and external partners which remanufacture and directly offer products to customers. - High quality service provision through network of actors.
Key Activities	- Attract customers which are willing to keep products for longer time. - Provide warranties for the product functionality and performance. - Provide upgrade plan to gain commitment. - Upgrade plan for B2B customers which require constant performance from the product in use. - Educate customers on how to use products in order to achieve longevity. - Initiate repair plans and accompany products with services.
Key Partners	- Ecosystem collaborations which will support repair and remanufacturing activities. - Make network and outsource activities related to maintenance and repair while the service offering remains with the initial manufacturer.
Resources & Capabilities	- Design products to last longer in order to reduce faults, damages and eventually faster disposal. - Offer product upgrade and modules which will make the customer keep the product for longer. Upgrade with additions, software, service. - Technological resources to support upgradability, real-time data transfer and performance monitoring. - Technological capabilities and life prediction models which will ensure product life extension.
Channels	- Online and virtual channels to support after-sales services and upgrades. - Direct and online sales for remanufactured and refurbished products. - Virtual service for design customisation and long use support.
Cost Structure	- Financial savings from material savings since remanufactured products can be resold without the need for making new products.
Revenue Stream	- Revenue from ”premium” products with durable design. - Revenue from services for repair and upgrading. - Non-financial gains from customer lock-in and long-term relationships.

CBM Elements for Intensifying

The final category of CBMs which revolve around sharing of resources and products is clustered within the intensifying circular strategy. Offerings in this business model setting are accessed by multiple users increasing in that way availability options. The products are provided either for temporary ownership or through a use-based service which allows for product performance exploitation without the need for high investment costs. Platforms are also included in the agenda of the aforementioned products as points of connection between users in order to exchange resources and minimize waste. The targeted market segment includes customers who are in need of a low priced temporarily available solution or customers who want to make profit by sharing their own products through a facilitating platform. The customer relationships are withheld through temporary contracts or platform subscriptions and customer engagement management.

The core activities to be performed in order to shape an intensifying based CBM mostly relate to the firm-customer relationship in a way that can embrace loyalty and satisfaction. Customers should also be educated to share products within a circular economy manner and consume collaboratively. Additionally, an integrated product-service system and infrastructure design are required to support performance-based offerings and constant availability of products to customers. Key in this CBM is the contribution of a network of partners responsible for monitoring of the products, facilitating user connections and supporting internal and external capabilities integration for sharing offerings. The major capabilities and resources are built on the fact that the manufacturer is the service provider which maintains the ownership of the product in use by the customer. Therefore, technological and customer management (through platforms) capabilities are necessary to support product digitalization, monitoring, repair and redistribution for share.

The communication and value transfer to customers can be achieved through indirect customer-to-customer sales and online mean since multiple assets are in use by multiple users. Platforms are supporting channels which serve as connection points between the user and the service provider. Implementing an intensifying CBM supports savings from collaborative use and resources/energy minimization to a greater extend when considering the cost structures. In addition, new revenues can be introduced from charges and dynamic pricing per use and platform subscription fees. On top of that, recurrent revenues can also be yielded from temporary contracts related to services which lead to customer lock-in and loyalty schemes which can lead to customer/user base increase.

Table 13: Proposed structure of CBM elements when implementing the "intensifying" strategy.

CBM Elements	Proposed Formation in Intensifying
Product/Service	- Shared value with increased availability and lower price. - Temporary exploitation of product functionality, product owing remains by the manufacturer. - Structured platforms which support product/parts/components sharing or pooling.
Customer	- Network of users/consumers which aim for lower pricing and broad range of choices. - Customers which aim at making a profit from sharing or resources trading.
Customer Relationships	- Suppliers and external partners which support automated or personal assistance. - Customers engagement through platform and shared reviews regarding service quality. - Customer engagement management.
Key Activities	- Infrastructure building which can support products sharing. - Educate for collaborative consumption. - Management of customer relationships as a practice to ensure satisfaction and loyalty. - Design product-service-system which can support both the product being shared and the service which accompanies it.
Key Partners	- Suppliers management, connect internal and external capabilities to support sharing models. - Connection channels and platform for material/products sharing in a B2B basis. - Create network to inspect products in use and ensure quality, longevity and abuse reduction.
Resources & Capabilities	- Product ownership remains with the manufacturer which manages repair and redistribution. - Online platforms to manage product leasing/pooling and embrace sharing among users. - Technology-related resources to support digitalisation and product monitoring during collaborative usage.
Channels	- Apps and online webs for users connectivity and service delivery. - Online platforms for products/material sharing/trading. - Online advertisements as indirect communication channels to promote sharing and collaborative consumption. - Indirect sales through C2C channels.
Cost Structure	- Savings from products reuse by multiple users, benefits from extended lifecycles. - Savings from resources reduction and energy efficiency due to multi-usage.
Revenue Stream	Revenue from new non-ownership contracts. - Profit from performance- and function-based contracts, charging per use or for results. - Recurrent profits from temporary service contracts (customer lock-in). - Increase profit through customer loyalty. - Profit from platform fee for resources trading (subscription pricing). - Dynamic pricing through usage monitoring.

4.4 Connecting I4.0 Technologies with Circular Strategies and CBM Value Components

The final step of the framework development includes the dimension of the I4.0 technologies with regards to the circular value and the strategies. As mentioned in the literature, the technological capabilities act as enabling forces which allow manufacturing firms to integrate circularity in their business models. Therefore it is deemed necessary to indicate which technologies can support the implementation of the various circular strategies. On top of that it is also beneficial to identify how the capabilities of each technology can support the transition towards CBMs through the changes they impose on the circular value proposition, creation, delivery and capture.

I4.0 Technologies and Circular Value BM Components

Based on the information that have been collected throughout the literature review and compared through the third table in appendix B, it is possible to categorize the capabilities of the technologies based on their relevance with the value components of a business model, namely the value proposition, creation, delivery and capture. This can give a clear understanding on how technological capabilities mentioned by most researchers can be exploited to support circular value. With regards to section 2.8, the capabilities of the I4.0 technologies and their contribution in the value components were clustered and presented in the tables 14, 15, 16.

Table 14: Contribution of I4.0 technologies capabilities on the circular value proposition.

Circular Value Proposition	
Internet-of-Things	- Enables product customisation, collaboration for design and facilitates services development for product-service-systems. - Enables tracking of materials/products and flow mapping ensuring recycled materials quality for reuse. - Supports data collection regarding customer needs. - Supports data collection regarding energy consumption.
Big Data & Analytics	- Facilitates analysis of product requirements and optimises design processes to reduce resources utilisation. - Promotes reuse by enabling the development of "product passports" (digital documents containing information about the product).
Machine Learning, Artificial Intelligence & Augmented Reality	- Processes optimisation and energy consumption minimisation through prediction models based on previously produced products. - Enhance customer experience through virtual product demonstrations and training (no need for physical products). - Prediction models for product performance to reduce deficiencies and keep customer satisfied.
Blockchain	- Enables reliable informational or financial transactions with verifiability and security (especially between users).
Cyber-Physical System & Additive Manufacturing	- Enables remanufacturing and assembly/disassembly in an energy and resources efficient manner based on automated process control. - Allows for interaction between manufacturing workforce and robots for process optimisation. - Enhances customisation and connects customers with product design, prototyping, assembly and direct material collection from suppliers (treated waste as feedstock for 3D printing). - Reduces energy consumption in terms of transportation due to mobile options, brings customer closer to production. - Supports quick product repair and printing of damaged parts for product life extension. - Efficient maintenance processes through automation.
Cloud Computing	- Facilitates real-time data collection for process or design optimisation and resources efficiency. - Enables live product performance monitoring allowing for modifications to increase customer satisfaction. - Supports upgradability and constant software support through platform integrations. - Enhances customer experience through live tracking, logistics monitoring and product-service performance.
Simulations	- Company-customer digital product co-development to increase customisability and enhance proposition while reducing rework and waste. - Supports digital design of products for easier recycling and repurposing. - Supports digital design of products for easier recycling and repurposing.

Table 15: Contribution of I4.0 technologies capabilities on the circular value creation & delivery.

Circular Value Creation & Delivery	
Internet-of-Things	- Facilitate data collection through RFID, sensors and barcodes. - Facilitates resources flow tracking through the life cycle and along the value chain.
Big Data & Analytics	- Connection between service providers and users via communication platforms, hyperconnectivity. - Large data processing as collected by IoT for product lifecycle tracking and resources use optimization. - Analysis of energy consumption (through sensors) and optimization for increasing renewables share and reduce overall cost.
Machine Learning, Artificial Intelligence & Augmented Reality	- Prediction models for remaining useful life and maintenance planning for product use extension.
Blockchain	- Secures product traceability and accuracy in data collection from sensors and IoT. - Offers transparency in information flows especially in complex supply chains with multiple connections and actors. - Supports reverse logistics systems with transparency and enhances customers trust and confidence regarding processes and product quality.
Cyber-Physical System & Additive Manufacturing	- Automation of production and waste shorting processes to minimize energy consumption and increase material separation efficiency. - 3D printing facilitates waste repurposing and material reuse for new product development which reduces energy and resources emissions.
Cloud Computing	- Updated and live data to keep a balance between supply and demand for resources efficiency.
Simulations	- Facilitate prognostic models for processes optimization and product lifecycle management through digital trials. - Allow for performance calculations in closed-loop supply chains and optimization for maximum resources efficiency. - Facilitates the development of product digital twins in the design and conceptualization stage and indicate potential value creation which reduces waste needed otherwise for trials.

Table 16: Contribution of I4.0 technologies capabilities on the circular value capture.

Circular Value Capture	
Internet-of-Things	- Data collection for process or product optimisation purposes which will reduce overall cost. - Supports platform and app integration for sharing purposes creating new revenue streams.
Big Data & Analytics	- Provides open-source capabilities and data access for recycled products which enhances resources trading (new revenue streams).
Machine Learning, Artificial Intelligence & Augmented Reality	- Financial predictions and efficient optimisation of processes for energy, resources and cost reduction.
Blockchain	- Facilitates safe contracts and connections between customer, suppliers and company which reduces digitalisation risk. - Transparent financial transactions which increase customers trust and willingness to pay.
Cyber-Physical System & Additive Manufacturing	- New revenue streams through manufacturing-as-a-service subscription pricing. - Savings on prototyping costs with use of by-materials in lower and customized prices.
Cloud Computing	- Operating cost reduction for storing and analysis of data.
Simulations	- Enables error identification in design phases before the process is performed (avoids error cost).

From those tables it is clear that the different technologies falling into the I4.0 agenda, have mainly capabilities that can enable or facilitate different activities in order to promote circular value. In a broader sense, data technologies, for instance IoT, big data, ML, AI, AR and cloud computing can collect, store and analyse data deriving from the whole life cycle of a product. With those capabilities the quality of the products and its functionality can be ensured during a circular proposition. The value proposed is being created and delivered through data analysis, useful life prediction models and services all supported by the data technologies as described in the table. Additionally, the value is captured by optimized processes which allow for cost reduction and service charges leading to new revenue streams. A share in circular value have also robotic, CPS, AM and simulation technologies which enable product customization, automation and optimization of processes as well as servitization of manufacturing for additional financial benefits. Finally, it is clear that, blockchain is stressed by most researchers as the one to secure data transparency and permit trustworthy transactions (financial, resources) and therefore it is placed within the map of I4.0 technologies which enable circular value.

I4.0 Technologies per Circular Strategies

The technological capabilities identified in the literature were further grouped based on their relevance to the circular strategies of greening, narrowing, cycling, extending and intensifying. The categorization is based on information collected from the literature and summarized in the third table of appendix B. Through this table it is possible to map the different circular practices and the technologies that could be applied to support them. The selected papers are highly cited and closely related to the topics of circularity and Industry 4.0 capabilities. Since the practices have been clustered within the circular strategies in section 4.1, the same structuring is also followed here for coherency purposes. This step is necessary as it will provide the link between the technologies of the I4.0 agenda, the circular strategies and the value components of a CBM. Based on that and the key points deriving from the study performed (Third table in appendix B), the following table 17 was formed.

Table 17: Contribution of I4.0 technologies per circular strategy.

I4.0 Technologies	**Contribution per Circular Strategy**	
IoT	***Greening:*** - Data collection for energy efficiency - Connectivity with partners ***Narrowing:*** - Data collection for service monitoring - Connectivity for supply and demand monitoring ***Cycling:*** - Resources tracking and condition monitoring - Connectivity with customers for products return	***Extending:*** - Data collection of usage and customer needs - Resources tracking and condition monitoring ***Intensifying:*** - Resources tracking and condition monitoring - Connectivity with customers for products return
Big data, Analytics & Cloud Computing	***Narrowing:*** - Data analysis for consumption pattern recognition and reduction	***Extending:*** - Usage patterns identification for services improvement, upgrade ***Intensifying:*** - Real-time data exchange and connectivity - Usage pattern analysis and sharing
CPS & AM	***Cycling:*** - Automation for optimised resources recovery - Efficient resources collection and shorting	***Extending:*** - Automation for efficient maintenance and manufacturing/remanufacturing - Customised manufacturing and product designs ***Intensifying:*** - Multi-user access to automated manufacturingas-a-service (3D printing)
ML, AI & AR	***Narrowing:*** - Prediction algorithms for supply and demand - Life-cycle expectancy prediction ***Cycling:*** - Material/product condition prediction - Consumption patterns analysis for reselling and efficient redistribution	***Extending:*** - Predictive maintenance for service support - Upgradability suggestions and dynamic pricing ***Intensifying:*** - Usage and end-of-life prediction - Dynamic pricing - Connectivity provisions through matching algorithms
Blockchain	***Cycling:*** - Data transparency and verifiability - Secure resources trading among stakeholders	***Extending:*** - Secure product information management for disassembly, repair and maintenance ***Intensifying:*** - Transparent intra-user transactions - Privacy and security insurance
Simulations	***Greening:*** - System (energy, ecosystem) modelling - Scenario testing (weather conditions, energy loads) ***Narrowing:*** - Conceptual service development and user education - Scenario testing for product development with alternative or less materials	***Extending:*** - Conceptual design for longevity and performance checks - Design and maintenance scenario testing ***Intensifying:*** - Scenario testing for complex supply chain management - Customer education and experience improvement

5 Case Studies

This chapter describes how the theoretical research, and the HCBMT framework are being applied in a real business setting to give a practical complexion to the study. To gain an understanding of how the findings can contribute to the broader circular economy era, subject matter interviews were performed with experts in the relevant field. As discussed also in the methodology, experts with a background on circularity and business development were approached as relevant audience to convey knowledge insights. At that point, it is worth mentioning that the targeted unit of analysis was technology manufacturing companies which perform circular activities in their business settings. However, due to time restrictions and the limited network of contacts, it was challenging to reach only this cluster of manufacturing firms. Therefore, businesses from different industrial clusters have been contacted and a diverse agenda of experts was employed for conducting the interviews, with circularity to be their common line. In that way, the limitations mentioned turned out to be benefits for this study as multiple industrial clusters have been studies allowing for comparisons and interdisciplinary data extraction. The interdisciplinary agenda of the companies employed for the cases is given in table 18.

Table 18: Company profiles and brief description.

Company Description	Industry	Company Age (years)	Location (NL)
Philips A global leader, offering cutting-edge solutions in healthcare, consumer lifestyle, and lighting, with a mission to improve lives through innovation and human-centered design.	Healthcare and Domestic Appliances	100+	Eindhoven
Royal Ahrend A renowned company specializing in sustainable office furniture solutions. They blend functionality, aesthetics, and ergonomic design to create comfortable workspaces that foster productivity and well-being.	Office Furniture	100+	Amsterdam
Sif Group A prominent player in the offshore wind sector, providing custom steel foundations for wind farms. They deliver high-quality solutions, contributing to the renewable energy transition with their expertise and commitment to sustainability.	Steel Offshore Wind Turbine Foundations	50+	Rotterdam
Additive Industries A top-tier company in 3D printing, providing advanced solutions for industries like aerospace, automotive, and healthcare. They drive innovation, optimize production, and enable groundbreaking design possibilities through their expertise in additive manufacturing.	Industrial 3D Printers	10+	Eindhoven

The companies mentioned in the table already demonstrate partial circular actions in their product offerings and possess some experience in the field. Philips and Royal Ahrend show a stronger commitment to circularity with recycling and circular design activities; however, their participation in the present study aims to explore CBMs beyond their current operations. On the other hand, Sif and Additive Industries, being less active in the circular economy, are particularly interested in developing CBMs to enhance their products and optimize resource utilization.

5.1 Findings

This section provides an overview of the findings as derived from the expert interviews. The qualitative data were analysed by positioning the discussion points in code and sub-code clusters as described in the methodology section. To keep a coherent structure, the data will be presented per case based on the points identified to be key for covering the discussion objectives. A more extensive analysis of the expert interviews can be found in the appendix C where the family codes as emerged from the discussion are presented and comprehended. It is worth repeating at that point that the findings presented derive from an interview saturation methodology whereby questions with similar meanings were posed to the participants within the same interview to gauge the consistency of their insights. This is reflected in the codes of the thematic analysis which represent the main concepts discussed with no additional insights being encountered although redundant questions were asked to an extent.

Case 1: Healthcare and Appliances Manufacturing Company (Philips)

The key findings of the expert interview are stemming from the codification as presented in the first table in appendix C. Based on the three phases of the interview, the points with the most relevance to the study were summarized and presented in a form of key findings based on core themes. Those themes are, the importance of circularity and the challenge towards its implementation, the structuring of the CBM (based on strategies, elements and technologies) and the evaluation of the HCBMT framework. For coherency purposes, the same structuring will be also used for the other cases as presented below.

Keynote: Drivers to circularity

- Large organisations need to change their traditional linear processes in order to be more efficient and sustainable.
- Circularity enables new relationships with the customers which are necessary to regain products and increase revenue from waste.
- The essence of circularity is linked with innovation of supply chains and is required to stay competitive in the market.

Keynote: Challenges towards circularity

- Legal implications which restrict the reselling and the refurbishment of products. Its difficult to implement those strategies since the strict regulations are applied regarding the quality and the functionality of the product.
- The customer trust in circular offerings is a big barrier for implementing and introducing circular practices. Customers prefer to buy new products instead of a refurbished or reused product.
- Customers luck motivation and knowledge to bring products back at the end-of-life, therefore closing the loop is hard to implement without their contribution.
- Calculating the cost and benefit from remediating resources, materials and parts is hard to justify leading to delays in the implementation of circular actions.
- Tracking product after sales is hard to control especially those that have been produced in high volumes and are distributed internationally.

Keynote: Circular Value Chain

This keynote concerns the circular strategies along the value chain with regards to the company's orientation.

- The cycling strategy in reverse logistics is the main focus in order to take back valuable resources.
- All the stages of the value chain need to be running fully on green energy in order to increase sustainability, from production to distribution to reverse supply chain.

- The circular strategy starts at the level of design & manufacturing where the product is necessary to be designed for ease of disassembly. The extending strategy can be applied as a circular option in that stage.

Keynote: CBM structure

This keynote is divided into two thematic sections. The first one refers to the elements of the business model (divided by the value proposition, creation & delivery and capture) as mapped by the expert on the framework. The second one concerns the application of I4.0 technologies to support the implementation of the business model.

Circular Strategy & Value Proposition

- Applying the cycling strategy and enabling take back systems and reverse logistics will allow for product offerings made of recycled materials.
- The product is proposed as sustainable and low price offering which should be collected by the manufacturer at the end-of-life.
- Environmentally incentivized customers in need of low priced products is the targeted segment in the market.
- Offerings with take back proposition aim at long term relationships and collaboration with the customers along the product life cycle (synergistic relationship).

Value Creation & Delivery

- Key activity to perform is the education of the customers to bring back the used products in exchange to new ones.
- To enable take back systems facilitators are required as partners to support and structure a reverse logistics plan.
- Technologies are required to enable product tracking. In addition, collection points are needed to solve the problem of resources shorting.
- The circular products can be delivered to customers via traditional direct channels or through online means to strengthen the communication of sustainability. Distribution can be also aimed through third party retailers.

Value Capture

- Retrieving value from waste and using old resources in new products can save production cost and lower product price.
- Buy-back schemes can introduce new revenue streams and motivate people to make use of take-back systems.

Contribution of Industry 4.0 Technologies

- Internet of Things is a tool that can be used to monitor the high value and low volume products in order to ensure its functionality. This can be a way to support the value proposition of refurbished products and cycling based offerings.

- Tracking through RFID technology will allow for data gathering of the exact location of the product in order to easily take back and closing the loop.
- Calculating the savings from the value retrieved will require big data and analytics for defining the remediation cost structures.
- Products with high complexities might require additional technologies to be supported while in use. The choice of specific technologies depends on the product or the service to be offered.

Keynote: Evaluation

- The framework can be useful for the value proposition creation phase to provide insightful information about the circular strategies and actions along a business model.
- Easy to use with structured, high value knowledge that can spark discussions and ideas.
- The framework leans more towards theoretical ends but it can be informed in an ideation workshop to support brainstorming around circularity.
- Examples of companies that have performed circular strategies are missing. This would make the framework more tangible from a business perspective.
- More time is required to navigate through the framework to zoom into details.
- Metrics for the potential value retrieved by applying circularity could be beneficial to have but is hard to collect data since companies are not sharing (confidential).
- To further help generate ideas during a workshop, examples of imaginary products or services based on the company examined will be required to inspire idea generation and guidance.

Case 2: Furniture Manufacturing Company (Royal Ahrend)

The key findings of the expert interview presented bellow are stemming from the codification as presented in the second table in appendix C.

Keynote: Drivers to circularity

- Satisfying the constantly changing customer needs can be achieved through the flexibility of circular leasing options.
- Circular design can lead to product life extension allowing for long lasting profits from the same product.
- With circular actions the company has a sustainable face towards society.

Keynote: Challenges towards circularity

- Applying circularity to other countries is challenging from logistical and perceptional point of view.
- Convincing customers about leasing equipment in a broader circular manner is hard to achieve.
- A circular design can be of benefit to other companies and its hard to secure exclusive profit.

Keynote: Circular Value Chain

- Taking back and recycling the product is the main focus to close the value chain.
- The extending strategy is applied at the design stage (design for refurbishment).
- During the use phase applying leasing options can intensify the value of the product and reduce the production of new products. Therefore it is preferable to sell the product-as-a-service in this stage.

Keynote: CBM structure

Circular strategy & Value Proposition

- The main focus is on innovation of new materials that will narrow the use of old recycling materials. This can be complemented by taking back actions.
- The product proposition is based on a lightweight offering with innovative materials and reduced environmental footprint.
- The targeted customers have sustainability as a common factor.
- Customer relationships should be flexible in circular offerings to built loyalty and experiment along with them.

Value Creation & Delivery

- The key activities in a combined narrowing and take back system is customer education and direct communication.
- Local partners are required with low social and environmental footprint to support more the narrowing strategy.
- Testing the new products is important therefore long-term relationships with partners and customers are required. Pilot programs and platforms can assist the product offering.
- The platform can serve as intermediate point between customers and the company to take products back and transport.
- To innovate on materials R&D capabilities are required.

Value Capture

- A buyback scheme would secure product take back and savings on materials and production cost.
- New revenue can be aimed through collaboration with customers leading to loyalty gains.

Contribution of Industry 4.0 Technologies

- RFID technology can contribute in product location tracking and monitoring.
- Building knowledge on materials through material technology is useful to innovate material used as part of circular offerings.
- For the customization of the products simulations can support the circular value offerings.

Keynote: Evaluation

- The framework can be helpful to approach circularity in a process and can be used in an ideation phase since it contains structured knowledge points.
- The material and social point of view are missing as components.
- The scope seems familiar and complete, more time would be beneficial.

Case 3: Steel Structures Manufacturing Company (Sif Group)

The key findings of the expert interview presented bellow are stemming from the codification as presented in the third table in appendix C.

Keynote: Drivers of circularity

- Circularity is an opportunity to reduce resources and increase the share in sustainability actions.
- Gaining sustained competitive advantage is something that can be achieved by circularity.

Keynote: Challenges towards circularity

- When the product is part of a larger system its hard to apply circularity.
- There are financial barriers since large investments are required for circular actions.

Keynote: Circular Value Chain

- The reverse logistics is the main stage to have in order to close the loop, take products back and recycle.
- Green energy and electrification are key strategies to apply in production which consumes most of the energy in the value chain.

Keynote: CBM structure

Circular strategy & Value Proposition

- Cycling is the main target from which products are taken back and value is aimed through recycling. This can be combined with a novel production method for less energy consumption.
- The product offering will be the same but its composition will be based on recycled materials. (more sustainable value proposition)
- That offerings are targeting environmentally incentivised customers.
- To take old products back long-term relationships are required both with customers and suppliers.

Value Creation & Delivery

- Partnership with the suppliers are required to initiate resources trading. Additional partners are needed to allow reversing of the supply chain and take products back.
- The key activities should include accessibility to the product at the end of life and production line changes to allow recycling.

- Important activity is also the communication of the new circular concept directly with the customers.
- A shorting facility is required. Additional special equipment should be considered to take products back.

Value Capture

- Using material from old products in new products can save energy and resources.
- Revenue can be admitted from selling recycled products with a fee for taking products back.

Contribution of Industry 4.0 Technologies

- Data collection is important for condition prediction and support of the recycled products value proposition.
- Material passports with data about the product can be supported by big data and analytics.
- Automation can contribute in waste streams minimization.

Keynote: Evaluation

- The framework can initiate discussions especially for companies which lack knowledge on circular actions.
- The value gained by each strategy is not quantified.
- It would be beneficial to let companies ideate first on the steps required for circularity and then present the components of the framework.

Case 4: Industrial 3D Printers Manufacturing Company (Additive Industries)

The key findings of the expert interview presented bellow are stemming from the codification as presented in the fourth table in appendix C.

Keynote: Drivers of circularity

- Circular implementation can lead to resources reduction and provide efficiency over the competitors.

Keynote: Challenges towards circularity

- Knowledge is missing on the circular aspects which restricts its implementation.

Keynote: Circular Value Chain

- Servitization can be applied at the use phase for selling the performance and not the ownership of the machine.
- The use extension can be combined with narrowing by upgrading the product at the customer location. Also narrowing can be applied in marketing and sales by providing services.

Keynote: CBM structure

Circular strategy & Value Proposition

- Additive manufacturing is a flexible technology and multi-client use can be an opportunity.
- The value proposition of the product-as-a-service can offer access options and reduce the investment costs for clients.
- The target customer segment in such proposition range from manufacturers to suppliers, to end users who want to have access to the product for temporary use.
- In a product-service system direct communication with the clients and special relationship per case is key.

Value Creation & Delivery

- To deliver the leasing value suppliers are required as partners. In addition facilitators are needed to take over outsources activities.
- At the end of use reverse logistics partners are required.
- First key activity is the calculation of the leasing costs.
- When activities cannot be performed in-house, partners and facilitators are required for outsourcing.
- Educating customers and communicating the new value is crucial.
- Gathering information during the product use is necessary and a platform is required as a key capability.

Value Capture

- Benefit can be admitted from the modularity aspects of the product which will allow for profitable changes.
- Profit can be gained through fee for ugradability (optional) and subscription scheme for using the product in a service mode.

Contribution of Industry 4.0 Technologies

- Field data during product sharing are necessary to ensure a good condition. Through big data, information can be analysed to improve printing and multi-use processes.
- Data sharing trust is key and blockchain technology allows for secure transactions.
- Simulations can be optional but will allow customers to customize prints and oversee the machine operation.

Keynote: Evaluation

- The framework looks clear and the way of thinking familiar.
- More time would be needed to navigate through and some examples for the practical aspect.

Based on the key findings from the discussion a summary board is presented showing how the manufacturing companies studied use technologies. Figure 9 highlights the different I4.0 technologies used by the cases to shape their CBMs. As presented, each firm proceeds with a circular strategy and certain technologies to enhance a circular value proposition, creation, delivery or capture which are all mapped on the following board. In that way it is also possible to identify commonalities and differences among the different manufacturing sectors and also understand their viewpoints with regards to the technological choices for supporting their transition towards CBMs.

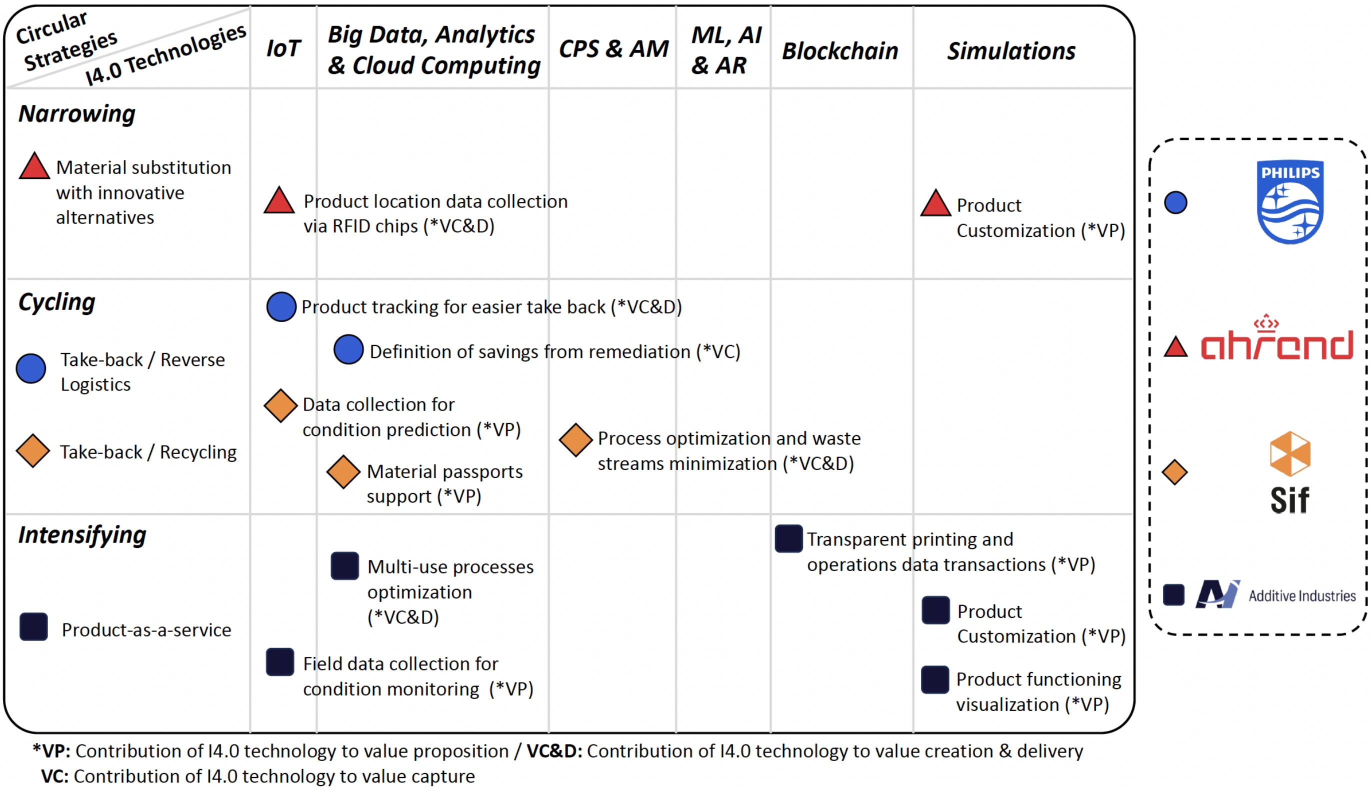

Figure 9: Technological landscape for enabling CBMs per case.

5.2 Interpretation of Findings

The findings from the interviews can be deemed as important as the literature information since a combination of theoretical and practical insights can enrich the content of the research study. The cases can be used, in that way, as a mean to refine the HCBMT framework as proposed in section 4 with key points regarding both the content of the framework but also the visual attributes. The experience of the companies in the circular economy was key to unlock knowledge regarding the potential strategies, the required technologies, the value chain steps as well as the formulation of the CBM elements.

Drivers and Challenges towards circularity

Taking into account the key points discussed in each case it is possible to understand why those manufacturing firms are keen on transitioning towards CBM, which increases the value of the study and the framework from a practical point of view as well. In general, companies see circularity as an opportunity to be efficient on resources and energy consumption and as a mean to promote its actions on the face of sustainability. In all the cases, retrieving value from the waste is a chance towards new revenue streams and profit. In addition, circularity can offer advantage over competing companies which continue on a linear basis without closing-the-loop. Finally, the flexibility which can be offered through sharing CBMs is a way to satisfy the constantly changing needs of the customers. Those are the major drivers for companies to apply circularity and BM based on it, as discussed by the present case studies.

Implementing circularity comes also with challenges which can be identified among five aspects. The first is the legal frames which are imposing strict regulation when a manufacturing firm wants to proceed with reuse of products which have to follow certain rules. On the other side the trust of the customers on recycled products along with their lack of motivation to bring products back are blocking factors towards the implementation of CBMs as encountered by the manufacturers. In addition, one of the cases showed that when a product is designed in a circular way and sold in the market, it is hard for companies to secure the exclusive ownership of the product. In that way circular actions might end up having no value for the manufacturer as others companies are taking advantage of the circular design and perform refurbishment. Besides that, an important barrier towards circularity that has been identified through the cases is that manufacturers sometimes lack knowledge and guidance on how to apply circular strategies in their BMs, an issue that the current study opts to surpass to a greater extent.

Circular Value Chain

The aspect of the circular value chain has also been discussed and a commonality among the different manufacturing companies highlights that a reverse logistics stage is necessary in order to close the loop of resources and take old products back. Those products can thereafter be used as inputs to the new products and contribute to the circular aims. In addition, based on cases cross comparison, the greening strategy can be applied in all the stages of the value chain to gain sustainable value and should be communicated and promoted in the marketing and sales stage. With regards to the use stage in the value chain, combining the narrowing strategy with the extending strategy can bring additional circular value. This can be performed by upgrading the product at the customer's location in order to further minimize energy consumption for back-and-forth transportation.

Circular Business Models and I4.0 Technologies

In terms of the cycling strategy, companies aim to take back products for recycling or refurbishment in order to create new value propositions. Applying this strategy shapes the BM elements in a way that not only the manufacturing firm but also the network surrounding it embrace the transition towards cycling. More specifically, in that case mostly environmentally incentivized customers are targeted with long-term relationships and direct communication to be of utmost importance for securing product take-back. Partnerships play a crucial role in facilitating reverse logistics and closing the resource loop while recycling activities, along with key resources and capabilities, are essential for value creation. When the products of a company are produced in high quantities and distributed among a plethora of clients, a more sophisticated take-back system is required compared to companies producing in smaller quantities. By utilizing recycled materials, companies achieve energy and resource savings, while also generating revenue streams through buyback and collection fees. This strategy seems to be selected mostly by manufacturing companies (two of the studied cases have selected this strategy and the other two perform partially recycling activities) as an easy to apply strategy and well known so far. However, with that specific strategy value can be lost during the life cycle which might have been otherwise exploited by other mid-stage strategies (e.g., extending). For companies in sectors where complex and expensive material are used for the product offerings (e.g., the steel and the appliances manufacturing companies), the cycling strategy and more specifically actions related to take back and recycling are highly relevant since precious value can be admitted and exploited after the end of the customer use.

The intensifying strategy involves offering products as a service to customers. Depending on the physical composition of the product, the intensifying strategy can be applied by manufacturers where multi-use can be supported. To do so, the CBM elements are shaped in a way that promote product accessibility and constant constant security of performance while the ownership remains with the manufacturer. As indicated by the 3D printers manufacturer case the most important element is the service that supports the product sharing and how the CBM elements are shaped to support this service. In this type of offering, direct communication and special relationships with clients are crucial for ensuring customer satisfaction at first. Partners play also a vital role in ensuring product functioning and take-back after use. Besides the support of the partners, technology for the constant monitoring of the products is crucial for the company to oversee the utilization and the performance, especially in cases where the customer pays per product use and not the full ownership. For companies aiming to offer a PaaS cost calculation and customer education are among the key activities required as revealed from the cases. Building on this model, suggests revenue streams to be generated through subscription schemes while additional benefits can be admitted when companies combine the sharing offerings with options for upgradability. When compared to the cycling strategy, the intensifying one focuses also on the value creation and capture but from the sharing and the ownership keeping perspective. In sectors where the products can be servitized (e.g., the 3D printers manufacturer) the intensifying strategy can be of high relevance for transitioning towards CBMs. This can also be applicable to the appliances sector in a form of use-based offerings, securing in that way both the sharing of the products and the take back since the ownership remains with the manufacturer. This commonality between manufacturing sectors indicates that different proposition of the same product can lead to different circular strategy and therefore a different CBM.

For the furniture manufacturing sector where already recycled materials are used, further reducing the environmental footprint with alternative innovative materials is of high importance. Therefore, in cases or sectors that circular practices relate to materials substitution, the narrowing strategy seems to be a good fit. This strategy is structuring the CBM elements in a way that resources reduction in customer offerings and localization are core. In such offerings, flexible relationships with environmentally aware customers are important for testing new materials. By combining strategies such as narrowing and take-back and translating them into relevant CBMs, companies can create new value propositions and enhance their relationships with customers. Customer education and pilot programs for experimentation are crucial in this regard and are highly suggested for companies which aim at introducing new sustainable products in the market. Direct sales, local partners, and a minimal transportation footprint can support a sustainable delivery of the created circular value while also supporting the local community. R&D capabilities and a platform for company-customer connectivity are necessary resources for communication especially when the products are relatively new in the market. Through the narrowing strategy cost reduction can be achieved which is based on material savings from buyback schemes. In addition, companies working closely with customers can benefit from loyalty gains which can also be considered as a circular value capture mechanism with regard to new eco-friendly products which require customer engagement for building purchasing trust. Compared to the cycling strategy, the narrowing-based CBMs pay attention to the customer relationships and the local network instead of the product itself for exploiting circular value. When comparing the different sectors of the cases studied, the furniture manufacturer aiming at transitioning towards a narrowing-based CBM puts more focus on the proposition of circular products whereas sectors applying the cycling or intensifying strategy rather focus on creating circular value.

Overall, the manufacturing sectors with increased material costs and high-value products, for instance, the appliances and the steel manufacturing companies, focus on taking this value back in order to reduce the total production costs. In that case, the cycling strategy is the one that can highly shape the CBM elements towards this direction and assist the manufacturing companies transition in a circular era. On the other hand, in sectors where products can be shared among customers, as the emerging 3D printing industrial sector, the intensifying strategy can be a wise option to evaluate. Following the principles of this strategy can give specific direction to the CBM elements structuring while assisting manufacturing firms build a service and a strong network in order to transition to a product-service CBM. In addition, manufacturing firms clustered in a sector where sustainable offerings and less material utilization are the main objectives, for instance in the furniture manufacturing sector, the CBM structuring can be based on the principles of the narrowing strategy. Based on this strategy, manufacturing firms can apply different practices e.g., eco-friendly products and local networks and structure narrowing-based CBMs which will assist them achieve their circularity and sustainability goals.

For implementing circular strategies the technological contribution is necessary and at some points crucial as indicated by the cases. Among the various technologies presented in the I4.0 era, data technologies seem to have the greatest impact for the firms on the implementation of CBMs. IoT, RFID and big data technologies are commonly referred among the manufacturing sectors where monitoring and tracking the products along their life cycle is necessary for enabling circular offerings. Based on the cases in this study, all the manufacturers from the different sectors have selected the aforementioned technologies for monitoring the condition, the location and the life expectancy of the offered products. To apply CBMs related to the cycling and the intensifying strategy, data collection and analysis is of high importance, as discussed, for ensuring the product functionality and performance. In that way the manufacturing companies can enable their value creation which can propose to the customers. For the first and the third case where expensive and valuable materials are used in products, ensuring the location of the product via data technologies is a requirement when they want to initiate a take back system as a potential cycling based CBM. The value of tracking is especially embraced by companies with high volume productions which entails wide product distribution in the market, as for instance in the domestic appliances case. Product and condition tracking seems also to be important for the value proposition in the intensifying strategy as indicated by the 3D printing sector (fourth case), where IoT, cloud computing and big data analytics can play a significant role.

For the third case (heavy structures manufacturing sector) where material quality tracking matters when implementing circular strategies, big data technologies supporting material passports are more valuable than other technologies. On the other hand, companies which rely on circular product customization and face changing customer needs, for instance the furniture and the industrial 3D printers manufacturers, simulations technology is key enabling force to shape the value offered. In CBMs where data transactions are the core of the daily activities (e.g. sharing, PaaS models), the blockchain technology is highly demanded from manufacturing companies to secure transparency and increase customer trust. In that way, manufacturing companies transitioning towards intensifying-based CBMs, for instance the industrial 3D printer manufacturer use blockchain technology to enable secure value capture and create additional value (e.g. for processes optimization) within the same CBM. In addition, as commonly discussed by the furniture and the 3D printers manufacturers, simulations technology is also important to consider to enable both customization and drive circularity with customer satisfaction. In that way, circular products can be designed digitally along with the customer reducing the chances for changes and excess resources waste further downstream.

Overall, within the four CBMs that have been built among the cases, data collection technologies (e.g., IoT and RFID) seem to be the common technology the different manufacturing sectors studied would use for creating circular value and propositions while transitioning towards more circular offerings. In addition, big data technologies were also mentioned to be required as enabling forces, when product or materials quality monitoring matters for transitioning to a circular proposition. This is especially relevant to manufacturing sectors related to medical appliances and structural foundations where quality of circular offerings needs to be paramount for safety reasons. At that point, it is worth mentioning that none of the cases embraced the capabilities of the currently booming AI, ML, and AR technologies as a means to enable circular value. This indicates either that firms are still lacking knowledge in that area or that pose a trust-based opposition to new technologies with regards to circularity. On the simulations side, this technology is recognised as a key enabler for manufacturing firms to deliver value in a circular way particularly within manufacturing clusters where product proposition highly depends on customization. In essence, all these indicate that the implementation of circularity is hard to be informed without the support of technology (especially in the manufacturing sector) thereby both concepts should be approached simultaneously for the circular economy to be accelerated.

Evaluation

As can be seen from the case findings, overall, the HCBMT framework received positive feedback and is seen as a tool with structured knowledge which can support manufacturing firms in their ideation phases. Talking about its potential use, the framework has been envisioned by the experts as a mean to provide guidance during an ideation workshop set by companies to support their transition towards circular business models. The limitations identified among all the cases was the time constrain and the lack of metrics which will represent the value gained by applying each strategy. It was suggested that there should be an intermediate step for familiarizing with the board first and thereafter ideate on potential business models which can be extensively applicable to a workshop session. Integrating metrics about the value would have been more practical for companies but, as mentioned, gathering those information by companies will be hard since they can not be shared publicly.

5.3 Framework Enrichment

Based on the different perspectives and the information gathered by the cases, the framework has been enriched with the additions which will be thoroughly discussed in this section. Based on those additions and the aspects covered by the literature study, the refined HCBMT framework will be able to assist manufacturing companies in their transition towards circular actions and business models. Although the components and the perspectives of the framework do not encounter any changes, additions can be performed in terms of hoe the CBM elements can be structured based on the expert views. This can later help other manufacturing companies have a unique blend of literature and expert perspectives which can assist them further with their transition towards CBMs. In that way the research streams with regards to the CBM elements are also enriched since the perspectives to be following are not mentioned as made clear from the cases are required to be considered when building the various CBMs.

From the findings it becomes clear that the circular value chain is thoroughly defined and therefore no big changes are encountered. An addition that has been identified is the *optimize and reduce transportation* which can be applied as a narrowing strategy at the *use & service* stage. This is purposed at optimizing the iterative transportations between the manufacturer and the client. For instance, when products experience failures the manufacturer commutes to the customers locations and repairs the product instead of transporting the product to a maintenance facility, repairing it and transporting it back to the customers.

Based on the findings and the discussion that has been performed the following aspects can be added to the HCBMT framework with regards to the elements of a CBM and the I4.0 technologies that can support its implementation in the context of manufacturing firms. Those additions are purposed to supplement the tables 9-16 but for repetition avoidance, the refined tables will not be presented anew.

Greening strategy

- Product value proposition: Products produced with novel energy efficient methods.

Narrowing

- Customers: Green consumers with high sustainability awareness.
- Customer relationship: Flexible relationship to built loyalty and experiment new sustainable products, Direct communication to allow experimentation.
- Key activities: Pilot programs to test the new products.
- Capabilities: R&D capabilities to innovate new materials.
- Revenue streams: Loyalty gains from long-term relationships.

Cycling strategy

- Customer relationships: Long-term relationships aiming at product take back after use (synergetic relationship).
- Channels: Indirect channels through retailers.
- Key activities: Production line changes to allow recycling.
- Resources: Additional special equipment per case to allow take back.

Intensifying

- Product proposition: Inventory cost reduction instead of lower price.
- Key activities: Calculation of leasing costs, Customer education to create awareness of the sharing provision.
- Revenue stream: Profit from modularity leading to intra-use upgrades and changes.

Technologies

- Value proposition: Special technologies to support complex product use.
- Value capture: Big data to support savings calculation on value retrieved.
- Value creation: Material technology supports knowledge building on material aspects.
- Value proposition: Simulations support product functioning visualization.

Based on the evaluation performed by the experts on the framework some visual and structuring aspects have been performed. Metrics on the value gained per strategy and quantification were not performed as it is out of this study's scope. The positioning of the aforementioned additions in the HCBMT framework are presented visually providing a refined version of figure 7 as follows below. The extended version of the figure 10 can be found in Miro board (link), an assistive software for a more detailed representation of the components.

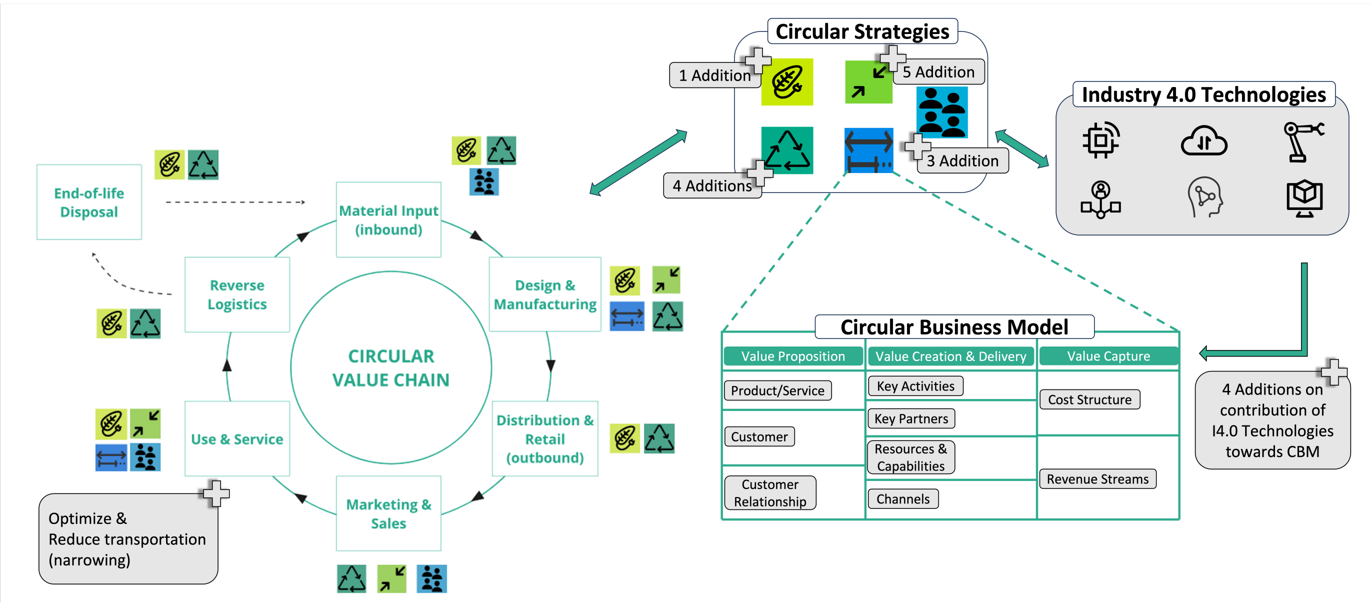

Figure 10: Enriched HCBMT framework with additions from case studies.

6 Discussion

The present study is purposed on making two distinct contributions, one on the academic and one on the practical side with regards to the transition towards circular business models. From a research perspective, three research streams have been combined providing an all-encompassing way of approaching the topic of circularity. This approach consists of the circular strategies, the contribution of those on the elements of a circular business model, the application of those strategies along the value chain and the contribution of Industry 4.0 technologies as enabling forces for informing the circular models. Structuring this novel approach in an HCBMT framework has also contributed on the practical side by providing an ideation tool able to assist manufacturing companies with the transition towards circular business models. Since the transition is informed in two phases, the ideation and the realization phase, and since the realization has been scarcely observed in manufacturing sector, the focus turned towards the first phase. By enhancing the ideation phase, practitioners will be able to take quicker and more structured decisions in order to increase the chances of the realization phase being applied.

Building the ideation tool was made in a form of a proposed framework as presented in section 4. The methodology to develop the HCBMT framework is based on literature and academic analysis, comparisons and comprehension which has been combined and structured in components. To enrich the academic field, the framework have been implemented and tested through cases of manufacturing firms where expert insights allowed to enrich the literature findings and supplement with a practical complexion. To have a diversity of insights and test the application of the framework in a broader sense, manufacturing companies from different industrial clusters were chosen to complement this study. The sections following bellow discuss more in details the contributions to the research and the practice as well as how the HCBMT framework has been developed.

6.1 Literature Insights

From a theoretical point of view, this study adds to the literature by proposing a combination between three major research streams, namely the CBMs, the circularity concept along the value chain and the contribution of I4.0 technologies on circular actions. More specifically, this study adds to the existing publications a structured tool which allows for structuring a CBM by showing how the BM elements should be approached when a specific circular strategy is being employed. Through the literature research it was revealed that the currently used tools do not proceed with a direct connection of the circular strategies with the BM elements. Key studies such as that of (Lüdeke-Freund et al., 2019) and (Geissdoerfer et al., 2020) perform such connection but only on the value level without providing a clear and structured overview of how each BM element should be formed to support the transition towards CBMs. In addition, a limitation that has been identified and searched further was that, none of those studies as well as the additional publications researched in section 2 have acquired the technological perspective which has been identified as a disconnection between circularity and Industry 4.0 paradigm which seem to progress in parallel nowadays.

Through the analysis of the literature on the aforementioned concepts, it was possible to first identify that there is a continuous ambiguity on which aspects are considered as circular strategies and which as circular practices. It has been revealed that the mostly the cycling and the extending strategy have been discussed, however, all the strategies have been considered and analysed to address commonalities and unique characteristics. Strategies that were overlapping with each other based on their characteristics and attributes were eliminated leading in that way to five distinct strategies, the greening, narrowing, cycling, extending and intensifying. Although the narrowing and the greening strategies are not entirely linked to circularity, they can be considered in the strategies agenda as they contain principles which can be characterised as circular. For instance, applying renewable energy can support depleting resources consumption and designing for material reduction can be considered circular on its own.

In addition, this study approaches the circularity topic from the perspective of the value chain. Other tools such as the "Butterfly Diagram" (EMF, 2023), suggest different practices along a value chain but based on the literature findings, in every value chain stage more than one practices can be applied. Apart from that, the tool mentions the different practices but does not provide guidance on how those can be linked to a BM of a company or organization. To add to this disconnection, after defining the circular strategies and clustering the circular practices under them (based on their characteristics) it was possible to get a broader view on the value chain. More specifically, the strategies have been applied directly along the seven stages of the circular value chain which later have been connected directly to the elements of a CBM. Finally, this study builds upon the capabilities of the I4.0 technologies and provides a clear understanding of how technologies can support the implementation of the various circular strategies and the transition to CBMs to a greater extend. Overall, through this study, it was made clear that all three perspectives (strategies, value chain and technologies) should be considered in order to better understand how circularity can be supported and informed.

6.2 Framework Development

The second phase of the study concerns the development and proposition of a framework in order to structure the knowledge collected from the literature and translate it into a handy tool that can be later used by practitioners. The studies collected were analysed and compared leading to a HCBMT framework which includes the five distinct circular strategies, seven stages consisting a circular value chain, nine dimensions related to the CBM elements, thirty-two circular practices and six distinct technologies with its capabilities and contribution to the circular value. Those dimensions have been chosen based on literature studies with the common connection points to be the circular practices and strategies. The approach for developing the HCBMT framework was based on an effort to connect the various research streams with the five distinct strategies as those have been clearly defined and supported by publications. With that in mind, the following interconnections have emerged based on the literature that has been studied, circular practices clustered under circular strategies, circular strategies clustered per value chain stage, CBM elements clustered under each circular strategy and I4.0 technologies clustered under each strategy. To have a complete set of dimensions but also remove the possibility of overlapping between the elements discussed by scholars, the MECE principle has been employed. This indicated that the components of the framework are mutually exclusive and collectively exhaustive.

From the framework development some findings can emerge regarding the connections and the structuring of the CBM elements based on the particular strategy. Firstly, when considering the I4.0 technologies, a connection with the strategies have been made but not directly with the elements of the CBM. Although this has been considered, the only connection that can be identified in the literature is that of technologies and their contribution on the value proposition, creation, delivery and capture. This has also been the case for the HCBMT framework, since the purpose was to include the technological aspect as an enabling force and not as a requirement in the CBM elements for achieving the transition towards circularity. More specifically, the capabilities of the technologies studied have been mapped per circular strategy and not per CBM element. However, since circularity and I4.0 era go hand in hand, and the technologies are a key factor for enabling circular value it would be beneficial to further research and map its contribution directly on the elements of a CBM, an aspect that has been kept out of this study's scope.

Secondly, from the framework structuring it is clear that network contribution is key for the implementation of the circular strategies and the transition towards CBMs. This shows that the BM elements are dynamic and depend on the choices and actions of the various stakeholders, including customers, suppliers and partners which indicates that the need of the circular value chain concept in the CBM development is necessary. In that way, the connection between the strategies with the stages of the value chain not only supports the concept structuring but also gives a dynamic perspective on the CBM elements. Through this aspects it can be possible to implement different CBM and map them on the various stages of the value chain, however, this requires additional research and comprehension.

6.3 Framework Implementation and Evaluation

Since the HCBMT framework has been developed from the theoretical side but purposed for practical contribution, it was rendered valuable to implement it in real business settings and gain some additional insights from a practical point of view. This is achieved through four distinct cases of Dutch manufacturing companies which have adopted CBMs in the past of have plans to admit the value of circularity in the near future. The purpose of the case studies was firstly to validate the statement that circular economy is of high importance for manufacturing firms and identify some key challenges towards CBMs and secondly to test and validate the functionality of the theoretical framework in practice. The first aspect revealed that the manufacturing companies studied are willing to transition towards circular business models as an opportunity to reduce resources and energy consumption as well as build an advantage over their competitors. On the other hand, the major challenges identified relate to legal and financial barriers, lack of customer education and motivation as well as some knowledge missing on how CBMs are structured. This indicated that the HBMT framework that have been developed can be a potential tool to close the gap and allow the manufacturing sector succeed in its journey towards circularity.

The second objective of the cases was to apply the framework findings on specific cases and products/services in order to assess its clarity, usability and completeness from an expert viewpoint. The experts selected, have affinity on the topic of circularity and BM development and therefore were key elements for enriching and further extending the dimensions of the theoretical framework. With this implementation it was possible to assess to what extend the framework can assist those manufacturing firms ideate into building a CBM, choosing the right strategy for their products and highlighting the need for technologies required for a successful circular transition. Among the four companies, two have proceeded with the cycling strategy, one with the intensifying and one with the narrowing strategy while based on those they have built their CBMs. The appliances company and the steel manufacturer are focused more on taking the products back and retrieving value from waste, since in those sectors materials are the core of the product and the offerings. On the other hand, the furniture manufacturer focused on using more innovative materials to substitute the currently used, as in this industrial sector the product durability and sustainability are highly valued. In the sector of industrial machinery, for instance that of the additive manufacturing company, the CBM built is oriented towards leasing and servitizing of the product. The production of such machinery is customised and comes in small quantities therefore CBMs focusing on product availability are preferred since they can potentially yield significant economic advantages over the large productions and the direct sales.

As also discussed in the findings section, through the implementation process it was possible to identify points that was missing from the framework which have been added to enrich its content. From the cases, it was clear that the relationships with the customers should be based on a long-term manner in the case of the cycling strategy in order to allow the companies to take the products back but also motivate people to act in a circular way. Since the research is based on manufacturing companies, when applying the cycling strategy, changes in the production line to accommodate recycling should be encountered as key activities in their CBM. Additionally, as discussed, special equipment might always be needed in order to support certain activities attributed to each case in the form of resources and capabilities. On the other hand, the perspective of the narrowing strategy and the offering of innovative products calls for flexible customer relationships which will allow for experimentation and built upon loyalty among the two sides, namely the company and the customer. This should be aimed through flexible contracts as well as pilot activities to introduce novel products in the market. In that way, the manufacturing company will be able to admit not only the financial benefits as discussed in the literature but also non-financial benefits through loyalty gains.

When considering the intensifying strategy, the cases showed that the value proposition is not only related to broad product availability and access options but also on the fact that a product is offered in such way aiming to exempt customers from high investment costs. In addition, the cases revealed that the revenue element of an intensifying-based CBM can be also supplemented by product modularity. Giving the option to the clients to upgrade their products while in use can extend the life of the product, satisfy the customers and also provide an additional profit to the company. This action can be applied both in the extending and the intensifying strategy and shape the corresponding financial element of the CBM accordingly.

The companies that have been studied are not fully digitalized and therefore only a few technologies from the ones suggested in the framework could be applied in the different cases. Based on the findings, the manufacturing companies recognised the value of the I4.0 technologies and their role into enabling the implementation of the circular values. What was made clear through the cases is that each company would use different technologies to implement and support its CBM which is based purely on the physical composition of the product and the culture of the company. For instance, in manufacturing sectors where material condition and monitoring are the main focus, it is important to collect data about the products and use big data technologies to support material passports and analyse the value retrieved from circular actions respectively. ON the other hand, in manufacturing sectors where process data exchange is core, blockchain technology is required to assist with safe transactions on the use of the machines while simulations will be also required to visualize the product functioning for customer education purposes. Additional technologies might be required per case to enable circularity, as the material technology mentioned by the furniture manufacturing firm. A commonality among the cases was the need for data collection about the location and the use of the product through IoT technology which will be used in the cycling, extending and intensifying strategies for taking the products back, tracking the product quality and monitoring the product condition respectively. An aspect worth highlighting from the discussion with the experts is the contribution of the AI technology in the CBMs. Little reference has been made to this emerging technology which indicates that companies are reluctant to use technologies that are not fully explored and settled. Little attention can be also emerging due to insufficient knowledge on the topic or potentially due to defensive action (wait-and-see) until the technology matures. To fully unleash the capabilities of AI technology in relation to the circular economy, additional research is necessary to explore its practical applications. The literature discussed in this study indicates the technology's immense potential for driving circularity, making further investigation essential for real-world implementation.

Although the framework has been applied in those cases assisting manufacturing firms towards CBMs, can not be entirely generalized since additional data and insights are required. In addition, the cases were analysed based on the perspective of one company expert and therefore it would be beneficial to have the contribution of multiple experts within the firm to get a clear view on the dimensions and components of the HCBMT framework and the CBMs. This could have been achieved, beyond the scope of this thesis, through a group session or an ideation workshop with all the targeted manufacturing firms to identify differences and create a clear understanding of how the framework could be used from a multi-expert perspective. On the other side, to ensure that the framework provides an overview of the concepts and assists manufacturing companies with their transition towards CBMs with the assistance of the technologies, a follow-up feedback session would be required. This should be conducted after the company proceeds with an application of a circular strategy and a new CBM as built through the HCBMT framework. The aim would be to understand better to what extent the companies followed the steps in the framework and if the BM element are structured in the way presented or if other factors and aspects should be added. This however requires a commitment of 2-3 years with iterative processes and constant communication and therefore is kept out of scope of this thesis but can be explored in a follow-up study.

7 Conclusion

7.1 Briefing and answer to Main Research question

The objectives of this study are aimed towards developing a greater understanding of how circular strategies and I4.0 technologies can support manufacturing companies with their transition towards CBMs. Through an organized methodology consisting of a structured literature review, a conceptual framework development and case studies built on reputable Dutch manufacturing companies it was possible to obtain the research goals and complement the current literature on the topic of circular economy. Starting with the theoretical background, the different circular strategies have been identified, compared and comprehended. Although various strategies are mentioned in the literature, through this study it was possible to understand which of them overlap leading to a creation of a distinct set consisting of five strategies (greening, narrowing, cycling, extending and intensifying). As revealed from the various studies, there is a confusion between the circular strategies and circular practices which makes the circularity concept blur and does not provide a clear understanding under which the CBMs are formed. This knowledge confusion poses barriers to companies which want to transition from a linear business model to a circular one. Therefore it was deemed necessary in this study to develop a HCBMT framework which provides clarity in the aforementioned research streams and can be able to assist companies with their circularity journey.

Although numerous frameworks have been identified in the literature regarding circularity, the direct connection of the circular strategies with the business model elements is missing which made it clear that an enrichment was needed. In addition, the frameworks reviewed do not consider the technological and the value chain aspect, two factors that are important to be incorporated, the first as an enabler towards CBMs and the second as a holistic view of the company in a network. To fill those gaps, the HCBMT framework has been developed and built on the basis of the identified circular strategies as defined before. From the framework development, it is worth mentioning that the circular practices are clustered under the circular strategies which are connected to nine elements of the CBM. Those elements relate to the product offered by the company, the customer perspective, the activities and the resources, the interaction with the partners and the profit generation to mention some. On top of that, the circular strategies are applied on the various stages of a company's value chain in order to give a perspective of the actions that can be performed to make this chain circular. Adding this component on the HCBMT framework was deemed necessary since the company operates in an environment with external actors and stakeholders and is not considered as a sovereign entity. This can give a network view perspective to the company when deciding which strategies and actions can be applied along its value chain and how those can thereafter be connected to the BM elements. Finally, the dimension of the I4.0 technologies is added as a way to understand how CBMs can be implemented with their assistance. The technologies have specific capabilities which if applied can support the value proposition, creation, delivery and capture and the structuring of a CBM based on a specific strategy. A key aspect considered here is that the technologies are enabling factors towards circularity and not requirements to be added in the core of a CBM, namely its elements.

The HCBMT framework was tested and evaluated through cases which studied the implementation of CBM in Dutch manufacturing companies. Through this studies the framework was used as a tool to ideate on potential CBM implementation. The strategies chosen among the manufacturing firms focused more on the cycling, narrowing and intensifying while most of the participating companies highlighted the need for integrating a reverse logistics stage in their value chain. On the technological side, most of the firms highlighted the need for data collection and analysis through IoT, big data and cloud computing when it comes to circular value creation as it is important to constantly monitor the location and predict the condition of the product. Since the circular offerings will come with a new value proposition, additional technologies, for instance, simulations, robotics and blockchain, will be needed to increase customer engagement and trust and make processes even more efficient. While building their CBM the manufacturing firms embraced the clustering and acknowledged the structured classification of the concepts as well as the multiple perspectives with regards to value chain aspect and technologies. In that way, the framework proved to be a valuable tool for addressing knowledge-lacking challenges and guiding manufacturing firms in making structured decisions during the ideation phase of CBM development.

In a nutshell, the study contributes to the academic and practical domains by offering valuable insights that facilitate a comprehensive understanding and practical application of circularity. These insights serve as essential tools for organizations seeking to embrace circular business models, fostering sustainable practices and enhancing their overall resilience in a rapidly changing climate landscape.

Main Research Question

How can circular strategies in relation to Industry 4.0 technologies contribute to the transition of manufacturing companies towards circular business models?

The transition towards circular business models is of high importance for the manufacturing sector as a way to reduce resources consumption and efficiently use energy for various activities. In order to proceed with a change from a linear to a circular era, companies have to apply certain strategies and actions which will assist them adapt to the new business model settings. Those strategies form the foundations of CBMs and can be activated through certain circular actions, giving in that way a better understanding on how circularity can be informed. Among others, the greening, narrowing, closing, extending and intensifying have been identified as the core strategies based on which business models can be structured and implemented. In that way manufacturing companies can move towards circularity by adapting their business models according to the requirements of each strategy. This can be achieved through changes on the business model elements as each strategy suggests, assisting in that way the transition process.

On top of the strategies, the Industry 4.0 technologies have also a high potential on assisting manufacturing firms towards the circular transition. In a sense, technologies have a contributing role on the elements of a business model and assist the way circular value is being proposed, created, delivered and captured. Based on their capabilities, technologies can enable the implementation of each strategy and allow the manufacturing firms admit the circular value. For instance, artificial intelligence and machine learning technologies can support the extending strategy by analysing data deriving from products in use and prediction its remaining useful life. In that way the manufacturing company can take decisions in order to extend the product use and keep the customers satisfied. In such manner, circular value is created and sustained.

Circular strategies can also contribute to the transition of manufacturing firms towards CBM by providing a holistic view of the value chain. Mapping the different strategies along the value chain has the potential to assist firms understand what actions they can take along the product life-cycle and how they can interact with their network of customers and suppliers to admit circular value. Through this interconnection, firms can decide with which strategies they want to proceed, what actions can be applied on the various value chain stages and based on that built and transition towards an all-encompassing circular business model. The viewpoint of the value chain is used in this study not only to assist in answering the research question but also to highlight that companies are not sovereign but belong to a greater network which is dynamic and should not be neglected. Ultimately, embracing this convergence of circular strategies, I4.0 technologies and value chain, holds the potential to drive sustainability, resource efficiency, and competitiveness and support the transition towards circularity within the manufacturing sector. Further research is required to investigate implementation strategies, assess economic viability, and evaluate the environmental and social impacts of such transitions.

7.2 Contribution to research

The presented study makes a noteworthy contribution to research in several ways. Firstly, it introduces a novel approach to categorizing circular strategies and establishing their links not only with technological aspects but also with the value chain stages. Secondly, the study contributes to three distinct research streams: a) the examination of circular strategies' impact on CBM elements, b) the application of circular strategies within the value chain, and c) the correlation between Industry 4.0 technologies and circular strategies through the value components (proposition, creation, delivery and capture) of a circular business model. By building a framework the academic information gathered can be structured in order to provide a comprehensive understanding of how those research streams are interconnected. Furthermore, the study's significance lies in its inter-sectionality among the three aforementioned research fields since other studies lack a multi-aspect connection of the concepts. This provides a more clear and deeper understanding on the CBM concept within the academic terrains. Giving an additional academic complexion, the HCBMT framework developed unlocked insights which further enrich the literature on how circular strategies can shape the CBM elements and what capabilities I4.0 technologies can offer to support the transition from a linear to a circular setting. This interdisciplinary approach not only expands the horizons for future research but also opens up possibilities for additional research streams in this direction, as will be discussed in the future research suggestions. Ultimately, this study's contribution provides valuable insights and delineates the complex relationships among circular strategies, CBM elements and I4.0 technologies while paving the way for further exploration in this emerging domain.

7.3 Implications for practice

The practical contribution of this thesis lies in providing valuable guidance and insights for manufacturing companies aiming to embrace circular business models. By developing a comprehensive framework that integrates circular strategies, Industry 4.0 technologies, and the circular value chain, the study offers a practical tool for analyzing and designing CBMs in a holistic manner. The HCBMT framework enables manufacturing sector to make informed decisions and implement sustainable practices that promote resources efficiency and waste minimization. The case studies conducted as part of the present research further validate the applicability and effectiveness of the framework in real-business settings, offering practical insights and real-world examples. Overall, the outcome of the thesis equips practitioners with the necessary knowledge and tools to navigate the complexities of circularity in a way that fosters ideation. With the application of the framework, manufacturing companies can identify the circular strategies that best apply to their products while taking fast decisions, in the ideation phase, on how to structure their CBM elements and what technologies can drive their efforts towards realizing a circular future.

7.4 Relevance to Management of Technology

This thesis shows also a strong link with the principles of the Management of Technology (MoT) programme in the areas of circular strategies, management and emerging I4.0 technologies. Through a comprehensive analysis of the scientific literature, exploring how circular strategies and technologies can be implemented in CBMs is made possible. In that context, the various subjects were presented and mapped along a framework to provide structured knowledge over circularity. This contributes into understanding how companies can effectively adopt circular strategies and leverage I4.0 technologies to successfully transition towards circular business models and practices. Based on the principles of the MoT programme, the present study highlights the role of innovative technologies on shaping circular strategies and also provides an understanding of how CBM elements should be shaped including both the internal and the external to a company perspective. Applying this aspect in real businesses allows for perceiving technology and strategy as a corporate resource which can drive the transition towards circularity. By that means, technology management as presented in this study can accelerate the implementation of circular practices and assist companies improve their productivity, anticipate environmental challenges, reduce resources and support a sustained competitive advantage.

This research is also embracing the principles and the curriculum of the MoT programme by following the knowledge developed through some of its core courses. The Research Methods course assisted with the structuring of a rigorous academic methodology while the Leadership and Technology Management course helped to acknowledge management strategies among various business settings as performed in the cases. In addition, the principles of the Technology, Strategy & Entrepreneurship and the Emerging & Breakthrough Technologies courses provided key guidelines with regard to the technological side of this study. With the knowledge gained it was possible to analyse the technological capabilities with the CBM components as well as showcase how technology influences the strategy of a firm. Overall, the thesis establishes a strong link with the MoT curriculum and aligns with the program's objectives of exploring the intersection of technology and business management, understanding technology as a corporate resource, and using scientific methods to analyze current trending subjects.

7.5 Limitations

As with every study, this also comes with some limitations which need to be mapped and considered. With regards to the literature study, the research stream considered for the framework development is based on highly cited literature studies and a few publications of well-known circularity-oriented organizations. Additions of grey literature and practical aspects might be worth exploring to supplement the taxonomy of the circular business strategies. In addition, the technologies and the BM elements used for constructing the framework are distinct and limited to what literature studies refer to as state-of-the-art. However, the CBMs and the technologies enabling them pose a dynamic research field that is constantly changing and therefore it calls for ad-hoc investigation. With regards to the data collection site, it is worth mentioning that the spectrum of manufacturing firms was limited to companies in the Netherlands for proximity and ease of sampling reasons. In addition to that, the companies studied are limited to the manufacturing sector where intense consumption of resources and energy is noticed when compared to different clusters besides the ones studied. As the topic of circularity is not extensively applied in this sector the cases studied were limited in quantity but provided insightful results and different approaches. Within this frame, the concepts of circular strategies and I4.0 technologies could be updated and informed however an extension to additional sectors will be required for a more generic outcome.

Furthermore, the number of interviewees per case was limited due to inaccessibility and busy schedule from the site of the experts. However, additional data could provide extensive insights into the circularity framework and its application and will be aimed at future research. Based on that, it is also worth recognizing the limitations of the data collection method, namely the snowballing. Following this method introduced sample limitations since the experts contacted were based on personal contacts. In that way, contacts besides the immediate network could have been missed posing a limitation to the sample diversity which has been partially surpassed with the various industries studied. On the site of the data analysis, an additional limitation should be noted with regard to the expert interviews. The codification of the transcripts as the thematic analysis suggests, lacks inter-rater reliability. The assessment of the codes by multiple raters could have revealed additional insights which could improve and comprehend the study results. However, to reduce the aforementioned limitation, a proof rating step was performed by the supervising researcher at the level of the interview questions which served as a base for deriving the themes and the codes during the data analysis. Beyond that level, a multi-rater evaluation of the codes and the themes they are assigned to could have reduced further the potential subjectivity and increased the reliability of the findings, therefore it is recommended.

7.6 Future Research

The topic of circular economy is booming as do the Industry 4.0 technologies which continue to develop in number and capabilities. Therefore the discussions of those topics, as also performed in this study, will continue to concern the scientific communities to get a clear understanding on how loops can be closed more efficiently and in an accelerated tempo. For future research, it is suggested that the HCBMT framework is applied further in practice. The number of manufacturing companies as cases of application was sufficient to derive the first outcomes, however, additional companies should be studied (increase in quantity). For this matter, a combination of data collection methods can be aimed beyond the snowballing and the personal contacts, increasing in that way the participation of companies interested in the circular economy. In addition, further sectors can be studied for gathering a diverse portfolio of insights both from an intra- and international aspect since changes might apply when crossing borders. In that way the HCBMT framework can be further validated and enriched in order to serve as an all-encompassing tool which combines theoretical and practical aspects which could assist manufacturing companies with their transition towards CBMs.

As suggested also by the cases experts, future work may focus on collective implementation and testing of the HCBMT framework in business settings. This can be performed through an expert workshop (Delphi study) where companies can come together and ideate on their future business models concerning circularity and enabling technologies. This application could provide a spherical overview of the strategies and practices that can be applied in a circular manner and would further validate if the framework is properly functioning with different products and services. As a future work it could also be interesting to research how multiple companies or companies in a cluster can apply circular strategies in a network perspective, how would this change the elements of a circular business model and how technologies could enable this implementation among various parties. It is also worth researching aspects that have not been fully covered in this study, for instance the contribution of the AI technology in the circular economy actions of the future. Since this technology lacks thorough discussion within the cases it would be strongly suggested to be further explored as an emerging field in the I4.0 era.

In addition, as future research, it is suggested to monitor the implementation of the HCBMT framework and the success of the manufacturing companies into applying circular business models in order to retrieve meaningful information about the value and the correlation of the theoretical concepts in practice. Finally, through the transition monitoring, it would be possible to gain insights about the value retrieved per circular strategies. This can be later translated in metrics measuring key performance indicators (financial value, energy savings, etc.) which will supplement the literature in that area and assist practitioners with their decisions.

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A Appendix I - Emerging and breakthrough technologies background information

The technologies that are used by the manufacturing sector in the era of Industry 4.0 which could be potential enablers of circular economy are listed bellow. This is based on the comprehensive literature analysis performed by Bag et al. (2021) since all the critical technologies are stressed specifically how those are leveraged by the manufacturing sector to enhance circularity.

Internet of Things (IoT)
IoT devices can be integrated into products to provide real-time data on usage patterns, performance, and maintenance requirements. This data can then be used to optimize product performance, reduce waste, and increase the lifespan of the product.

Big Data
Big data refers to the vast amount of data generated by individuals and organizations. This data can be analyzed to reveal insights and patterns that can be used to optimize processes and reduce waste. In the context of circular economy, big data can help companies to identify inefficiencies in their resource usage, track the movement of materials and products throughout the supply chain, and analyze consumer behavior to design more sustainable products and services.

Cloud Computing
Cloud computing platforms can be used to store and process data generated by IoT devices, enabling companies to access this data in real-time from anywhere in the world. This data can then be used to make informed decisions about how to optimize their operations for circularity.

Additive Manufacturing (3D Printing)
Additive manufacturing or 3D printing technology can be used to produce spare parts and components on-demand, reducing the need for inventory and waste. This also enables companies to repair products more quickly, extending their lifespan.

Artificial Intelligence (AI), Machine Learning (ML) & Augmented Reality (AR)
AI and machine learning algorithms can be used to analyze data from IoT devices and other sources to identify patterns and make predictions about product performance and maintenance requirements. This information can be used to optimize the use of resources and reduce waste.

Cyber-physical Systems (Robotics)
Since the processes are becoming demanding and autonomous robotics are utilized to support and increase the production. This technology is capable of reducing the time required for an industrial activity and efficiently provide the intended outcome. Robotics can perform variable tasks and additionally interact safely and effectively with humans in a cooperative manner to increase productivity and flexibility while also reduce mistakes in the overall industrial process.

Blockchain
Blockchain technology can be used to track the life-cycle of products and ensure that materials are properly disposed of at the end of their life. This increases transparency and accountability in the supply chain, enabling companies to adopt circular business models.

Sensor Technology
Sensor technology involves the use of sensors to collect data on various parameters such as temperature, humidity, pressure, and motion. In the context of circular economy, sensor technology can be used to monitor the performance of equipment and identify potential problems before they occur. This enables companies to perform maintenance and repairs, extending the lifespan of equipment and reducing the need for replacement. By minimizing waste and optimizing resource usage, companies can become more sustainable.

Simulations - Digital Twin

Simulations involve creating virtual models of real-world systems, while digital twins refer to a digital replica of physical objects, processes, and systems. In the context of circular economy, simulations and digital twins can be used to optimize processes, design more sustainable products and services, and create closed-loop supply chains. For instance, digital twins can be used to simulate the entire lifecycle of a product, from design to disposal. This enables companies to identify opportunities for recycling and repurposing, and design products that are more durable and easier to recycle.

Augmented Reality (AR)

AR falls under the category of simulations which can be used to provide customers with virtual product demonstrations and training, reducing the need for physical product samples and reducing waste. This can also be used to visualize and communicate the circularity of the company's operations, building trust and transparency with customers.

B Appendix II - Overview of the studies reviewed, analysed and compared

In this section the summary of the studies reviewed in order to understand the circularity topics and construct the framework, is presented in three tables. Firstly a summary of different frameworks regarding the classification of the various circular strategies/practices and their connection to the circular value is presented. As second, follows the table which summarizes the various studies regarding the circular practices along the value chain. Finally, the studies related to the capabilities of the I4.0 technologies and their support ton the CBMs are summarized and compared in the third table of this appendix section.

Table A: Overview of studies regarding circular strategies and circular business models (elements, taxonomies, connections)

Author	Circular strategies	CBM value components	Comment
Bocken,2016	**Closing:** 1 - Extending resource value (collection, sourcing of wasted materials) 2 - Industrial symbiosis **Slowing:** 1 - Access and performance model (satisfy users with a service) 2 - Extending product value (exploiting residual value after usage) 3 - Classic long-life model (design for durability and repair) 4 - Encourage sufficiency (reduce end-user consumption through durability, warrantees, reparability) **Narrowing:** 1 - Is not intended at cycling of products but rather at fewer resources utilization	**Closing:** 1) **VP:** Affordable green products from collected and recycled material **VC&D:** Firm-customer collaboration and take-back/collection systems **VC:** Turning "waste" into new value 2) **VP:** Intra-firm collaboration for cost and risk reduction **VC&D:** Exchanging by-products, network collaborations for services sharing **VC:** Joint cost reduction and new production lines **Slowing:** 1) **VP:** Service vs ownership **VC&D:** Manufacturer manages the product and is responsible for maintenance **VC:** pricing scheme according to the usage 2) **VP:** Economically affordable product through remanufacturing **VC&D:** Product return with deposit system **VC:** Cost reduction through material reduction 3), 4) **VP:** High-quality and longevity-based products and high-level service **VC&D:** Design for durability **VC:** Premium pricing and product warrantee	The "narrowing" strategy is excluded from the analysis as it is not purposed at cycling of products but rather as reducing materials utilization during the production process.
Moreno,2016	**Slowing:** - Sharing platform - Extending product value (access model and performance, result-/use-oriented services) **Cycling for longer:** - Product life extension (services, refurbishment, remanufacturing) **Cascaded uses:** - Resource value (upcycling and recycling) **Narrowing:** - Circular supplies (renewable energy based, fully recyclable inputs)	Value is created and proposed through design actions which are relevant for each circular business model strategy. Slowing: **VC:** Profit from increased utilization from multiple users (sharing), charging per-use, material ownership by the manufacturer Cycling for longer: **VC:** Profit from maintenance services or reselling and high-price premium products Cascade uses: **VC:** Profit from recovery of resources and energy, cooperation with companies to exploit by-products Narrowing: **VC:** Profit from fully recyclable input and savings from material reduction	Focused on the value capture mechanism that each business model is linked to. Value proposition and value creation & delivery are not clearly stated. Mostly based on the logic provided by \autocite{Bocken,2016}.
Lewandowski,2016	Take back aspect is implemented in the BM Canvas as a circular practice along with the adoption factor (external factors influencing the adoption of circularity)	**VP:** Incentivized take-back products/materials, transformation into new valuable output **VC&D:** Take-back system and reverse logistics, community recycling **VC:** Cost reduction through collect-back resources	The adoption factor is not clearly analyzed, difficulty to connect external political and sociocultural factors with resources efficiency and how those might affect the value logic.

Urbinati,2017	**Upstream circularity:** - Interaction with value network - Establish core relationships which will upgrade circularity in product design level **Downstream circularity:** - Pay-per-use **Full circularity:** - Full integration both in upstream and downstream aspects, internally and externally	**VP:** Focus on pay-per-use instead of ownership of the product **VC&D:** Cooperation with companies and reverse supply chain **VC:** Profit from use-based or performance-based services Value can be admitted through downstream (internal) integration, upstream (external) integration and full (external and internal) integration	Focusing on the value network and the collaborations/interactions among actors. Circular strategies are mixed and not clearly separated to show the taxonomy of activities.
Nußholz,2017	**Closing:** - Material recycling - Reuse vs. Replacement (in case that the new product is more energy efficient than the old one) **Extending useful life:** - Repair - Remanufacturing - Efficient use - Second life vs. rebound effects (value gained at the end-of-life is not reducing primary production resources but rather offset efficiency gains) **Narrowing:** - Reducing material use in products - Substituting conservative with innovative materials **Demand reduction:** - **Leakage/Emissions reduction:** -	**VP:** Life-long products, customers with high environmental awareness, service-contracts, buy-back scheme **VC&D:** leasing vs owing, collection points, educate customers to return products, secondary material provided by suppliers **VC:** Reselling and redistributing post-customer products, high-price for high-life, substitute primary with secondary materials and decrease price	Explanation on the tools to be used in order to manage networks for closing the loop is missing. Demand reduction and leakage/emissions reduction lack further explanation from the value logic perspective but refer to network education and internal processes modification.
Khan,2018	Upgradability for product life-cycle extension **Beginning of life:** - Design for X (reliability,durability, attachment, ease of maintenance, upgradability, dis-/re-assembly, standardization, modularity) **Midlife:** - Sharing - Reuse/redistribute - Recall (fault prevention) - Predictive maintenance - Repair - Upgrade **End-of-Life:**	**VP:** Upgraded product with improved functionality, or adaptable product to changing needs **VC&D:** Collaborative "make-to-upgrade", addition of exchanging modules, service upgrade, upgrade plan for the customer **VC:** Profit through new non-ownership contracts, fee for upgrade	Focuses on the upgradability concept in a product-service-system which is purposed for product life extension. No additional circular practices are studied and the concept of upgradability is mainly focused on the midlife of the product. Unclear how upgradability will influence the other stages.

	- Remanufacture (with upgrade) - Refurbish - Reuse of materials/parts - Recycle		
Planing,2018	**Circular Business Models** - Collaborative consumption - Performance model/Product-as-a-service - Reuse /refurbish/maintain/next-life sales - Hybrid model (long-lasting products, short-living consumables) - Remanufacturing - Upgrading - Product transformation (transform components of products to new products) - Recycling - Energy recovery (energy from waste)	CBMs are applied in circular flows with starting point to be the customers. **Customer to Customer:** Access model/collaborative consumption **Customer to Service provider:** Reuse/refurbish/maintain/next life sales Product-as-a-service **Customer to product manufacturer:** Remanufacture Hybrid model **Customer to Material processor:** Product recycling **Customer to Disposal:** Energy recovery	Focused on the CBMs and not on the strategies that lead to those models. However, a detailed classification of the BMs reveals the interconnection between the circular flows. How this connection affect the BM elements remains unclear.
Lüdeke-Freund,2019	**Cycling:** - Recycling - Organic feedstock - Cascading & repurposing **Extending:** - Reuse & redistribution - Repair & maintenance - Refurbish & remanufacture	Recycling: **VP:** Green inputs, uptake of residues from customers or B2B relations **VC&D:** Reverse logistics, collection/take-back valuable resources **VC:** Additional revenue from waste, resources trading Organic feedstock: **VP:** Waste processing and products based on waste **VC&D:** Take-back systems and recapturing products **VC:** Revenue from waste Cascading & Repurposing: **VP:** Reusable products through waste management **VC&D:** Reselling through retailers, take-back systems **VC:** Additional revenue from reselling Reuse & Redistribution: **VP:** Used products from take-back systems **VC&D:** C2C suppliers, manufacturers, retailers and service providers reselling products, components and waste **VC:** Additional revenue from reuse, lower price Repair & Maintenance: **VP:** Maintained and controlled products **VC&D:** Product repair through manufacturers and service providers, product-based services **VC:** Function- or result-based payment	Comprehensive study with clear distinction of the CBM patterns based on the circular practices. The dematerializing and intensifying strategies lack exploration.

		Refurbish & Remanufacture: **VP:** Used but refurbished and repurposed products, materials or waste **VC&D:** Upgrading and refurbishing with the support of manufacturers and collectors, B2B customers **VC:** Savings from resources reduction	
Whalen,2019	**Sub-types of BMs for extending:** - Facilitator (assisting intermediary force between suppliers and customers) - Redistributor (organizing and running take-back services and deposit-refund schemes) - Doer (providers of similar services to both suppliers and customers)	Facilitator: **VP:** Product re-contextualizing without direct product interaction **VC&D:** Connection channels between suppliers and customers, online platforms **VC:** Revenues from obsolete products sales, transaction fees Redistributor: **VP:** Product re-contextualizing with minimum product interaction, provide collection services **VC&D:** Collection, inspection and packing of products via actor channels and partners **VC:** Direct sales/commission, take-back service fee, trade-in credit system Doer: **VP:** Remedial of products and direct offer to suppliers and customers **VC&D:** Product repair, refurbishment and remanufacturing **VC:** Resale and lower production cost from re-used components	The meaning of re-contextualizing is unclear as also this of remedial actions. Life extension or slowing is the only circular strategy that is being clearly analyzed in the study.
Geissdoerfer,2020	**Cycling:** - Reuse - Repair - Remanufacture/ refurbish - Reverse logistics - Recycling - Design for X - Incentives to return **Extending:** - Upgradability - Timeless design (never goes out of style) - Long-lasting products - Consumer education on long-lasting usage - Maintenance/after-sales support **Intensifying:** - Sharing platforms - Rental/leasing - Pooling models - Product availability (open elements, user cooperatives) **Dematerializing:** - Software vs. hardware - Service vs. physical product - Reduce customer demand through education	Cycling: **VP:** Retrieved from other scholars **VC&D:** Suppliers outsourcing and collaborations, Access to end-of-life products, make incentives to take back from customers **VC:** Retrieved from other scholars Extending: Retrieved from other scholars Intensifying: **VP:** Retrieved from other scholars **VC&D:** Capacity management (demand and supply balance), digital capabilities, orchestration of suppliers **VC:** Retrieved from other scholars Dematerializing: **VP:** Reducing need for hardware **VC&D:** Technology for digitalization, consumer education for demand reduction **VC:** Cost reduction through resources saving, pricing per service provided	The study is a combination of the business models and the circular practices proposed by \textcite{Bocken,2016} and \textcite{ Lüdeke-Freund,2019}. The energy recovery dimension is missing as a strategy to enhance circularity.

Konietzko,2020	**Narrowing:** - Design with low-impact input (more eco-friendly offerings) - Localize supply - Maximize capacity use of products (sharing) **Slowing:** - Turn disposable into reusable (reuse) - Maintenance and repair - Design for ease of maintenance **Closing:** - Reuse & resell **Regenerating:** - Sustain ecosystems (local ecosystems) - Transportation with renewables - Recover nutrients (bio-waste) **Informing:** - Track resources intensity - Online platforms for circular products marketing	Regenerate: **VP:** Renewable powered transportations and production, recovered natural resources, use of living materials **VC&D:** Renewable capacity build-up, creative partnerships, restore ecosystem **VC:** Increased reputation through sustainable actions Inform: **VP:** Efficiency increase and lifetime prediction **VC&D:** tracking products, data collection, circular design through collected data, online platforms for co-creation, virtualization **VC:** -		Inform and Regenerate were added as new circular strategies which aim at data integration and clean production. Dematerialization and intensifying aspects are missing from the analysis or being hidden within the other circular strategies. Cost aspect is not included in the framework of this study which limits the understanding of the value capture mechanisms for each circular strategy.
Bocken,2021	**Resources strategies:** - Open-narrowing (ecosystem resources minimization) - Open-slowing (partnerships which promote reusing and sharing) - Open-closing (make use of ecosystem disposed materials) - Close-narrowing (internal processes resources minimization) - Close-slowing (internally built repair and refurbishment system) - Close-closing (take-back system from own customers)	Open-narrowing: **VP:** Reduced waste and resources in design and production **VC&D:** Leveraging of technology and enhance network collaborations to reduce cost **VC:** Cost and resources saving Open-slowing: **VP:** Reuse sources to broaden customer options **VC&D:** Generative models (connect internal and external flows) **VC:** Increased transactions in ecosystem Open-closing: **VP:** Circular offering, low environmental and resources footprint **VC&D:** Resource flows from external ecosystems as customer offerings **VC:** Lower cost of offerings, brand and image improvement (non-financial value capture)	Close-narrowing: **VP:** Same as open-narrowing **VC&D:** Internal utilization of technology to reduce processes cost **VC:** Cost and resources saving Close-slowing: **VP:** High quality products and high customer value **VC&D:** Design for longevity, repair service **VC:** Premium price, creation of customer loyalty Close-closing: **VP:** Post-customer materials recovery and maintenance **VC&D:** Customer retention and increase through take-back systems **VC:** Savings from materials efficiency, creation of reputation	Three strategies have been studied from the internal and the external/ecosystem perspective. Additional strategies related to dematerialization or service vs. product are missing. Stresses the interconnection of circular activities with the firms capabilities and those an ecosystem can offer to enhance circularity. BM elements are highly related to internal and external actions and change accordingly.

Table B: Overview of studies regarding circular strategies and circular value chain (stages, connections, circular practices)

Author	Circular Strategy or Practice	Value Chain Stage		Comments
Pavel,2018	- R0 – Reuse - R1 – Rethink - R2 – Reduce - R3 – Reuse - R4 – Repair - R5 – Refurbish - R6 – Remanufacture - R7 – Re-purpose - R8 – Recycle - R9 – Recover	**Material sources:** - R0 - R1 - R2 **Design:** - R0 - R1 - R2 **Manufacturing, distribution, marketing & service:** - R0 - R1 - R2 - R3 - R4 -R5	**Consumption & use:** - R0 - R1 - R2 **Reverse logistics:** - R0 - R1 - R2 **Evaluation of materials:** - R6 - R7 - R8 - R9	Only the 10-R strategies are positioned along the value chain with business models related to product-service-systems to be missing. R0, R1, R2 practices are implemented in each value chain stage except from the materials evaluation stage.
Reike,2018	- R0 – Reuse - R1 – Reduce - R2 – Resell - R3 – Repair - R4 – Refurbish - R5 – Remanufacture - R6 – Re-purpose - R7 – Recycle - R8 – Energy recovery - R9 – Re-mine	**Material Production:** - R7, R9 **Component production:** - R5 **End-product manufacturing:** - R4 **Retail:** - R2 (B2B and B2C) - R0 - R6	**Consumer:** - R1 - R2 - R3 **Collection:** - R7 - R8 **Land fill:** - R2 - R7 - R9	More comprehensive positioning of the circular practices along the value chain. Energy recovery, re-mine, resell are added in the circular practices agenda, however rethink is missing from the list. Value chain consists of 7 steps as the landfill stage is purposed for material re-mining.
Kalmykova,2018	45 different circular practices are mentioned and positioned along the value chain	**Material Sourcing:** - Cross-sector linkages - Energy autonomy - Green procurement - Life Cycle Assessment - Material substitution - Taxation - Tax credits and subsidies **Design:** - Customization - Design for recycling - Design for modularity	**Collection & Disposal:** - Extended producer responsibility - Incentivized recycling - Infrastructure building - Separation - Take-back system **Recycling & Recovery:** - By-products use - Cascading - Downcycling - Elements/substance recovery - Product-as-a-service	The value chain consists of ten stages. This study considers remanufacturing, materials sourcing and circular inputs as different value adding action in the value chain. Through those stages, upgraded products or extracted materials are being looped in the first stages of the value chain to close the resources loop. Important takeaway in this study is that the product-as-a-service practice or business models is being applied to consumption and use phase of the circular value chain. However, the ownership remains with the manufacturer/firm who offers all the lifecycle activities and therefore it highlights the application of PaaS all over the value chain.

		- Eco design - Reduction **Manufacturing:** - Energy efficiency - Material productivity - Adaptable manufacturing **Distribution & Sales:** - Optimized package design - Redistribute and resell **Consumption & Use:** - Community involvement - Eco-labelling - Product-as-a-service - Product labeling - Reuse - Sharing - Responsible consumption - Stewardship (for resources protection) - Virtualization	- Energy recovery - Extraction of bio-chemicals - Functional recycling - High quality recycling - Industrial symbiosis - Restoration - Upcycling **Remanufacture:** - Refurbish - Upgrading, maintenance and repair **Circular inputs:** - Bio-based materials	
Preston, Lehne and Wellesley,2019	- Slowing - Narrowing - Creating loops	**Material supply chain:** - Slowing - Creating loop (Recycle/Industrial symbiosis **Design and manufacturing:** - Slowing (enabling additional use cycles through design) - Creating loop (replace, remanufacture)	**Distribution and use:** - Narrowing (change utilization aspect) - Creating loops (reuse, repair) **End-of-first-life:** - Narrowing (new business model to create additional lifecycle loops) - Creating loops (repeating the whole process in additional life cycles)	Connection of the circular strategies in four stages of the value chain. Slowing is effective for material supply chain and design/manufacturing, narrowing is positioned at distribution, use and end-of-life while closing (creating loops) is purposed for all the stages. The links are not further discussed and interpreted.
Bianchini,2019	- Recycled materials - Damaged components - Good parts/components - Regenerated products - Pay-per-use - Share - Waste - Recovered materials - Materials for new components - Components for new products	**Manufacturing:** Close loop with - Waste - Recovered materials from assembly - Materials for new components from sales - Damaged components from maintenance - Recycled materials from collection **Assembly:** Close loop with - Components for new products from sales - Reuse of valuable parts from maintenance	**Distribution & sales:** - Pay-per-use (from use stage) - Regenerated products from maintenance **Use:** - Share - Regenerated products from maintenance **Maintenance:** - Disassembly and regeneration of products to feed the previous stages **Collection and energy recovery:** - Recycle of materials where possible, rest are considered as waste	Adds maintenance, collection (take-back) and assembly as stages in the value chain. Assembly refers to the manufacturing activities so it can be considered as a classic value chain stage. Closing the loop strategy is clearly stated however no additional strategies are being stressed in the study. Links the input and the output flows from each value chain stage. Suggests design-for-X actions for each stage to ensure resources efficiency.

Table C: Overview of studies regarding circular strategies and I4.0 technologies (capabilities, connection to circular value)				
Author	**I4.0 Technologies**	**Circular Practices**	**Capabilities & Performance**	**Key Takeaways**
Pagoropoulos,2017	Data Technologies: - Internet of Things - Big Data - Machine learning - Radio Frequency Identification (RFID) - Relational database management system (RDBMS) - Product lifecycle management (PLM)	- Reverse flows - Reuse/ Redistribution - Repair/ Remanufacture	**IoT:** - Information collection for products in use - Stakeholders connection (customers, suppliers with the firm) **Big Data:** - Data processing of data collected from IoT - Analysis of resources flows data from RFID systems or sensors **Machine learning & AI:** - Control of production processes and optimization for resources efficiency - Product life prediction and optimization to design for longevity **PLM:** - Integration of information across product lifecycles and stakeholders in the value chain - Product passport (accompanies products with information related to remaining life, design, disassembly and recycling) **RFID:** - Tracking tags to monitor products and implement reuse, repair and remanufacture **RDBMS:** - Integration of heterogenous data collected from various sources - Data storing and integration reducing operational costs	**Reverse Flows:** - IoT: Connectivity with partners for facilitating resources flows - Big Data: Support analysis of data collected from resources flows through other technologies **Reuse /Redistribute:** - IoT: Facilitate reuse via data collection - Big Data: Enable data integration and processing for reuse - ML & AI: Enables product life cycle predictions for reuse and resell - PLM: Supports the provision of product passport - RFID: Enable tracking of products to ensure quality for reuse **Repair/Remanufacture:** - IoT: Facilitate repair and remanufacture through disassembly data collection - Big Data: Enable data integration and processing for remanufacturing - ML & AI: Support processes optimization for resources efficiency - PLM: Supports the provision of product passport - RFID: Providing complete information about the product to facilitate remanufacturing and repair RDBMS is referring to systems enhancing data integration and provides data storage and aligning capabilities. Although not entirely used in that form, RDBMS can be compared to cloud storage which allows for operating cost reduction.
Jabbour,2018	- Cyber-physical systems (sensors and automation systems) - Cloud manufacturing - IoT (RFID, sensor, barcode, smart phone) - Additive manufacturing (3D printing)	- Regenerate - Share - Optimize - Loop - Virtualize - Exchange	**IoT:** Regenerate (data collection on energy consumption for sustainable operations), Share (data collection), Optimize (process and production, cost reduction), Loop (product passport, data collection), Virtualize (connectivity), Exchange (-) **Cloud manufacturing:** Regenerate (-), Share (data sharing, improve products and services through behavior tracking), Optimize (-), Loop (enables selling of refurbished/reused products), Virtualize (link supply and demand to enhance customer experience), Exchange (-) **AM:** Regenerate (-), Share (-), Optimize (-), Loop (-), Virtualize (enables product customization and improves service provision), Exchange (enables reuse of recycled materials in exchange to new materials) **Cyber-physical systems:**	**Regenerate:** - IoT for sustainable operations and reduction of natural resources consumption (based on data collected through sensors) **Share:** - IoT and Cloud manufacturing to provide information about supply and demand - Product monitoring and life span extension through data. **Optimize:** - Capabilities to identify failures in processes/production and optimize with interaction between cyber-physical systems and IoT. **Loop:** - Information about product disassembly and recycling through IoT (product passport) - Optimized reverse logistics through IoT - Reused and refurbished products buyers approach through cloud manufacturing **Virtualize:** - IoT and cloud manufacturing for suppliers, customers and manufacturers virtual connection - Data collection and improvement of services - Product customization through platforms

			Regenerate (-), Share (-), Optimize (enhances customization, reduces failures in production and therefore waste), Loop (enables efficient material shorting), Virtualize (-), Exchange (-)	- Performance monitoring and maintenance plan for optimized use (IoT and cloud manufacturing)	- Service provision through logistics tracking to enhance customer experience **Exchange:** - Additive manufacturing offers renewable production and reduces material use (waste recycling)
Nascimento,2019	- Smart production systems (cyber-physical, cloud computing) - Additive manufacturing	Reducing waste and resources regeneration in a circular supply chain: - Selective waste collection - Waste shorting - Waste treatment - Product printing - Product assembly	**Selective waste collection:** - Cloud computing for waste types, real time data collection - Collection roots optimization through cloud services - Waste type registration through apps **Waste shorting:** - Data collection for efficient waste shorting management through app - Automated CPS for shorting and separation for efficient material extraction **Waste treatment:** - Material input for 3D printing (recycled materials as 3D printer feedstock) **Product printing:** - Automated printing through additive manufacturing ensure resources efficiency and production waste minimization **Product assembly:** - CPS for effective assembly which is monitored via sensors and data are collected for optimization - CPS support minimization of energy waste	**Material/Waste shorting and Informing - Cloud Computing:** - Enables data collection through apps - Supports material shorting and management of material types **Remanufacturing and Recycling - AM:** - Enhances automated remanufacturing with use of recycled materials **Assembly and Separation for Reuse - Cyber-physical systems:** - Enables material separation - Efficient stock supply to AM machines - Supports efficient product assembly	
Rosa,2019	- Additive Manufacturing (AM) - Cyber-physical Systems (CPS) - IoT - Simulations - Big Data & Analytics	- Recycle - Reuse - Remanufacture - Optimize for resources minimization - Circular smart services	**AM:** - New sustainable recycling and digitalization of manufacturing processes - Remanufacturing and CBM development based on recycling and reuse **CPS:** - Maintenance and remanufacturing efficient management - Supports dynamic manufacturing **IoT:** - Use data gathering options for life extension - Product information transparency within supply chain - Enabling waste management strategies and allow for collaboration through connection capabilities - Dynamic manufacturing feedback loops **Simulations:** - Prognostic models for efficient product lifecycle management - Design, processes and logistics optimization, performance calculations **Big Data & Analytics:**	**Recycle:** AM (Enables products made of recycled materials, IoT (Enables connectivity and collaborations for waste management), Big Data (Supports industrial symbiosis and material exchange) **Reuse:** CPS (Enables remanufacturing optimization through automation), IoT (Enables data collection for product quality), Big Data (Enables secondary material assessment, supports reuse through open source data which ensure product quality) **Remanufacture:** AM (digitalizing manufacturing process), IoT (Enhances data collection for dynamic manufacturing), Simulations (Support assembly/disassembly modeling), Big Data (Enables improvement for assembly/disassembly) **Optimize for resources minimization:** Simulations (Enables optimization in resources management, design and logistics within the supply chain)	

			- Assessing secondary materials through data collection and analysis - Open source and data for promoting reuse practices - Product lifecycle data gathering and smart manufacturing practices implementation (assembly/disassembly)	**Circular smart services:** AM (Enables product's life cycle management), IoT (Enables digitalization for smart industrial settings), Big Data (Support data analysis for cloud services and platforms)
Khan,2021	- Blockchain	- Circular procurement - Circular design - Recycling/ Remanufacturing	**Circular procurement:** - Transparency in information flow through blockchain reliability and verifiability - Real-time accurate data sharing reduces carbon footprint in supply chains **Circular design:** - Product customization via reliable data collection from complex supply chains through blockchain **Recycling & Remanufacturing:** - Accurate data gathering and immutable traceability which increases trust for recycled materials and refurbished products	This publishes article focuses entirely on the blockchain technology and its capabilities for enabling CE. Only three practices are being discussed, namely circular procurement (material input), circular design (manufacturing and production phase) and recycling & remanufacturing (life cycle extension phase).
Toth-Peter, 2023	- IoT - Big Data & cloud data - AM - Blockchain - AI/AR - Product-Service System (PSS)	Reverse flows Circular collaborations Circular design Product life extension	**IoT:** - Facilitates connection between product and service - Supports sharing and leasing - Enhances pay-per-use models - Enables real-time data collection - Enables resources control - Supports hyperconnectivity - Enables product traceability, tracking and monitoring **Big Data & Cloud Data:** - Facilitates virtual platforms for connectivity - Provides insights for previous products - Enables optimization practices for resources and energy consumption - Facilitates monitoring of usage for optimizing product lifecycle - Supports hyperconnectivity **AM:** - Enables prototyping and adaptability - Enables customization and allows customers to design the product - Contributes to waste reduction for prototyping and modeling - Enables less transportation and remote manufacturing **Blockchain:** - Supports secure traceability of products - Enables resources visibility and transparency - Enables monitoring of complex supply chains - Supports fraud minimization and enhances trusted transaction (financial, resources data) - Supports monitoring and control of usage **AI/AR:** - Enhances processes optimization - Enhances customer experience during design phase - Enables product life prediction models - Predictions based on previous products (resources, energy, pricing) **PSS:** - Facilitates smart contracts among users - Supports upgradability (product supported by after-sales service) - Identifies error and optimizes to reduce failure	**Reverse flows:** Big Data & Cloud Data (Facilitates monitoring of usage for optimizing product lifecycle), Blockchain (Supports secure traceability of products, enables resources visibility and transparency, enables monitoring of complex supply chains, supports monitoring and control of usage) **Circular design:** Big Data & Cloud Data (Provides insights for previous products), AM (Enables prototyping and adaptability, enables customization and allows customers to design the product), AI/AR (Enhances customer experience during design phase), PSS (Supports upgradability (product supported by after-sales service)) **Product life extension:** IoT (Facilitates connection between product and service, supports sharing and leasing, enhances pay-per-use models, enables real-time data collection, enables resources control, supports hyperconnectivity), Big Data & Cloud Data (Enables optimization practices for resources and energy consumption), AM (Contributes to waste reduction for prototyping and modeling, Blockchain (Supports secure traceability of products), AI/AR (Enhances processes optimization, enables product life prediction models), PSS (Identifies error and optimizes to reduce failure) **Circular collaborations:** IoT (Supports hyperconnectivity), Big Data & Cloud Data (Facilitates virtual platforms for connectivity, supports hyperconnectivity), Blockchain (Supports fraud minimization and enhances trusted transaction (financial, resources data)), PSS (Facilitates smart contracts among users)

C Appendix III - Tables of cases codification and analysis

In this section the codification and thematic analysis of the interviews performed with the subject matter experts is presented. In the following pages, the codification of the discussion as performed per case is analysed, supplemented with sentences and insights from the transcripts.

Case 1: Philips			
Overarching Code	**First Level Code**	**Sub-Codes**	**Discussion Quotes**
Key Driver to CBM	Financial	• Product value	"It's good to consider the value of the product, because if you can generate revenue, it can be one of the biggest drivers for closing the loop."
	Innovation	• Supply chain	"Circular economy is interesting particularly for large organizations which traditionally have been linear and have invested in a forward supply chain. Circularity is seen as innovation to make reverse supply chains and close the loop."
Challenges towards CBM	Customer-related barriers	• Motivation and trust	"In a consumer setting you have to make sure that customers trust you and know what to do and that they are motivated to return products."
	External and organizational barriers	• Linear design	"It's a real challenge to close the loop and create a reverse process as a lot of the products that we're dealing with were designed in a linear mentality."
		• Cost	"The relative cost of remediation is quite high and means that it is a lot harder to create a circular justification."
		• Regulations	"There are also lots of legal implications if you try and reuse devices, particularly in the medical industry."
Company operation	Value chain	• Positioning	"For many products we buy standard and customer parts and then we do the assembly. For the logistics we have lots of partners in up and downstream."
		• Circular actions	"Circular activities are mainly focused on large medical devices which are easy to track in the installed base. Projects to salvage parts and remanufacture systems are easier to justify as they retain greater value."
Long-term vision	Circular actions	• Take-back products	"We have set the target to be able to take back all small medical devices by 2025. One of the challenges will be to close the loop on these devices."
		• Recycling	"Initially we will focus on recycling which is the worst-case scenario. Hopefully in the future we will be able to retain more value."
Strategies	Target high volume products	• Product remediation	"The main focus is on remediating existing products which are produced in high volumes."
		• Close the loop	"A target is close the loop at the end of use for B2C where you have lower value consumer goods in high volumes."
	Take back & recycle	• Value retrieval	"We want to make a system where we take products back and then recycle and recover any value."
		• Set-up	"Setting up a take back ecosystem is challenging, partly because products are distributed among thousands of users."

CBM Elements	Product proposition	• Recycled components	"New products are made using recycled content where possible, and small medical devices at the end of use will be recycled as part of our 2025 targets."
		• Price	"The price of new products with recycled content might be lower but depends on the resources and energy required to initiate a project."
	Customers	• Target segment	"We will be taking back smaller devices that may sometimes be disposed of after use as they replace them with new models."
		• Collaborative relationships	"Ongoing relationships with end users are key so that they are aware of responsible end of use options for their devices."
	Partners	• Logistics management	"To take back you need logistics partners to manage the collection."
	Activities	• Incentives	"We need to incentivize customers to bring products back."
		• Infrastructure	"Large products end up concentrated in hospitals and are easier to trace and process."
	Capabilities & Resources	• Design for longer	"Large, complex products are produced in lower volumes but take more resources to produce. However, if they are designed well, value can be retained by enabling circular economy loops through design."
		• Attention to materials	"Whereas, if you produce millions of simple products, you need attention on the materials consumed."
	Financial Benefit	• Savings	"Taking back products in high volume would reduce negative impact but it's harder to justify as it is harder to retain value."
		• Revenue	"The value is dependent on the product complexity. If it can easily be reprocessed, then remediating those products cancreate opportunities for new revenue streams."
Technologies	Contribution to circularity	• Value monitoring	"Big data can be used to track the installed base and understand where value is concentrated in the market."
		• Product tracking	"Internet of things would be useful to have some information about where the product is and what its condition would be."
	Other technologies	• Diversification	"We have different products that would require different technological setups, tailored to the individual requirements."
Evaluation	Practical Implication	• Usability of framework • Clarity and potential	"This is relatively high level information. So it would be kind of near the beginning of when a business unit is thinking about what product they want to develop and by using the framework they understand which of these strategies can help them meet their targets."
			"I think the framework could work well as a basic structure in anideation workshop, although should be open to being challenged and edited by the participants."

	Limitations	• Quantification with metrics	"A metric is missing of not just complexity of products, but also value of product."
		• Financial evaluation	"In a circular financial model, you must consider how much value you can recover and how much it costs to unlock that value."
	Improvements	• Examples	"Tangible examples of businesses that implemented circular economy would be really useful."
		• Strategies mapping	"It may be useful for the strategies to be mapped onto the butterfly diagram by EMF."
	Insights	• Perspective difference	"When we talk about circular economy we don't necessarily talk about renewable energy and emission reduction, so I think for greening people have different ideas."
		• Visual-related	"Just from a visual perspective, I would use the same colors that you've got over on the right when presenting circular strategies."

Case 2: Royal Ahrend			
Overarching Code	**First Level Code**	**Sub-Codes**	**Discussion Quotes**
Key Driver to CBM	Customer preferences	• Flexibility with leasing	"Customers didn't really know if the need an office for a long or short period. The circular design and the leasing flexibility allow them to send back what they don't need and then we bring them something else that's, they might need."
		• Sustainability	"So, both the flexibility and the sustainability go hand in hand in the leasing proposition from our point."
	Financial	• Extended profit	"We have been designing for years products that all the parts can be easily taken apart for recycling. This can lead to extend the life of the product and be profitable for longer."
Challenges towards CBM	Operational barriers	• Logistics • Cultural perception	"We are looking to implement circularity and expand in other countries but from a logistical point of view its difficult and the perception changes per country."
		• Securing the design	"Companies that benefit from the fact that we have designed our products circular because they do the refurbishment part of it."
	Customer barriers	• Conviction	"Everything is leased except for the furniture. So, I don't know why we still have to do a lot of convincing there because some customers are still purchasing our products."
Company operation	Value chain	• Positioning	"We do everything in the value chain compared to most of our competitors who work through dealers."

		• Customer focus	"We mainly focus on a B2B setting. A B2C model has a completely different scope."
Long-term vision	Servitization	• Product-as-a-service	"Customers can also lease our products, which is also from our point of view, the preferred scenario because then we don't have to produce that many products to still be profitable."
	Recycling	• Materials	"We are focusing on the adoption of more recycled materials in our product. So we want to increase the share of recycled plastics…"
		• Environment	"…that's one of our main goals with the ultimate goal to reduce the environmental footprint of the product."
Strategies	Reverse logistics	• Product take back	"And actually, when we position the products in the market, we want to make sure that we get the product back always."
	Eco-design	• Sustainable materials	"Making the product completely out of recycled plastic is one of the focus points that we have."
		• Materials innovation	"The quality of recycled materials is not always that good. This is a really big challenge for us so we need novel materials. So, the material input is a topic that we are focusing on right now, for example to substitute with recycled materials as in the narrowing strategy. Material sourcing has also the biggest environmental impact on the value chain."
CBM Elements	Product	• Value proposition	"The design of the product to be offered will be really lightweight and high quality, and it has been eco designed compared to the previous product. That would be our value proposition."
	Customers	• Long-term relationships	"We have a broad range of customers with changing needs and requirements but sustainability is their common sense."
		• Collaboration	"The customer needs a flexible relationship. Sometimes we are in a more traditional contract with a customer where we are the supplier and they are the buyer. They can also decide for example on a more loyal relationship where we could also experiment maybe with your customer."
	Partners	• Localization	"Because we want to have a sustainable impact collaborating locally going with other partners so that you don't really do the collection, or everything yourself, but you work with them."
		• Take back network management	"Creating an ecosystem of different strategic partners is key because we want to take the product back, refurbish it, repair it and go to the customer's location to see if they're still happy with the product."
	Activities	• Awareness	"The customer needs to be aware that when they start using or when they are done using the product that we have the first right to buy the product back."

		• Pilot programs	"We have been piloting the option of sharing the products via a platform which we haven't rolled out in a big scale. It is something that can be explored with our customers. We also want our partners to have a low impact also on environmental and social footprint."
	Capabilities & Resources	• Platform	"As a key capability we need to facilitate a platform that customers can share the availability of their products when they don't want to keep them for more. In a local level, we can do the intermediate delivery. So if we do the transportation part we could also refurbish parts if necessary, add value in that step and make some benefit for us. So, we need transportation means."
		• Infrastructure	"We need R&D capacity to build new sustainable materials or partners to outsource those activities."
	Financial Benefit	• Buyback	"Giving the customers, for example, a lower price at first when they buy the product and have also in place a buyback system can be financially beneficial and would allow for material and cost savings."
		• New revenue streams	"Working together with customers creates a kind of loyalty. In that way a loyalty scheme can be used to gain profit."
Technologies	• Monitoring	• Product tracking	"When we are the owner of the furniture, it's really important that we know where the products are. So adding RFID chips can help with product monitoring."
	• Contribution in design	• Material technology	"We collaborate with a lot of partners to get knowledge about other materials that we could use in our product because I think technology from a material point of view is also important as a special and rapidly growing technology."
		• Simulations	"Simulations that can help the design process and the customization of the products."
Evaluation	Practical Implication	• Usability of framework	"I think it's really helpful for companies, to approach circularity in a process, so to have the steps where they can take and wherever they want to go. So it looks pretty complete."
		• Clarity and potential	"I think it could be helpful in an ideation phase. What's in the scope seems familiar with points that we were thinking of but not in that structured way."
	Limitations	• Material options	"The material point of view is missing which could also be a choice."
		• Time constraint	"I didn't get the chance to read everything so more time is required to go through the framework."
	Improvements & Advice	• Social perspective	"The social part could be integrated as well. But, I can also imagine that if you focus only on the environmental side of the circular economy, that could also be a choice."

Case 3: Sif			
Overarching Code	**First Level Code**	**Sub-Codes**	**Discussion Quotes**
Key Driver to CBM	Business opportunity	• Financial benefit	"We see circular economy as an opportunity to reduce resources when others see it as a challenge."
		• Competitive advantage	"Since we are market leaders, companies want to copy and imitate. Therefore, circularity can give us a competitive advantage, which can also be sustainable competitive advantage."
	Impact	• Sustainability	"We want to enhance our contribution to the sustainability and circular economy can increase our share in that direction."
Challenges towards CBM	Barriers	• Product nature	"The product we offer in the market is part of a larger system therefore collaborations need to be established"
		• Financial	"To apply circular actions large investments are required and profit margins need to be carefully calculated."
Company operation	Activities	• Value chain	"We take metal sheets from our suppliers, perform the fabrication and marketing to build a leading brand around wind turbine monopiles. We support the whole value chain by optimizing the design, logistics and maintainability"
		• Green production	"The production processes are fully running on renewable energy and we move further with the electrification of our facilities. Green energy is the currently applied circular strategy."
Long-term vision	Circular actions	• Take-back products	"Taking back our products after decommissioning is something we are interested in the last year."
		• Recycling of materials	"In that way we can recycle the materials and reduce our net balance or resources."
	Eco-footprint reduction	• Renewable energy	"Green hydrogen is an option for the future since high temperatures are required to produce green steel."
Strategies	Recycling	• Close the loop	"Until now our business model was focusing on selling the product to the clients and they were responsible for the product after the end of the cycle. We want to close this loop."
		• Value from waste	"We want to add another step to our value chain which is closing the loop and returning of products. In that way we can regain value from products that would have been scraped after decommissioning."
	Resources reduction	• Reuse old products	"The goal is to reduce our resources by retrieving the products at the end of their life cycle and use them as input for the new fabrications."
		• Production approach	"In addition, a novel method will be used which requires less energy to process the steel."
CBM Elements	Product	• Value proposition	"By using the old product to remanufacture the new one, we aim for a different value proposition by keeping the same product offering."

	Customers	• Target segment	"Our target group will continue to be the same, including wind farm developers who are highly environmentally aware and need sustainable products."
		• Long-term relationships	"To be able to take old products back and remanufacture them, we need long term relationships from two sides. One is that of the customers for getting the product and the other is that with our suppliers to get the right resources and materials for the new products."
	Partners	• Resources trading	"Our supplier is the main partner that we need in the value chain in order to trade resources and material between new and old products. For that a partnership is necessary."
		• Reverse logistics management	"Additional partners are required which will facilitate the reversing of the supply chain and manage the product decommissioning and take back to the manufacturing facility."
	Activities	• Access • Production	"Getting the products means that we have access to them at the end of their life. Thereafter, the production process should change in order to facilitate the new concept."
		• Customer communication	"Now the customers are having full ownership of the product even at decommissioning. To be able to access the products customers need to be informed and approached directly about the new value proposition."
	Capabilities & Resources	• Resources shorting facility	"For supporting the recycling an investment to a shorting facility is required."
		• Special equipment	"To take the old products back additional equipment might be required for special cases which will be defined later."
	Financial Benefit	• Minimization of cost and energy	"Using the resources from the old monopiles and new production methods will reduce production cost and resources quantities."
		• Take back fee	"We can explore new revenue streams by charging a fee for taking products back."
Technologies	Data technologies	• Condition prediction	"The technologies will be enabling the new value proposition as with sensors we can collect data and predict the conditions of the products offshore."
		• Material passport	"Big data and analytics are needed to support the material passports which are our way of proving to the clients the quality of the steel used in the products."
	Waste minimization	• Automation & Optimization	"We need to introduce automation processes to optimize the shorting activities and in parallel minimize the waste streams."
Evaluation	Practical Implication	• Completeness & potential use	"The framework looks complete to me and can be initiate a lot of discussions about circularity especially among those who are not aware of the actions and the strategies."
	Limitations	• Quantification	"The quantification of the value gained per strategy is missing."
		• Time constrains	"The framework is extensive and to my opinion someone needs more time to go through each element in detail."
	Improvements & Advice	• Presentation order	"It would be beneficial to present the roadmap first with all the steps that need to be taken, let people brainstorm and then show them all the strategies."
		• Products examples	"Add examples of products along the value chain to make it more practical."

Case 4: Additive Industries			
Overarching Code	**First Level Code**	**Sub-Codes**	**Discussion Quotes**
Key Driver to CBM	Benefits of circularity	• Competitive advantage	"Material that have not been used for the construction of a component are reused, which can be seen as a circular process.
		• Resources reduction	"We directly recycle these materials within the printing process which makes us more efficient than our competitors"
Challenges towards CBM	Knowledge	• New topic	"We are a machine manufacturer, so we are not really focused on what happens after the end of life of a machine. Circularity is a new topic we want to explore more and gain knowledge"
Company operation	Value chain	• Outbound	"We mainly focus on the outbound logistics. We have a sophisticated supply chain that we collaborate with in order to manufacture these machines.
		• Sales	"We do the assembly, marketing and sales in house."
Long-term vision	Servitization	• Machine-as-a-service • Non-ownership	"Currently we are investigating how the clients can take advantage of the performance of the machine without owing it which can be a business opportunity"
	Customer	• Product upgrade • Preference	"Part of our business case is to upgrade the machines preferably at the location of the customer which can also be a circular process in my opinion"
Strategies	Intensifying	• Multiple use • Opportunity	"Using the machine in a way that multiple clients can have access to it might be an opportunity for extending the current sales-based business model"
	Narrowing	• Marketing and sales	"Narrowing strategy might be applicable to the marketing and sales by providing printing services"
CBM Elements	Product	• Increase availability	"By offering the product as a service you can increase the amount of companies that might be interested…"
		• Investment reduction	"…especially when their budget is not sufficient to purchase the machine"
	Customers	• Target segment	"The targeted customers would be mainly manufacturers of complex components, suppliers or either end users, which they would want to reduce their investment costs and have accessibility to a machine all the time"
		• Relationships & Communication	"The relationship with the customers is key and depends on the use case. A direct customer service is required and direct communication channels"
	Partners	• Suppliers	"To support a leasing program, we would need suppliers in order to exchange resources and facilitators that will be able to support processes that cannot be done by ourselves."
		• Facilitator	"We need collaborations for the reverse operation of delivery to bring products back for upgrading"

	Activities	• Calculations	"Perform calculations and decide the leasing cost, that would be step one check if it would be to provide a product in that way"
		• Awareness	"The next step would be to create awareness that we would offer an alternative since education is very important in this market"
	Capabilities & Resources	• Monitoring	"We already perform monitor when the clients are using the machines."
		• Platform	"Through a platform we could facilitate several ways of working in this direction"
	Financial Benefit	• Upgradability	"The modularity of the product allows for change procedures to be profitable. The products can be upgradable which can allow for a circular serviceable business case."
		• Profit	"For the upgradability a fee can be incorporated in the leasing cost or invoiced as a different cost. The profit from a product-as-a-service can be gained through subscription."
Technologies	Data	• Collection & learning	"Big data and analytics are required. The more machines in the field, the more information can be gathered from these machines to optimize processes, learn from mistakes and issues."
		• Sharing transparency	"Some clients might not want to share their way of working with the machine so blockchain is required mainly for data transactions."
	Simulations	• Optimization and customization	"Simulations of the functioning can be an optional part of the machine to analyze components before printing That gives the client the option to see how the machine operates and how the customize the prints."
Evaluation	Practical Implication	• Potential of framework	"We already apply this way of thinking but it is always good to have some external inputs"
		• Clarity	"Looks very good and clear"
	Limitations	• Time constraints	" More time is required to have a deeper look at the framework."
		• Companies examples	"Some examples would help more from a practical side."

D Appendix IV - Complete representation of the framework (Miro Board)

The framework used for the interviews and the interaction with the experts is developed with the assistance of the Miro software. Screenshots from the tool with the additions from the cases are presented bellow. For more details and better navigation experience the framework is provided under the link Miro Link.

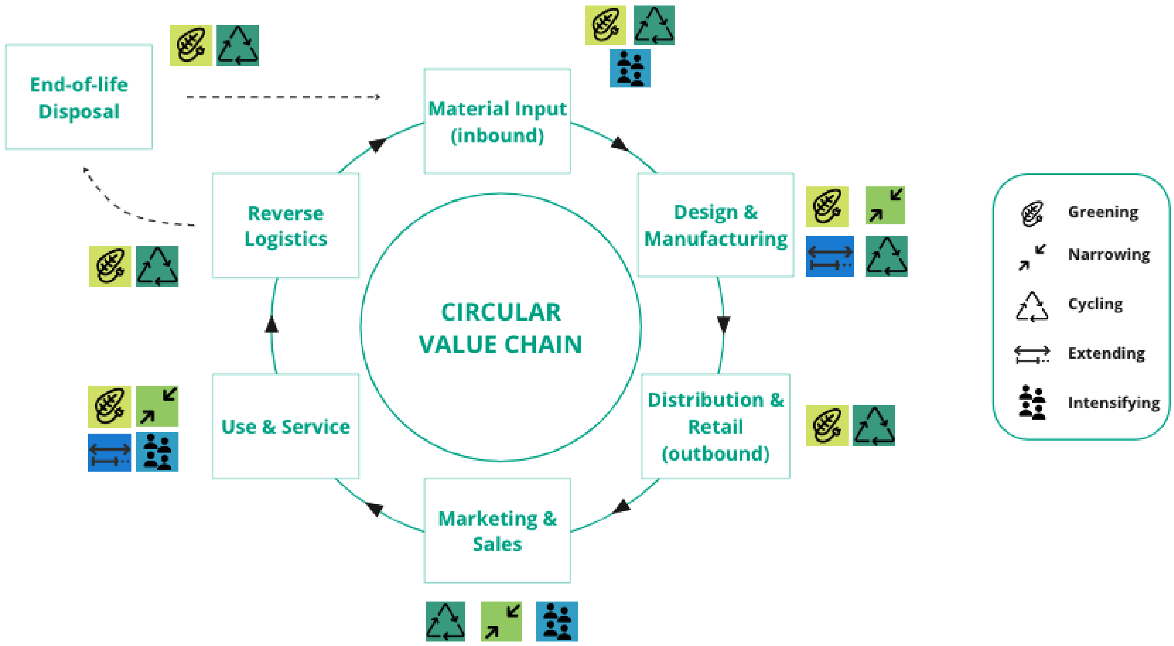

Figure 11: Circular value chain and strategies (Miro)

Figure 12: Circular practices linked to value chain stages (Miro)

Industry 4.0 Technologies Capabilities & Circular Economy	Value Proposition	Value Creation & Delivery	Value Capture
Internet of Things (IoT) Big Data, Analytics & Cloud Computing Cyber-Physical Systems & Additive Manufacturing Machine Learning (ML) & Artificial Intelligence (AI) & Augmented Reality (AR) Blockchain Simulations	Internet-of-Things: - Enables product customisation, collaboration for design and facilitates services development for product-service-systems. - Enables tracking of materials/products and flow mapping ensuring recycled materials quality for reuse. - Supports data collection regarding customer needs. - Supports data collection regarding energy consumption. Big Data & Analytics: - Facilitates analysis of product requirements and optimises design processes to reduce resources utilisation. - Promotes reuse by enabling the development of "product passports" (digital documents containing informations about the product). Machine Learning, Artificial Intelligence & Augmented Reality: - Processes optimisation and energy consumption minimisation through prediction models based on previously produced products. - Enhance customer experience through virtual product demonstrations and training (no need for physical products). - Prediction models for product performance to reduce deficiencies and keep customer satisfied. Blockchain: - Enables reliable informational or financial transactions with verifiability and security (especially between users). Cyber-Physical System & Additive Manufacturing: - Enables remanufacturing and assembly/disassembly in an energy and resources efficient manner based on automated process control. - Allows for interaction between manufacturing workforce and robots for process optimisation. - Enhances customisation and connects customers with product design, prototyping, assembly and direct material collection from suppliers (treated waste as feedstock for 3D printing) - Reduces energy consumption in terms of transportation due to mobile options, brings customer closer to production. - Supports quick product repair and printing of damaged parts for product life extension. - Efficient maintenance processes through automation. Cloud Computing: - Facilitates real-time data collection for process or design optimisation and resources efficiency. - Enables live product performance monitoring allowing for modifications to increase customer satisfaction. - Supports upgradability and constant software support through platform integrations. - Enhances customer experience through live tracking, logistics monitoring and product-service performance. Simulations: - Company-customer digital product co-development to increase customisability and enhance proposition while reducing rework and waste. - Supports digital design of products for easier recycling and repurposing. + Support product functioning visualization. + Special technologies to support complex product use.	Internet-of-Things: - Facilitate data collection through RFID, sensors and barcodes. - Facilitates resources flow tracking through the life cycle and along the value chain. Big Data & Analytics: - Connection between service providers and users via communication platforms, hyperconnectivity. - Large data processing as collected by IoT for product lifecycle tracking and resources use optimization. - Analysis of energy consumption (through sensors) and optimization for increasing renewables share and reduce overall cost. Machine Learning, Artificial Intelligence & Augmented Reality: - Prediction models for remaining useful life and maintenance planning for product use extension. Blockchain: - Secures product traceability and accuracy in data collection from sensors and IoT. - Offers transparency in information flows especially in complex supply chains with multiple connections and actors. - Supports reverse logistics systems with transparency and enhances customers trust and confidence regarding processes and product quality. Cyber-Physical System & Additive Manufacturing: - Automation of production and waste shorting processes to minimize energy consumption and increase material separation efficiency. - 3D printing facilitates waste repurposing and material reuse for new product development which reduces energy and resources emissions. Cloud Computing: - Updated and live data to keep a balance between supply and demand for resources efficiency. Simulations: - Facilitate prognostic models for processes optimization and product lifecycle management through digital trials. - Allow for performance calculations in closed-loop supply chains and optimization for maximum resources efficiency. - Facilitates the development of product digital twins in the design and conceptualization stage and indicate potential value creation which reduces waste needed otherwise for trials. + Material technology supports knowledge building on material aspects.	Internet-of-Things: - Data collection for process or product optimisation purposes which will reduce overall cost. - Supports platform and app integration for sharing purposes creating new revenue streams. Big Data & Analytics: - Provides open-source capabilities and data access for recycled products which enhances resources trading (new revenue streams). + Support savings calculation on value retrieved. Machine Learning, Artificial Intelligence & Augmented Reality: - Financial predictions and efficient optimisation of processes for energy, resources and cost reduction. Blockchain: - Facilitates safe contracts and connections between customer, suppliers and company which reduces digitalisation risk. - Transparent financial transactions which increase customers trust and willingness to pay. Cyber-Physical System & Additive Manufacturing: - New revenue streams through manufacturing-as-a-service offering. - Savings on prototyping costs with use of by-materials in lower prices. Cloud Computing: - Operating cost reduction for storing and analysis of data. Simulations: - Enables error identification in design phases before the process is performed (avoids error cost).

Figure 13: Indystry 4.0 technologies and circular value (Miro)

Circular Strategies	Circular Practices	Enabling Technologies (Industry 4.0)	Circular Business Model Elements								
			Value Proposition			Value Creation & Delivery				Value Capture	
			Product/Service	Customer	Customer Relationships	Key Activities	Key Partners	Resources & Capabilities	Channels	Cost structure	Revenue Streams
Greening Sustain & Regreen	- Use renewables (logistics, production) - Sustain natural ecosystems - Power products with renewables - Green-based partnerships	- Data collection for energy efficiency - Connectivity with partners - Energy management and optimisation - System (energy, ecosystem) modelling - Scenario testing (weather conditions, energy loads)	- Processes use renewable energy to transform materials into green products. - Products have low environmental footprint while being powered by renewable resources (solar panels, scalable wind turbines). + Products produced with novel energy efficient methods	- Incentivised customers which purchase only products which have been produced with green power. - Customers with high environmental awareness.	- Transportation is initiated based on renewably powered means (electric-based mobility, bikes, etc.). - Collaborative initiatives to sustain or regreen natural reserves and ecosystems. - Collaboration only with suppliers which support green initiatives.	- Educate customers to use only green products. - Create awareness about green actions and incentivise customers.	- Collaborative initiatives to restore and regreen natural ecosystems. - Delivery of supplies with the utilisation of renewable resources and non-fossil mean.	- Build-up renewables capacity and use it in production and by-processes. - Delivery of products in a sustainable way. - Make creative partnerships which embrace green energy. - Human resources to support green marketing and promote sustainability.	- Sustainable transportation and delivery. - Sustainable insights promotion through social media for customer and stakeholder education.	- Savings from renewable energy consumption. - Savings on transportation costs.	- Reputation due to green initiatives, can attract incentivised customers with high environmental awareness.
Narrowing Reduce & Localize	- Reduce materials usage - Substitute with innovative materials - Balance supply and demand - Service vs. Product - Incentivise to reduce consumption - Localise supply chain	- Data collection for service monitoring - Connectivity for supply and demand monitoring - Data analysis for consumption pattern recognition and reduction - Prediction algorithms for supply and demand - Life-cycle expectancy prediction - Conceptual service development and user education - Scenario testing for product development with alternative or less materials	- Products offered are build based on the minimum possible material consumption. - Service offering which completely substitutes the functionalities and capabilities of a physical product. - Products are being produced based on the demand, supply-demand ratio is balanced. - Products made of innovative materials which are purposed at reducing the consumption of conventional materials.	- Proactive customers willing to reduce consumption. + "Green" customers with high sustainability awareness	- Exploitation of local suppliers and partners in order to reduce energy consumed from transportation and materials trading. - Ensure product functionality besides the reduced materials utilisation during production. - Ensure service performance besides the lack of a physical product. + Flexible relationship to built loyalty and experiment new sustainable prod-ucts, + Direct communication to allow experimentation.	- Educate customers to reduce consumption where possible. - Reduce product consumption with service offerings. - Reassure that the service offered can cover customer needs. - Reduce resources utilisation by initiating recycling and reuse actions. + Pilot programs to test the new products	- Supply resources in local basis. - Innovate materials with advanced properties along with institutes which can substitute the traditional non-ecological materials.	- Substitute product with an equal service which can serve the same functionalities. - Capacity management in order to have an equilibrium between supply and demand. - Technological capabilities which can assist with service offerings and demand prediction. + R&D capabilities to innovate new materials	- Software delivery instead of product via performance/functionality provision. - Social media and online channels for offerings delivery. - Apps and online tools for service delivery (product virtualisation). - Direct sales of non-ownership products.	- Savings from on demand production and efficiency due to innovative materials. - Savings from transportation cost reduction due to local supplies.	- Profit from subscription schemes for software utilisation. + Loyalty gains from long-term relationships
Cycling Reversing & Reuse	- Reuse/Resell - Recycle - Redistribute - Take-back system / Reverse logistics - Incentivise to return - Cascade/Repurpose - Recover elements/materials/parts - Industrial Symbiosis	- Resources tracking and condition monitoring - Connectivity with customers for products return - Data transparency and verifiability - Secure resources trading among stakeholders - Material/product condition prediction - Consumption patterns analysis for reselling and efficient redistribution - Automation for optimised resources recovery - Efficient resources collection and shorting	- Products made of recycled elements/materials/components. - Second-hand/second-chance products which are being redistributed to market for reselling and reuse. - Value from biomass is returned to the ecosystem, cascading.	- Incentivised customers willing to purchase redistributed goods. - Customer segments with high environmental awareness.	- Facilitating suppliers and collectors which support reverse logistics activities. - Material/parts trade among industries to cover needs without additional resources input to the system. +Long-term relationships aiming at product take back after use (synergetic relationship)	- Incentivise customers to return products for reuse and redistribution. - Reassure that recycled or second-life products have good quality and can serve the intended functionalities and purpose. - Access end-of-life products and retrieve useful resources from waste. + Production line changes to allow recycling	- Reverse logistics partners which are purposed for product return and resources circulation. - Cooperation with facilitators and redistributors for product collection, inspection and direct selling. - Resources trading through cooperatives and by-products exchange.	- Take-back systems and products/materials return point. - Recycling processes and reverse supply chains. - By-products exchanging with industries, waste from a manufacturer can be used as a valuable input. - Mange product traceability with IoT and cloud technology. + Additional special equipment per case to allow take back	- Direct channels for resell either through retailers or online means. - Social media and apps to communicate recycling value to customers. - Virtual channels (media, platforms) for resources trading. - Reverse flow infrastructure as a channel for recycling. + Indirect channels through retailers	- Savings from reduced production costs. - Savings in material inputs with the exploitation of by-products. - Joint (customer, manufacturer) cost reduction and new production lines.	- Revenue from product offerings in lower price, reselling revenue streams. - Revenue from resources trading. - Reputation gains in "green" customer segments. - Direct and indirect sales (transaction fees) and revenue streams from reselling. - Additional profit from buy-back scheme, take-back service fee and trade-in credit.

Figure 14: Circular business models based on circular strategies (part i - Miro)

Extending Slow & Maintain	- Repair/Maintain - Remanufacture/Refurbish - Service support (after-sales service) - Design for ease of maintenance - Always-in-style design - Incentivise for long-lasting usage - Upgrade scheme - Design for durability/longevity	- Data collection of usage and customer needs - Resources tracking and condition monitoring - Usage patterns identification for services improvement, upgrade - Automation for efficient maintenance and manufacturing/remanufacturing - Customised manufacturing and product designs - Predictive maintenance for service support - Upgradability suggestions and dynamic pricing - Secure product information management for disassembly, repair and maintenance - Conceptual design for longevity and performance checks - Design and maintenance scenario testing	- Product is designed in a durable way to last longer. - Product is based on timeless design (does not fade out of style). - Defected or damaged products are being repaired to retrieve their capabilities without resources waste. - Upgrade to new modes (product or service) with additional features and high quality. - Product design is easy to maintain, disassembly, remanufacture and refurbish.	- Conscious customers willing to use the product for longer. - Customers segments which lengthen consumption to save on capital costs.	- Suppliers and external partners which remanufacture and directly offer products to customers. - High quality service provision through network of actors.	- Attract customers which are willing to keep products for longer time. - Provide warranties for the product functionality and performance. - Provide upgrade plan to gain commitment. - Upgrade plan for B2B customers which require constant performance and results from the product in use. - Educate customers on how to use products in order to achieve longevity. - Initiate repair plans and accompany products with services.	- Ecosystem collaborations which will support repair and remanufacturing activities. - Make network and outsource activities related to maintenance and repair while the service offering remains with the initial manufacturer.	- Design products to last longer in order to reduce faults, damages and eventually faster disposal. - Offer product upgrade and modules which will make the customer keep the product for longer. Upgrade with additions, software, service. - Technological resources to support upgradability, real-time data transfer and performance monitoring. - Technological capabilities and life prediction models which will ensure product life extension.	- Online and virtual channels to support after-sales services and upgrades. - Direct and online sales for remanufactured and refurbished products. - Virtual service for design customisation and long use support.	- Financial savings from material savings since remanufactured products can be resold without the need for making new products.	- Revenue from "premium" products with durable design. - Revenue from services for repair and upgrading. - Profit from performance- and function-based contracts, charging per use or for results. - Non-financial gains from customer lock-in and long-term relationships.
Intensifying Share & Collaborate	- Product sharing - Product-as-a-Service (PaaS) - Leasing/Pooling - Educate to share - Consume collaboratively - Resources trade (platforms)	- Resources tracking and condition monitoring - Connectivity with customers for products return - Real-time data exchange and connectivity - Usage pattern analysis and sharing - Multi-user access to automated manufacturing as-a-service (3D printing) - Usage and end-of-life prediction - Dynamic pricing - Connectivity provisions through matching algorithms - Transparent intra-user transactions - Privacy and security insurance - Scenario testing for complex supply chain management - Customer education and experience improvement	- Shared value with increased availability and lower price. - Temporary exploitation of product functionality, product owing remains by the manufacturer. - Structured platforms which support product/parts/components sharing or pooling. + Inventory cost reduction instead of lower price	- Network of users/consumers which aim for lower pricing and broad range of choices. - Customers which aim at making a profit from sharing or resources trading.	- Suppliers and external partners which promote products sharing for temporary use. - Customers engagement through platform and shared reviews regarding service quality.	- Sharing initiatives among consumers and educate to share. - Educate for collaborative consumption. - Management of customer relationships as a practice to ensure satisfaction and loyalty. - Design product-service-system which can support both the product being shared and the service which accompanies it. + Calculation of leasing costs, Customer education to create awareness of the sharing provision	- Suppliers management, connect internal and external capabilities to support sharing models. - Connection channels and platform for material/products sharing in a B2B basis. - Create network to inspect products in use and ensure quality, longevity and abuse reduction.	- Product ownership remains with the manufacturer which manages repair and redistribution. - Online platforms to manage product leasing/pooling and embrace sharing among users. - Technology-related resources to support digitalisation and product monitoring during collaborative usage.	- Apps and online webs for users connectivity and service delivery. - Online platforms for products/material sharing/trading. - Online advertisements as indirect communication channels to promote sharing and collaborative consumption. - Indirect sales through C2C channels.	- Savings from products reuse by multiple users, benefits from extended lifecycles. - Savings from resources reduction and energy efficiency due to multi-usage.	- Revenue from new non-ownership contracts. - Charging per use, temporary contracts. - Increase profit through customer loyalty. - Non-financial gains from customer lock-in and long-term relationships. - Profit from platform fee for resources trading (subscription pricing). - Dynamic pricing through usage monitoring. + Profit from modularity leading to intra-use upgrade and changes

Figure 15: Circular business models based on circular strategies (part ii - Miro)