Exploring the Role of Digital Twin in Enabling Circular Business Models for Electrical and Electronic Equipment Manufacturing

Master Thesis by
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Exploring the Role of Digital Twin in Enabling Circular Business Models for Electrical and Electronic Equipment Manufacturing

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in partial fulfilment of the requirements for the degree of

Master of Science
in Management of Technology
Faculty of Technology, Policy and Management (TPM)

at the Delft University of Technology,
to be defended publicly on Monday September 23, 2024.

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"The Universe is full of dots. Connect the right ones and you can draw anything. The important question is not whether the dots you picked are really there, but why you chose to ignore all the others."

- Sam Thomsen

Acknowledgements

The past few months have been a whirlwind of discovery and challenge. What began as curiosity about two emerging fields quickly turned into a demanding research journey. Each step revealed new complexities, and there were moments when the obstacles seemed too great. It wasn't an easy road, but I made it through thanks to the incredible support of those around me, and for that, I am truly grateful.

First and foremost, Johannes, thank you for giving me that initial push to take a leap of faith and pursue this research. Your insights and feedback have made me a better researcher. I'm especially grateful for your constant encouragement, always reminding me to hold my head high as I navigated the challenges along the way. I'm deeply grateful for your belief in my work. To Hanieh, thank you for offering me this unique topic and helping me uncover countless insights throughout the process. Your guidance has been invaluable in shaping the direction of this research. And to Linda, thank you for being the best chair I could have asked for. Your feedback, support, and constant reminders of all the things I could do helped shape me into a better researcher.

My gratitude also extends to all those who participated in this research. I hope I have done you all justice through my work. To my dear friends that I've made over these past two years, thank you for sharing the laughs and offering your constant support. To my beloved Mutia, thank you for everything—your love, patience, and unwavering encouragement have been the fuel that kept me going throughout this journey. To my family back home —Mom, Dad, Dian, and Ilham— thank you for always believing in me and praying for me despite the distance between us.

I would also like to extend my sincere gratitude to Indonesia Endowment Fund for Education (LPDP) for all the support that made this journey possible. I hope that, though this thesis may be just a small step, it can spark further inquiry and inspire others to explore these emerging fields with renewed curiosity and passion.

Fakhri Muhammad
Delft, September 2024

Executive Summary

Manufacturing firms, particularly in the electrical and electronic equipment (EEE) sector, have historically followed a linear economic model of 'take-make-dispose,' leading to substantial environmental degradation from high waste outputs. In 2022, the EEE sector generated 62 million tons of e-waste, with less than 23% recovered, highlighting the urgent need for sustainable practices to mitigate environmental and health risks.

The circular economy (CE) offers a sustainable alternative by prioritising resource recovery and regeneration. Circular business models (CBMs) central to this approach advocate for recycling, reuse, and waste reduction to maximize resource value. However, the adoption of CBMs in the EEE sector is constrained by challenges such as complex lifecycle management that demands detailed information at every product stage.

Digital twin technology has emerged as a crucial enabler for CE, providing digital replicas of physical systems that enhance decision-making, optimize processes, and facilitate lifecycle collaboration. This thesis explores how digital twin technology can support CBMs in the EEE sector by developing a framework for integration and identifying key capabilities and challenges.

The study aims to systematically investigate how digital twin technology can support CBMs in EEE manufacturing, focusing on circular strategies throughout the product lifecycle and identifying relevant capabilities and enabling technologies. The research involves an extensive literature review and interviews with eight experts to understand digital twin's potential applications and validate the framework.

Despite its emerging stage, digital twin adoption offers a holistic view of practical applications and challenges in CE. The research demonstrates how digital twin technology underpins CBMs at every product lifecycle stage, from design to end-of-life. It also establishes a link between digital twin capabilities and CBM value elements. The Digital Twin Nexus Circular Business Models framework provides a comprehensive strategy for integrating digital twin technology with circular strategies, delivering insights for EEE manufacturers to enhance sustainability. This framework helps identify lifecycle stages that can benefit from circular strategies and the necessary technologies for effective digital twin implementation.

However, implementing digital twin technology poses challenges such as the need for organisational alignment across the value chain and significant data governance and security hurdles, requiring clear data ownership and sharing guidelines. Product design must also evolve to safely manage hazardous materials in electronic products.

Despite promising insights, the study's limitations include its reliance on a limited number of expert interviews and the nascent stage of digital twin technology in the CE context, restricting the depth of theoretical exploration and empirical validation. Future research should refine the framework, conduct empirical studies, and explore the evolving relationships between economic, environmental, and social aspects in the context of the Digital Twin Nexus Circular Business Models framework. Further standardisation of digital twin concepts and exploration of new technologies such as Digital Product Passports (DPP) could enhance the integration of digitalisation and sustainability in manufacturing practices.

List of Abbreviations

Abbreviation	Definitions
AI	Artificial Intelligence
AR	Augmented Reality
BDA	Big Data Analytics
BM	Business Model
BMI	Business Model Innovation
BoL	Beginning-of-Life
CAD	Computer-aided Design
CAE	Computer-aided Manufacturing
CAM	Computer-aided Engineering
CBM	Circular Business Model
CE	Circular Economy
CRM	Critical Raw Material
DPP	Digital Product Passport
EEE	Electrical and Electronic Equipment
EoL	End-of-Life
ESPR	Eco-design for Sustainable Products Regulation
HCBMT	Hybrid Circular Business Model Tech
IoT	Internet of Things
ML	Machine Learning
MoL	Middle-of-Life
NFC	Near Field Communication
PaaS	Product-as-a-Service
PLM	Product Lifecycle Management
QR	Quick Response
RFID	Radio Frequency Identification
SBM	Sustainable Business Model
VR	Virtual Reality
WEEE	Waste from Electrical and Electronic Equipment

Contents

Figures

Tables

1 Introduction

1.1 Background

1.1.1 Current State of EEE Manufacturing Sector

Traditional business models in the manufacturing sector, especially within the electrical and electronic equipment (EEE) industry, are predominantly based on a linear economic approach. This approach is heavily reliant on the continual extraction and utilisation of finite natural resources, followed by the production of goods and the generation of revenue through their sales. A major inherent flaw of this 'take-make-dispose' model is its contribution to significant environmental degradation, as products that reach the end of their useful life typically become waste (Ellen MacArthur Foundation, 2015). The demand for EEE products is escalating as the global population grows, integrating these devices more deeply into the fabric of modern living. EEE products, which include a wide variety of household appliances such as refrigerators and washing machines to personal devices such as smartphones and computers, are essential yet contribute significantly to global waste challenges (Guzzo et al., 2021; Baldé et al., 2024). In 2022, this sector generated 62 million tons of e-waste but less than 23% was properly collected and recycled, which is inadequate to counteract the annual increase of generated waste (Baldé et al., 2024).

The increasing production of EEE and the resulting electronic waste are causing a greater environmental harm, noticeable both during resource extraction and waste disposal stages. Significant environmental and health risks are linked to the initial extraction of materials, which often requires substantial energy and the use of hazardous substances, frequently under dangerous working conditions (Ellen MacArthur Foundation, 2018). If the hazardous content in e-waste is not managed with effective recycling processes, it can lead to serious environmental and health issues (Ellen MacArthur Foundation, 2018; Baldé et al., 2024). Projections indicate a sharp increase in operational costs by approximately 15% by the year 2035, driven by factors such as rising landfill costs, increased distances to landfills, fluctuations in raw material prices, and stricter carbon emissions regulations (PwC, 2023). These circumstances highlight the critical need for the EEE manufacturing sector to explore alternative ways of doing business.

1.1.2 Going 'Circular'

The unsustainable nature of current linear economic models, with their short-sighted economic and environmental impacts, necessitates a paradigm shift towards a circular economy (CE). This model emphasises the importance of keeping resources in use for as long as possible by recovering and regenerating products and materials at the end of their service life (Ellen MacArthur Foundation, 2015). By promoting product design for longer use, easier repair, and efficient recycling, the circular economy approach significantly reduces waste and lowers the demand for new raw materials. Moreover, it aligns well with several Sustainable Development Goals (SDGs) including responsible consumption and production, climate action, and sustainable cities and communities. These goals collectively aim to extend product lifecycles, minimize waste production, and enhance the reuse and recycling of materials, effectively countering the detrimental impacts of traditional linear economic practices (Hollander et al., 2017). However, implementing circular economy principles in the EEE sector requires a systemic thinking approach that involves understanding the entire value chain and product lifecycles of EEE, from design to end-of-life stages (BSI, 2017).

The transition towards circular economy practices has brought the circular business model (CBM) to the forefront of the industry's strategic initiatives. CBMs also defined as an organisation's way in performing business to create, capture, and deliver value while improving resource efficiencies and closing material loops via circular practices (Nußholz, 2017). CBM advocates for a regenerative approach, aiming to retain the maximum value of resources through recycling, reusing, and reducing waste (Ranta et al., 2018). To obtain a sustainable competitive advantage, firms need to practically implement circular strategies through CBM Innovation (CBMI) (Geissdoerfer et al., 2020). However, even though many manufacturing firms are trying to implement CBM, only a few manufacturers have successfully adopted CBM, and it may differ between incumbents and start-ups (Hina et al., 2022). A major barrier in this transition lies in effectively managing product lifecycles and coordinating resource flows through multiple use cycles. Without proper visibility into the product's entire lifecycle and its condition, companies struggle to implement effective interventions for prolonging product life and closing material loops (Nußholz, 2018).

1.1.3 The Promising Digital Twin

Digitalisation is seen as a crucial enabler of collaboration in circular economy under the context of Industry 4.0 due to its strengths in product tracking across product lifecycle (Gebhardt et al., 2021). As digitalisation advances, it becomes a driving force in implementing CBMs at all stages of a product's lifecycle, enhancing resource efficiency and promoting circular practices (Kristoffersen et al., 2019; Neligan et al., 2022).

A digital twin, a digital replica of a physical entity throughout its lifecycle, offers numerous opportunities to address the challenges related to circular economy strategies in manufacturing (He & Bai, 2020). This digital representation of product lifecycle is enabled by several Industry 4.0 technologies such as Internet of Things (IoT), cloud computing, modelling tools and many others (Kritzinger et al., 2018). By providing real-time, detailed virtual representations of assets, digital twin can significantly enhance decision-making processes throughout the product lifecycle, aligning with circular economy strategies to optimise resource use, reduce waste, and lower costs (Preut et al., 2021; Mügge, 2022). For instance, a study by Wang and Wang (2018) developed a digital twin-based Waste from EEE (WEEE) management system, utilising Industry 4.0 technologies to support remanufacturing operations from design through to recovery. The digital twin provides all the necessary data across the product lifecycle that can be shared to all stakeholders involved in the production chain.

Despite the promising potential and growing academic interest in digital twin, there is still a limited number of studies that examine its role in supporting CBMs within the EEE manufacturing sector throughout the product lifecycle This means it is also important to understand how circular business strategies can be applied at various stages of the product lifecycle in this sector. This gap indicates a need for further research to explore how digital twin can be more effectively leveraged to support circular strategies and achieve sustainability goals in this specific context.

1.2 Problem Statement

The urgency for EEE manufacturing firms to adopt CE principles is highlighted by the sector's high waste generation and low waste recovery rates (Baldé et al., 2024). Additionally, regulatory pressures such as the EU Green Deal, which aims for a fully circular economy by 2050, are driving the need for substantial change. CE principles provide a framework for extending product lifecycles, reducing waste, and promoting the reuse and recycling of materials, challenging the traditional linear economic models characterised by a 'take-make-dispose' approach (Geissdoerfer et al., 2020). Despite the potential benefits, the adoption of CBMs in the EEE sector remains limited and is still in its early stages (Pollard et al., 2021). Research and industry practices tend to focus on circular strategies tailored for specific products and often neglect comprehensive integration across the entire product lifecycle (Bressanelli et al., 2020). This indicates a gap in understanding how circular strategies can be employed more broadly to transition business models across all stages of a product's lifecycle.

Digitalisation is recognised as a critical enabler in the transition to CE, with digital twin technology playing a central role in enhancing digitalisation across the entire product lifecycle (Bressanelli et al., 2020; Neligan et al., 2022). However, while digital twin technology has demonstrated capabilities and benefits in supporting CE, its specific role in CBMs within the EEE sector remains underexplored in both literature and practice (Liu et al., 2021; Preut et al., 2021; Kamble et al., 2022; Mügge, 2022). This gap highlights the need for targeted research to understand how digital twin can be effectively integrated into manufacturing processes to promote circularity and sustainability (Preut et al., 2021).

Addressing these critical gaps, this thesis explores the potential of digital twin technology to support and enhance circular business models across the product lifecycle within the EEE manufacturing sector. This exploration aims to deepen the understanding of digital twin capabilities and assess their utility as strategic tools in enabling and optimising circular business strategies at each stage of the product lifecycle, thus contributing to a broader application of CE principles.

1.3 Research Gaps

Based on the literature review, several research gaps have been identified as follows:

1. **Limited holistic understanding of CBMs across the entire product lifecycle in manufacturing sector, especially in the EEE sector.**

   There is a lack of structured knowledge and comprehensive understanding of how circular business strategies can be effectively implemented across all stages of the product lifecycle in the EEE sector. A holistic view is essential for truly circular practices, as effective CBMs should ideally address the entire lifecycle to close the loop and realise circular economy benefits (Bressanelli et al., 2020; Nußholz, 2018).

2. **Insufficient exploration and unified definition of digital twin in supporting CBMs in the EEE sector.**

   The dynamic and emerging nature of digital twin has resulted in a lack of a clear, unified definition, making it challenging to determine how digital twin can be utilised to its full potential in CE applications. Different interpretations could lead to varying expectations and implementations, hindering the effective use of digital twin. This ambiguity impacts the exploration of digital twin capabilities, such as simulation, predictive analysis, and lifecycle management, and how these capabilities can specifically support CBMs value.

3. **Need for more technology-specific frameworks integrating digital twin with circular business strategies.**

   While existing frameworks, such as the Hybrid CBM-Tech framework, have been developed (Tripodis, 2023) to integrate Industry 4.0 technologies with circular strategies, there is a need for more focused development of frameworks specifically designed for digital twin technology. Digital twin is recognised as having significant potential to support

CBMs, but current frameworks do not adequately address how digital twin can be effectively utilised to enhance circular practices. A technology-specific framework would help EEE manufacturing companies better understand how to ideate and implement CBMs in conjunction with digital twin capabilities. This framework would also clarify the specific values and benefits that digital twin technology can provide in supporting circular strategies across the product lifecycle.

1.4 Research Objective

The primary objective of this research is to explore how digital twin can be effectively integrated into CBMs throughout the entire product lifecycle in the EEE manufacturing sector. This research will first seek to establish a comprehensive understanding of how CBMs can be structured across all stages of the product lifecycle, from design and manufacturing to use and end-of-life stage. This is essential because each stage presents unique opportunities and challenges for implementing circular strategies, and a holistic understanding of these stages is necessary to fully leverage CE principles. By mapping out these stages and identifying the specific circular strategies that can be applied, the study will provide a foundation for examining how digital twin technology can support these strategies effectively.

Building on this foundation, the research will then investigate how the capabilities of digital twin technology, such as real-time data monitoring, simulation, and lifecycle management, can be aligned with CBMs at each stage of the product lifecycle to enhance circular practices. This involves identifying the key challenges and opportunities associated with implementing digital twin technology to support CBMs, including technological, organisational, and operational barriers, as well as potential enablers for its integration. Based on these insights, the research will develop a framework for effectively integrating digital twin capabilities with circular business strategies in the EEE sector, offering practical guidance for EEE manufacturing companies.

By successfully achieving these objectives, this research aims to advance the integration of digital twin technology into CBMs across the entire product lifecycle within the EEE manufacturing sector. This will lead to the ultimate goal of this thesis that is to develop a comprehensive framework that enables companies to envision and implement circular business strategies effectively, supported by digital twin capabilities. This framework will provide EEE manufacturing firms with the tools to align their business models with circular economy principles, leveraging digital twin technology to optimise resource use, extend product lifecycles, and reduce waste. Additionally, it will help companies to systematically identify and understand the potential circular strategies that can be applied at each stage of the product lifecycle, and to explore the specific digital twin functionalities that can enhance these strategies. By doing so, the framework will empower firms to enhance their circular outcomes and improve their offerings to customers, ultimately fostering a more sustainable and efficient industry.

1.5 Research Questions

This study is driven by the gap in the existing literature regarding the integration of digital twin with CBMs in the EEE manufacturing sector. Additionally, there is a lack of a comprehensive framework to guide companies in achieving their circular economy goals through advanced digital technologies. To provide a clear direction for this research, a set of research questions has been formulated to guide the study towards its objectives. These research questions serve as focal points for exploring the intersection of circular economy practices and the capabilities of digital twin technology within the context of Industry 4.0. The main research question of this study is presented as follows:

How can digital twin enable electrical and electronic equipment manufacturing firms to implement circular business models across the product lifecycle?

To answer this, the research will focus on the following sub research questions:

1. *How do different interpretations of digital twin technology influence its practical applications in supporting circular business models in the electrical and electronic equipment sector?*

   This sub-question aims to clarify the varying definitions and understandings of digital twin technology, establishing a common understanding for its role and potential in circular economy practices within the EEE sector.

2. *How can the capabilities of digital twin technology be applied at various stages of the product lifecycle to enhance circular business models in the electrical and electronic equipment sector?*

   The purpose of this question is to explore how the functionalities of digital twin, such as simulation, real-time monitoring, predictive analysis, and lifecycle management, can be utilised to support CBMs effectively.

3. *How do enabling technologies facilitate the integration of digital twin with circular economy practices in the electrical and electronic equipment manufacturing sector?*

   This question seeks to identify and explore how the enabling technologies that are necessary for the effective implementation of digital twin to support circularity.

4. *What are the key challenges in implementing digital twin technology to support circular business models in the electrical and electronic equipment sector?*

   This sub-question focuses on identifying various challenges in adopting digital twin technology in the context of CBMs.

5. *How can a framework be developed to guide electrical and electronic equipment manufacturing companies in integrating digital twin technology with circular business models across the product lifecycle?*

   This question aims to develop a structured framework that provides practical guidance for EEE manufacturing firms on how to effectively leverage digital twin technology to enhance circular business practices throughout the product lifecycle.

2 Literature Review

This literature review examines the current state of circular economy in EEE sector explores the understanding of digital twin technology as an Industry 4.0 innovation within the context of manufacturing. The chapter aims to investigate the intersection of digital twin technology and circular business models within the EEE manufacturing sector. This section is written in a narrative structure to effectively convey the context of the research further.

2.1 Circular Economy

The circular economy (CE) is an increasingly popular approach to sustainable development, challenging the traditional 'take-make-dispose' model with a regenerative system that benefits the economy, society, and the environment. This concept then was framed and popularised by Ellen MacArthur Foundation which drives the circular economy trend forward (Ellen MacArthur Foundation, 2015) There is no universal consensus on the definition of CE. For this research context, the CE definition is used by Geissdoerfer et al. (2017, p. 759) as an economic system in which resource input and waste, emission, and energy leakages are minimised by cycling, extending, intensifying, and dematerialising material and energy loops, which is illustrated in Figure 2.1 .

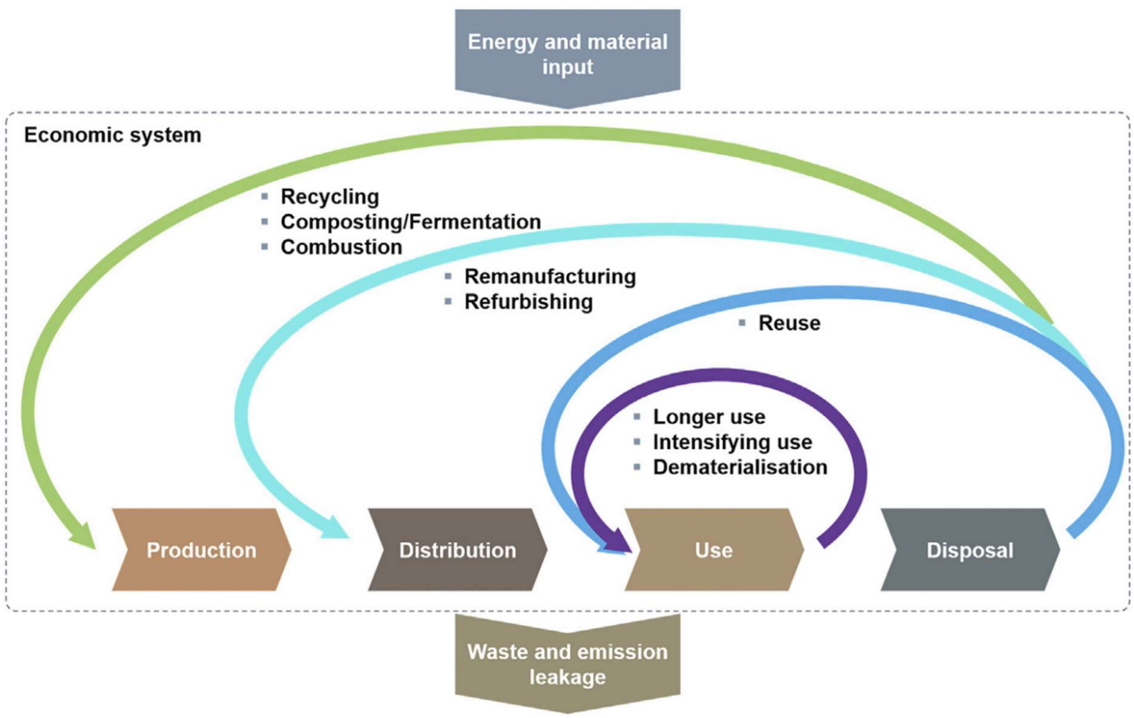

Figure 2.1 The Circular Economy (Geissdoerfer et al., 2017)

CE is considered successful when it can contribute to all three dimensions of sustainable development, economic, environmental, and social (Korhonen et al., 2018). CE practices can also contribute directly to achieving many SDG targets. The strongest relationships are observed with SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land). Schroeder et al. (2018) highlighted that CE practices can be seen as a ‘toolbox’ and implementation approach to achieve SDG targets.

2.2 Business Model

A business model describes the way an organisation creates, delivers, and captures value in the market. It serves as a blueprint for the operation of a business, detailing the products or services it will offer, the target market, and the financial strategy. Understanding the business model is crucial for organisations as it provides a clear roadmap for achieving their objectives, identifies revenue streams, and helps in strategic planning (Teece, 2010). It can also be defined as a framework that is centred around value for an organisation to execute their business strategy. The dimensions of the value are value proposition, value creation, value delivery and value capture, where each value serve a different role within an organisation. Value proposition refers to the offering and customer segmentation. Value creation and deliver are the way of firm creates value promised to customer through resources, value chain, structures, and processes. Value capture describes how the customer will generate revenue streams from the product or service delivered and the cost structure (Oghazi & Mostaghel, 2018; Shakeel et al., 2020).

2.2.1 Business Model Innovation

Business model innovation is created in response to change and to create more competitive advantage. It possesses the capability not only to create more profitable than product or process innovation but also offers a renewable source of competitive advantage. It enables a dynamic, sustainable competitive edge that is increasingly vital for strategic organisational planning. Business model innovation is also essential for companies aiming to fulfil their social and environmental goals through the adoption of effective technologies and solutions, thus improving their financial, social, and environmental outcomes and enhancing resilience against external risks (Geissdoerfer et al., 2020). With the urgency from the whole EU to be fully sustainable, firms are pushed to adopt and transit to sustainability business practices. Firms that do not comply may struggle to compete in the EU market in the near future, as both regulations and customer demands are likely to drive the need for compliance. Therefore, in order to stay in the market, the firms have no other choice but to change their business to be more circular (Oghazi & Mostaghel, 2018). Business model innovation (BMI) is seen as a potential facilitation for organisations in CE transition (EMF, 2013).

2.3 Circular Business Model

Alongside developments in CE, circular business models (CBMs) have evolved over recent decades, becoming a strategic blueprint for organisations to create a competitive advantage through circularity. CBMs are defined as an organisation's way in performing business to create, capture, and deliver value while improving resource efficiencies and closing material loops via circular practices (Nußholz, 2017). For a CBM to be successful, it is crucial that the ecosystems adopt circular practices in collaboration with all actors involved especially engaging customers behaviours that enable circularity (Asgari & Asgari, 2021).

Recent literature has adopted a dynamic approach to the study of CBMs, exploring how organisations transform their traditional business models by progressively incorporating CE practices (Pieroni et al., 2020). Several general CBM archetypes have emerged as instruments to aid this transformation (Bocken et al., 2016; Lopez et al., 2019; Lüdeke-Freund et al., 2018; Moreno et al., 2016; Planing, 2018; Yang et al., 2018). To have standardised terminology, Pieroni et al. (2020) consolidated and characterised these archetypes as dynamic conceptual aids that facilitate as fundamental for implementation of CBM. Pollard et al. (2021) further analysed and proposed the CBM archetypes that are relevant to EEE sector as sector-specific processes were deemed crucial to increase the adoption of CBM and address practitioner uncertainties (Pieroni et al., 2021).

Table 1 CBMs archetypes overview (Pollard et al., 2021).

Type of CBMs	Description
Circular supply chain	Embedding circular thinking into the management of the supply chain.
Recycling and recovery	Optimising material value by using secondary raw materials to new products and recycling
Product life extension	Designing products to be durable for a longer use period.
Sharing economy	Services of sharing and lending of under-utilised products.
Product service system	Services of both tangible and intangible or virtual offerings to meet customer needs.

CBMs play a pivotal role in achieving sustainability goals within the manufacturing sector. By redefining how products are designed, used, and disposed of, CBMs contribute significantly to reducing environmental impacts, improving resource efficiency, and fostering a more sustainable consumption pattern. In manufacturing, CBMs facilitate the transition toward a CE, offering not only environmental benefits but also economic opportunities through innovative business ventures and models designed for long-term sustainability. Implementing CBMs requires manufacturers to rethink their product designs, supply chains, and customer interactions to ensure that they align with the principles of circularity and sustainability (Lewandowski, 2016). Furthermore, business model design must evolve from focusing on single-use cycles to creating and recreating value throughout the product lifecycle, thereby reducing environmental impact (Nußholz, 2018). However, existing CBMI processes often overlook the importance of value management across the product lifecycle, highlighting a gap that needs to be addressed to fully realise the potential of CBMs (Nußholz, 2018).

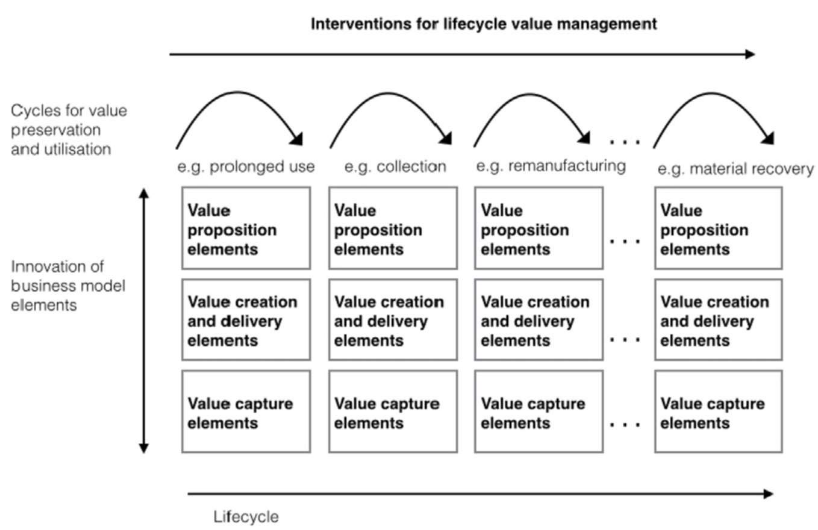

Figure 2.2 A conceptual framework for circular business model innovation (Nußholz, 2018)

In the EEE sector, some businesses are already successfully using circular business models (CBMs) without explicitly labelling them as "circular." For example, Xerox's product-service model, which is based on remanufactured products, follows this approach (Linder & Williander, 2015). There is substantial research on CBMs within the EEE sector, primarily focusing on specific products and CBM archetypes. However, there is a lack of holistic coverage of all lifecycle stages, as most studies concentrate on the use or end-of-life phases, with less emphasis on the design or manufacturing phases (Bressanelli et al., 2020). To date, the implementation of CBM in the EEE sector has been infancy, despite the potential benefits (Pollard et al., 2021). A recent report by PwC (2023) showed that compares to business-as-usual model, CBM scenarios in electronic industry led to a cost savings around 12% and carbon dioxide (CO_2e) reduction of at least 10% by 2035. This shows the benefits of integrating circular strategies into business models, regardless of the specific strategy employed.

2.3.1 Circular Strategies

Circular strategies are practices that firms adopt to operate in an environmentally sustainable manner, aiming to minimize waste and make the most efficient use of resources. These strategies are built upon the foundation of creating, delivering, and capturing value in ways that extend the lifecycle of products and resources, thus supporting the principles of a circular economy (Nußholz, 2017). Circular strategies have been well-explored in literature, with Potting et al. (2017) extending the traditional 3R framework (reduce, reuse, recycle) to a more comprehensive 10R framework, which ranks strategies from most circular (R0) to least (R9).

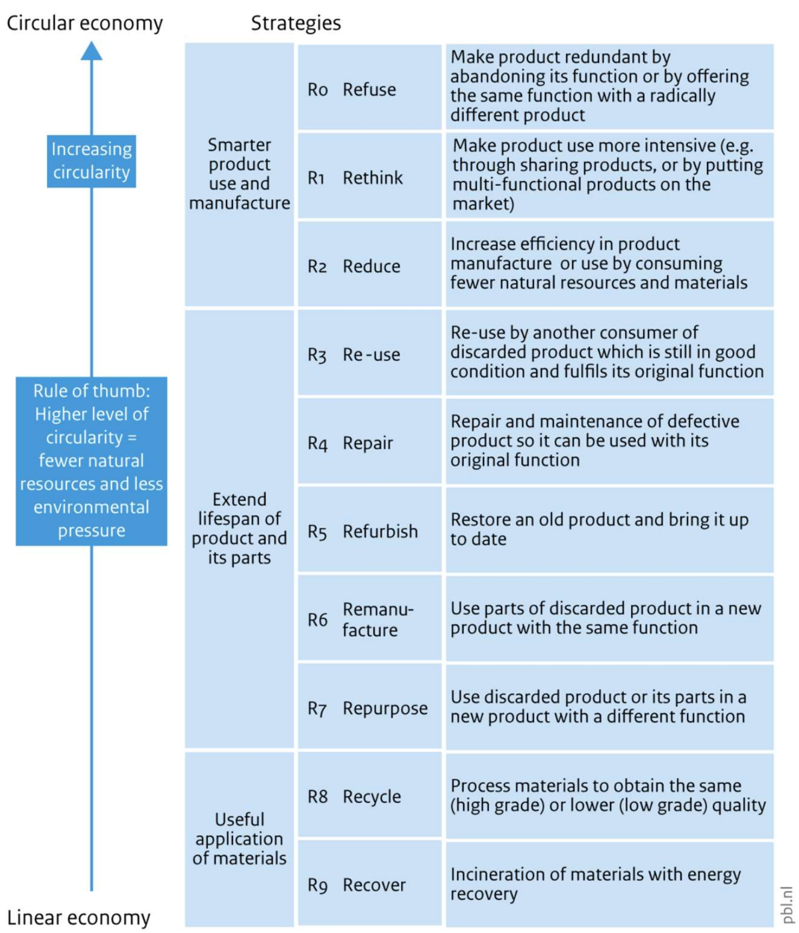

Figure 2.3 Circular strategies within the product chain, in order of priority (Potting et al., 2017)

In the context of the EEE sector, Pan et al. (2022) analysed these 10R practices, noting their broad spectrum of activities that enhance sustainability throughout the product lifecycle. For instance, 'Refuse', while rarely mentioned explicitly in literatures, this strategy involves from two perspective: consumers and manufacturers (Reike et al., 2018). From the consumer's perspective, it depends on their consumption behaviour, such as choosing to buy or use less, which helps prevent the creation of e-waste in the first place. From the producer's perspective, they can design EEE in ways that avoid the use of hazardous materials. 'Rethink' entails redesigning products and processes for improved sustainability, often incorporating modular designs that are easier to repair and upgrade. This strategy also focuses on making product use more efficient. 'Reduce' emphasizes lowering material use and energy consumption during production, while 'Reuse' and 'Repair' extend the lifespan of devices through maintenance and continued use. 'Refurbish' and 'Remanufacture' involve restoring used EEE to a like-new condition, providing a sustainable alternative to producing new products. 'Repurpose' involves modifying old EEE for new uses. Finally, 'Recycle' and 'Recover' focus on recovering materials and energy from EEE at the end of its lifecycle, ensuring valuable resources are reintegrated into the production cycle rather than disposed of. The integration of these practices not only supports environmental goals but also offers economic benefits by conserving resources and fostering innovation in product development.

Bocken et al. (2016) developed a framework for design and business that includes slowing and closing strategies aimed at achieving circularity. The slowing strategy focuses on designing products for extended use and longer lifespans, while the closing strategy emphasizes the recycling and reuse of materials after a product's life ends. In line with these strategies, Berwald et al. (2021) further elaborated on the closing strategy by providing specific guidelines aimed at enhancing the recyclability and reuse of materials used in EEE sector. The guidelines emphasise the necessity of incorporating both design 'for' and 'from' recycling strategies. The design 'for' recycling strategy emphasises the anticipation of a product's end-of-life during the design stage, ensuring that components can be easily accessed, separated, and processed by recyclers. Conversely, Berwald et al. (2021) also argued that the design 'from' recycling strategy encourages the use of recycled materials in new products, thus supporting the circular economy by reintroducing waste materials back into the production cycle.

Furthermore, Preston et al. (2019) has analysed and established connection between circular strategies and activities across product lifecycle from material input to the end-of-fist-life. The strategy to reduce the usage of resources and the demand for product can mostly be applied in first two stages, material input, design and manufacturing. Narrowing strategy can be applied into distribution, use and end-of-fist-life stages which involves shifting more efficient ways of using products. Closing strategies create a loop of resources returning to the production process at the end of a product's first life (Preston et al., 2019).

After studying 14 definitions of CBMs, Geissdoerfer et al. (2020) categorised the strategies into cycling, extending, intensifying, and dematerialising. These strategies have different name but have similar concept. For instance, extending and slowing show similarities with aim extend the useful life of products and materials. Intensifying, on the other hand, offers unique practices that involves in maximising value from products and materials with collaborative consumption. A strategy termed ”regenerate” by Konietzko et al. (2020) aimed at promoting sustainability development and incentive for clean energy usage for operations, production and distribution of products.

Recent research by Tripodis (2023) extended the available circular strategies from many studies and suggested a need for alignment in naming conventions to clarify their distinct purposes and characteristics. This alignment would allow these strategies to be more effectively integrated into business models and applied across the product lifecycle, helping firms gain a competitive advantage. The strategies can be seen in the following Table 2.

Table 2 Description and characteristics of circular strategies (Tripodis, 2023, p. 10).

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 the 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, dematerialising 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 digitising products and services. It promotes a demand reduction and service vs. product, which reduce resources usage and environmental impact
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
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
Intensifying	The strategy of maximising the value obtained from resources by increasing their overall utilisation, efficiency, and productivity	This circular strategy aims to maximize the value derived from products and materials, by optimising their use, improving their performance, and creating value-added services. It promotes a circular economy that increases economic value while reducing resource use

2.3.2 Circular Strategies and CBM Value Elements

Circular strategies, as the core of CBM, have a direct and intricate relationship with the business model value components. CBMs are designed to generate, provide, and retain value by employing strategies that extend the service life of products and components (extending) and facilitate the closure of material cycles (cycling) (Nußholz, 2017). The effectiveness of these circular strategies relies on an organisation's capacity to develop appealing propositions that maximize and sustain the embedded value of resources including energy, materials, labour, and capital for the longest possible duration (Hopkinson et al., 2018). Geissdoerfer et al. (2020) highlighted that these circular strategies have an impact on the elements of a business model, where varying arrangements can result in distinct business models and approaches to value creation. The link between the value elements of a business model and circular strategies is grounded in the specific circular practices inherent to each strategy. In context of EEE, Pollard et al. (2021) further developed a CBM canvas as one of the layers of CBM process framework that prompts the EEE manufacturer to identify CE actions that address each CBM elements and establish their relevance or feasibility within their business.

Tripodis (2023) identifies the practices associated with each circular strategy in existing research to understand the structure of CBMs by connecting CBM value elements with circular strategies.

Table 3 Circular strategies relation with circular business model value elements adapted from Tripodis (2023).

Circular Strategy	Value Proposition	Value Creation and Delivery	Value Capture
Greening (Regenerate)	Products based on renewable resources and living materials, highlighting sustainability (Konietzko et al., 2020)	Building renewables capacity, partnering for circularity, restoring ecosystems, and utilising sustainable energy for operations (Konietzko et al., 2020)	Enhanced reputation from sustainable actions and cost savings from renewable energy usage (Konietzko et al., 2020)
Narrowing	Designs minimising resource use and environmental impact, including dematerialisation to services (Bocken et al., 2016)	Optimising processes to use fewer resources per product (Konietzko et al., 2020). Customer rationalisation for demand reduction (Geissdoerfer et al., 2020). Implementing product-service systems with technology and network collaborations (Bocken et al., 2016)	Cost savings from reduced resource consumption, revenue from service pricing models (Bocken et al., 2016)
Extending (Slowing)	Services for maintenance and performance control, refurbished and durable products with always in-style designs (Khan et al., 2018)	Designing products for durability and longevity, facilitating maintenance and upgrades (Bocken et al., 2016). After-sale services suggestion (Lüdeke-Freund et al., 2018). Products are transformed to serve alternative purposes, extending their life cycle (Planing, 2018)	Profits from maintenance services or repair parts (Planing, 2018). Premium pricing for high-quality, long-lasting products, and customer loyalty (Bocken et al., 2016)
Cycling (Closing)	Emphasises products that reuse materials to drive down costs and resource waste (Bocken et al., 2016)	Take-back systems for recycling or repurposing, promoting reverse logistics (Lewandowski, 2016). Customer incentivisation for collection (Lüdeke-Freund et al., 2018). Both open and closed innovation for value creation through collaborations and internal systems (Urbinati et al., 2017)	Savings from recycled and reused resources (Bocken et al., 2016). Revenue from material trading (Whalen, 2019). Customer base expansion through lower-priced offers (Bocken & Ritala, 2022)
Intensifying	Products offered as services for multiple users, fostering collaborative consumption and reducing ownership costs (Bocken et al., 2016)	Capacity building and logistics for delivering performance, education on sharing (Geissdoerfer et al., 2020). Orchestration of suppliers/service providers, and technology platforms for tracking and monitoring shared products (Khan et al., 2018)	Revenue through temporary contracts (Geissdoerfer et al., 2020). Use-based charges, subscription and transaction fees (Whalen, 2019). Increased customer loyalty (Bocken & Ritala, 2022)

Furthermore, this section elaborates further the connection between each strategy and circular value business elements with instances of organisations that work in EEE sector.

Greening (Regenerate) Strategy and Circular Value

From a circularity standpoint, the greening strategy has not been extensively studied but is acknowledged for its contribution to a comprehensive approach to sustainability. Konietzko et al. (2020) introduced this strategy to address the early important concept of CE which are minimised toxic substances and increase of renewable energy and materials usage. In business context, this strategy involves activities that support and maintain natural ecosystem services, utilise renewable and non-toxic materials, and rely on renewable energy sources. Regarding the value proposition, this strategy provides sustainable solutions that enhance the natural environment while also meeting economic needs (Konietzko et al., 2020). For example, Apple uses renewable energy such as solar to power its operations, aligning with the growing demand for corporate responsibility in energy consumption (Apple, 2024). Another example by Fairphone that offers products from non-toxic materials showcases a commitment to sustainability that can attract customers who prioritize environmental responsibility (Fairphone, Safety and Hazardous Materials , 2024). Value creation in a greening strategy comes from developing and using processes that restore or enhance the ecosystem's health rather than depleting it. This also can be achieved through circular activities such as embracing eco-design to ensure product circularity across product lifecycle (Pollard et al., 2021). The delivery of this value then involves ensuring these processes and products reach the market effectively and efficiently. Value capture in this context can be achieved through various business models that monetize sustainable practices. These can come from using renewable energy that reduces energy costs and can provide energy surplus back to the grid, potentially earning revenue or credits.

Narrowing Strategy and Circular Value

The idea of narrowing involves using the least number of resources possible during design, production and distribution (Bocken et al., 2016). The value proposition of this strategy is centred around efficiency and reduction of waste. It offers products and services that require fewer resources both material and energy during their entire lifecycle, from design through to end use and recovery. This approach is designed to appeal to environmentally conscious consumers and organisations looking to minimize their ecological footprint and comply with environmental regulations. For example, HOMIE's pay-per-wash model incentivizes users to consume less, aligning with the growing consumer and regulatory demand for sustainable consumption (Bocken et al., 2018).

Value is created and delivered through innovative design and efficient use of resources, which reduces the overall consumption of raw materials and energy. By designing products that use fewer inputs and encouraging behaviours that minimize waste, companies can substantially decrease the costs associated with production and consumption (Konietzko et al., 2020). For instance, HOMIE’s business model not only reduces water and energy use per wash but also potentially extends the lifecycle of the appliances through less frequent use. It also involves not only providing the appliances but also ensuring that the service is user-friendly and that the benefits of reduced consumption are clearly communicated and realised by the consumers (Bocken et al., 2018).

Value capture in the narrowing strategy can occur through several channels. First, companies can differentiate their products in the market as environmentally sustainable alternatives, which can command premium pricing or appeal to a segment of consumers willing to pay more for green products. Second, business models such as HOMIE’s pay-per-wash system create ongoing revenue streams from existing products, reducing the need for frequent product replacement and capitalising on consumer usage patterns (Bocken et al., 2018).

Extending (Slowing) Strategy and Circular Value

The core of this strategy is to use the product for as long as possible. This can be achieved through several circular practices such as offering throughput instead of the product or product-as-a-service, design for longevity, remanufacturing, refurbish (Bocken et al., 2016; Konietzko et al., 2020). The proposition for this strategy in terms of offering throughput rather than product is reducing the need for frequent replacement, minimising waste and others respective intangible benefits (Pollard et al., 2021). This appeals to consumers and businesses interested in cost savings over time and reduced environmental impact. In EEE context, business such as Kaer –air conditioning company– offers its cool and fresh air service instead of its product (Kaer, 2024).

CBMs that incorporate this strategy can create value by designing products that are built to last and developing business models that maintain the value of these products over a longer period. The delivery of this value involves ensuring that these durable products and extended services are accessible and effectively integrated into the lives of consumers. For service models such as Kaer's, it means providing a seamless experience where the focus shifts from owning a product to enjoying its benefits (Kaer, 2024). This model requires robust support and maintenance services to ensure longevity and customer satisfaction.

Value capture in this strategy can occur through multiple avenues. For business models focusing on products as a service, companies capture value through subscriptions or ongoing service fees. For example, Kaer capitalises on a business model where customers pay for the cooling results rather than the air conditioning units themselves, ensuring steady revenue through service contracts (Kaer, 2024). Fairphone on the other hand, capture its value by selling their upgrade or maintenance part since their product centred in design for disassembly and recycling (Fairphone, 2024).

Cycling (Closing) Strategy and Circular Value

This strategy within context of EEE represents a solution to the global WEEE problem through recycling of e-waste and its components, and by providing secondary raw materials and components for manufacturing (Islam & Huda, 2018). The primary value proposition of this strategy is to provide a sustainable solution to the management of WEEE by enabling the recovery and reuse of raw materials, which reduces the reliance on raw material extraction and offers significant resource and energy savings. This approach addresses both environmental concerns and the economic challenges of material scarcity, responding to increasing regulatory pressures and consumer demand for sustainable products, making it appealing to stakeholders across the supply chain (Pollard et al., 2021).

Value creation in this strategy is achieved through the development and implementation of efficient recovery processes, product designs conducive to recycling, and effective reverse logistics systems (Cucchiella et al., 2015; Islam & Huda, 2018). In earlier phase of the lifecycle, designing products for ease of disassembly allows for more complete recovery of valuable components and materials (Berwald et al., 2021). Furthermore, the integration of reverse logistics maximizes economic and environmental efficiencies by ensuring that transporting these materials is cost-effective, crucial when dealing with large volumes of low-value goods (Cucchiella et al., 2015).

The delivery of this value is facilitated through technological advancements in recycling processes and the establishment of new business models that incentivize the return and recycling of electronic waste, including setting collection targets and developing standards for recycled materials to meet customer specifications (Tong et al., 2018). This ensures that the materials recovered from WEEE are of sufficient quality to be used in new manufacturing, thus closing the loop.

Value capture in this strategy is realised through triple bottom line (TBL) framework. Economically, companies can derive value from the production of secondary raw materials that reduce costs compared to virgin materials (Schreck & Wagner, 2017). In social manner, contributing to environmental sustainability, companies enhance their corporate social responsibility profiles, improving brand loyalty and customer satisfaction (Arya & Kumar, 2020). Environmentally, the strategy reduces the ecological impact of electronic waste, conserving natural resources and minimising landfill use, helping comply with environmental legislation and positioning a company as a leader in sustainable practices (Pollard et al., 2021).

Intensifying Strategy and Circular Value

This strategy, initially a part of the slowing strategy, emphasises intensive usage in a collaborative manner (Geissdoerfer et al., 2018). Unlike the narrowing strategy, which replaces a product with a service, the intensifying strategy provides the product as hardware for shared use among multiple customers, essentially promoting 'sharing'. Geissdoerfer et al. (2020) highlighted that this approach offers benefits such as lower ownership costs and reduced upfront investments, encouraging sharing and repeated use to decrease the overall demand for new products by maximising the use of existing ones.

The value creation and delivery within this strategy are achieved by integrating ICT platforms into business operations, which enables new or enhanced customer interactions for these offerings (Pollard et al., 2021). For example, Peerby, an online platform that allows individuals to share everyday and electronic goods, enhancing their utilisation and gradually decreasing the quantity of personally owned items in homes. This leads to optimised usage among various participants within a specific ecosystem (Peerby, 2024).

Value capture in this model involves introducing or enhancing offerings that generate recurring revenues, such as bundles of sales and services, rental services, and leasing options. This also includes remanufacturing through enhanced take-back schemes, generating revenue from shared or rented products rather than one-time sales (Pollard et al., 2021). This approach not only secures recurring income but also fosters a more sustainable business model by prolonging the product’s revenue-generating lifecycle. Additionally, Pollard et al. (2021) added that this strategy focuses on reducing the total cost of ownership and operation for customers through shared use, which can offer more economic benefits over the product's lifecycle, addressing the challenge of promoting options with lower lifetime costs over lower initial costs.

2.3.3 Circular Strategies across Product Lifecycle

Building upon the comprehensive strategies outlined by Moreno et al. (2016), a systematic approach to integrating circular economy principles can be articulated across various stages of the product lifecycle. In the resource acquisition stage, strategies such as cascaded uses and resource recovery focus on minimising and reusing resources by utilising recycled materials to reduce virgin resource consumption. Moving to the design stage, products are developed to maximize longevity and adaptability, with features that support easy maintenance, upgradeability, and disassembly, ensuring extended product life. At the manufacturing stage, the emphasis is on process efficiency and waste reduction, employing techniques that allow for modular manufacturing and minimize resource waste. During the distribution stage, efficiency and reduced carbon footprints are prioritised through localised production and distribution networks, alongside digital platforms that promote product sharing and optimise utilisation. In the use stage, models such as Product as a Service (PaaS) extend product usability and maintain quality through professional services, enhancing product life and functionality. Finally, the end-of-life stage focuses on closing the loop with recycling, upcycling, and energy recovery to reintegrate materials into the production cycle, thus minimising waste and fostering a regenerative economic model.

Furthermore, Potting et al. (2017) illustrated the various circularity strategies and the roles of different actors within the production chain, helping to establish a systematic approach to waste reduction and resource management. Starting with the extraction of natural resources, it traces the flow into the manufacturing industry, where the groundwork for efficient resource use is laid out through strategies such as ‘Refuse’, ‘Rethink’, and ‘Reduce’. Post-use, products are collected for reprocessing, which includes ‘Recycling’, ‘Remanufacture’, and ‘Repurpose’, ensuring materials are cycled back into the production stream rather than ending up as waste. Distribution chains further support the CE by facilitating ‘Repair’, ‘Reuse’, and ‘Refurbish’ processes, extending the life of products and reducing the demand for new resources. Consumers also play a pivotal role by engaging in reuse practices, particularly through ‘Reuse’ (refill) options. Lastly, any residual waste that cannot be reintegrated is directed through ‘Recovery’ practices or managed through incineration and landfill, emphasising the reduction of landfill use and the conversion of waste into energy (Potting et al., 2017).

Pavel (2018) expanded the stages where it started from evaluation to material which addresses the sourcing of materials, distinguishing between primary (natural resources) and secondary sources (urban mining or used goods). The circular value chain focuses on minimising the use of primary sources by enhancing the utility of secondary sources. At the end of the chain, the author also expanded from usage to reverse logistics to evaluation. After the consumption phase, products enter the reverse logistics chain, where they are collected for repurposing, recycling, or proper disposal. This stage is crucial for closing the loop in the circular economy by ensuring that products and materials continually re-enter the production cycle rather than becoming waste. This process is supported by evaluations that determine the best use of returned materials, whether for remanufacturing, refurbishing, or complete recycling.

In the same context, Reike et al. (2018) further systematically mapped more detail the 10R topology or retention options (ROs) into two diversified product lifecycle which are ‘production and use’ and ‘concept and design’. The authors positioned the circular practices along with seven eight of lifecycle stage with detailed the production flow with the explanation of the responsible stakeholders on each stage. This includes mining, material production, component production, end-product manufacturing, retail, consumption, collection, and landfill. Activities related to recycling, material recovery, and energy extraction occur primarily at the beginning and end of the value chain, where components are produced, or complete products are returned through collection points. Conversely, circular practices such as remanufacturing, refurbishing, repair, and repurposing are implemented during the middle stages, specifically during product manufacturing, retail, and usage.

Preston et al. (2019) further explored how circular strategies and activities are integrated throughout the product lifecycle from material input to the end-of-fist-life. They proposed a strategy to minimize resource use and product demand, which is mainly applicable in the initial two stages: material input, design, and manufacturing. The narrowing strategy targets the distribution, usage, and end-of-first-life stages, focusing on more efficient product use. Lastly, they outline a closing strategy that facilitates a circular flow of resources, where materials are recovered, recycled, and reintroduced into the production process at the end-of-first-life stage (Preston et al., 2019).

Recent research by Chioatto et al. (2024) explores the interlinkage of circular innovation (CI) with CE and CBMs. Although it has a different name, CI can also be seen as circular practices, acting as a catalyst for the conversion of business models. The study introduces a new categorisation method for CIs based on different stages of a product's life cycle: input, use, and end-of-life phases. In the input-based practices phase, innovations focus on the production stage, such as using renewable energy, bio-based materials, recyclable materials, and designs that reduce material and energy usage. These practices aim to minimize the environmental impact of the production process itself and optimize resource use from the start. In the use-based practices phase, innovations change how products are delivered and used, such as product-service systems (PSS) that include leasing, sharing, and pooling, or through dematerialisation, which shifts usage from physical products to digital services. These innovations aim to maximize the utility and lifespan of products, reducing the need for new resources. Lastly, in the end-of-life phase, innovations focus on managing products at the end of their lifecycle, such as recycling, upcycling, remanufacturing, and take-back management systems. These practices ensure that products, components, and materials are reintegrated into the production process, thereby closing the loop and supporting a circular economy (Chioatto et al., 2024).

Table 4 Classification of circular business models: the product life-cycle categorisation (Chioatto et al., 2024, p. 817).

Main Category	Circular Business Model	Example of Circular Innovation
Circular input	Cleaner Production	Use Renewable Energy
		Use bio-based, biodegradable, compostable materials
		Use Recyclable materials
		Reduce material/energy use per same output
		Use secondary raw materials
		Design for durability
	Extended-life span Production	Design for reliability
		Design for trust
		Design for repair/remanufacture
		Design for upgrade
		Design for dis-reassembly
Circular Use	Second-life Production	Design for compatibility
		PSS Product renting
	Product-service systems (PSS)	PSS Product renting or pooling
		Product sharing
	Collaborative Consumption	Product co-ownership
Circular Output	Product dematerialisation	Virtual access
		Upgrading
		Remanufacture
	Second life for products	Repair
		Upcycling

Main Category	Circular Business Model	Example of Circular Innovation
		Recycling (Downcycling)
	Second life for materials	Energy recovery from non-recyclable waste
		Supply of waste materials
	Take back management	Reverse logistic

2.4 Digital Twin

Digital twin technology represents a paradigm shift in how we interact with and manage physical systems, blending the lines between the physical and digital worlds. Historically, the concept of the digital twin emerged from the fields of aerospace and advanced manufacturing, where the need for exact replicas of physical assets in a digital form was paramount for testing, simulation, and maintenance purposes. The term "Digital Twin" was popularised in the early 2000s by Michael Grieves, who introduced it during a presentation on Product Lifecycle Management (PLM) (Grieves, 2014). Since then, the development of the digital twin has been closely tied to the rise of Industry 4.0 technologies and benefiting significantly from its advancements (Fuller et al., 2020).

Jones et al. (2020) conducted a review to pinpoint the characteristics of digital twin that supposed to possessed, which can be seen in summarised Table 5.

Table 5 Characteristics of Digital Twin (Jones et al., 2020).

Characteristics	Description
Physical Entity/Twin	This is the real-world artifact such as a vehicle, component, product, or system that exists in the physical environment.
Virtual Entity/Twin	A computer-generated representation of the physical entity that exists in the virtual environment. This digital replica is used for simulations, optimisations, and other computational techniques.
Physical Environment	The measurable real-world environment in which the physical entity exists. This includes all parameters that can influence the physical entity.
Virtual Environment	The digital space that replicates the physical environment. This can include any number of virtual worlds or simulations designed for specific use cases, such as health monitoring or production scheduling.
State	The current values of all parameters corresponding to the physical or virtual entity and its environment. This includes the operational status, health, and performance metrics.
Metrology	The process of measuring the state of the physical entity. This involves collecting data from various sensors and instruments to capture the current condition of the physical entity.
Realisation	The act of changing the state of the virtual entity based on the measured data from the physical entity, ensuring that the virtual and physical states are synchronised.
Twinning and Twinning Rate	Twinning is the synchronisation process between the physical and virtual states. The twinning rate refers to how frequently this synchronisation occurs, ideally in real-time.
Physical-to-Virtual Connection	The process of transferring data from the physical entity to the virtual entity. This includes the initial measurement phase (metrology) and the updating phase (realisation).
Virtual-to-Physical Connection	The process of implementing changes from the virtual entity back to the physical entity. This ensures that actions decided in the virtual environment can be executed in the physical environment.

Characteristics	Description
Physical Processes	The activities performed by the physical entity in its environment, such as manufacturing processes, operations, and maintenance activities.
Virtual Processes	The computational activities performed using the virtual entity, including simulation, modelling, optimisation, and predictive analytics.

Key features and functionalities of digital twin include the ability to create a highly accurate and dynamic digital representation of a physical asset or system. These digital replicas are capable of simulating, predicting, and optimising the performance and maintenance of their physical counterparts in real-time. The seamless integration of real-world data into the digital twin enables continuous monitoring and diagnostics, predictive maintenance, and the exploration of future scenarios through simulation. This integration is made possible through a combination of enabling technologies such as IoT for data collection, AI for data analysis and prediction, and advanced simulation models for accurate representation of physical behaviours (Qi et al., 2021).

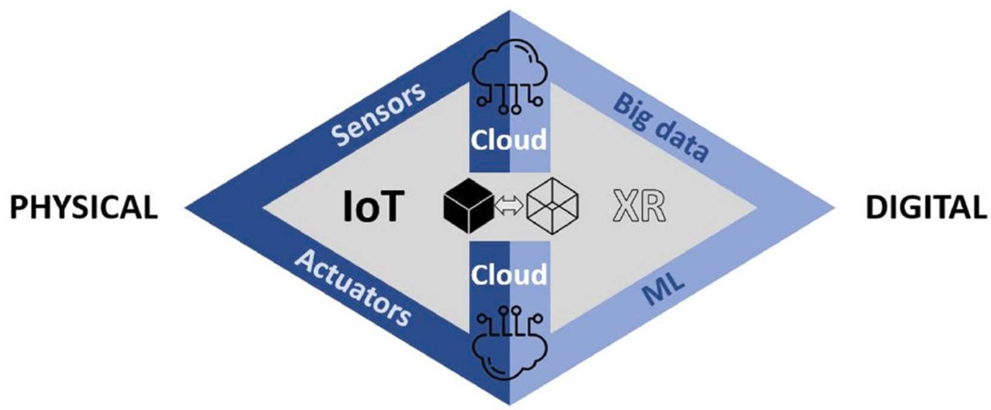

Figure 2.4 Digital Twin concept (Aheleroff et al., 2021)

There are different kinds of digital twin due to differences on how the data flows between the digital and the physical counterparts. Kritzinger et al. (2018) proposed a classification of digital twin according to the level of data integration. The first type is a 'Digital Model', which represents a physical object, either existing or planned, without any automated data exchange between the physical and digital versions. These models might include detailed descriptions, such as simulations of future factories or mathematical models of new products, but all data transfer happens manually. As a result, changes in the physical object do not directly impact the digital model, and vice versa. When there is an automated, one-way flow of data from the physical object to the digital counterpart, this setup is known as a 'Digital Shadow.' In this case, any changes in the physical object trigger updates in the digital version, but not the other way around. Finally, when data flows seamlessly in both directions between the physical and digital objects, the system is called a 'Digital Twin.' In this arrangement, the digital object can also influence and control the physical one. Additionally, other physical or digital entities can trigger changes in the digital object, creating a dynamic system where any change in the physical object is immediately reflected in the digital version and vice versa.

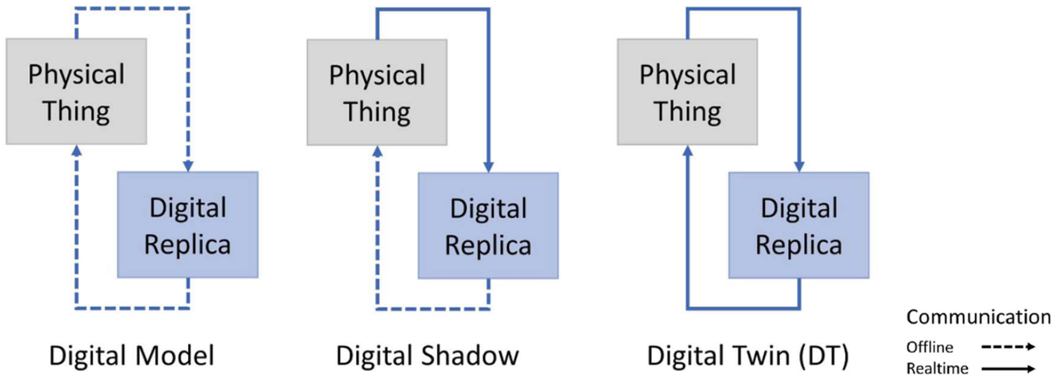

Figure 2.5 Digital Twin integration level. (Kritzinger et al., 2018)

2.4.1 The Digital Twin across the Product Lifecycle

Grieves (2014) conceptualises the lifecycle of a digital twin as beginning with the creation of a Digital Twin Prototype during the initial concept phase of a product. This digital model continues to evolve alongside the physical product throughout its entire lifecycle. Notably, since the virtual model can be preserved indefinitely, it can retain value even after the physical product has been retired, offering valuable insights for future analysis.

Stark (2011) defined the phases of product lifecycle as follows: Imagine, Define, Realise, Support/Use, and Retire/Dispose. Additionally, Jones et al. (2020) categorised research on digital twin into those that focus on the concept, those exploring implementation methodologies, specific case studies, and general literature reviews. This analysis indicates that most research is concentrated on the Realise and Support/Use phases, with a significant emphasis on methodologies and implementation strategies.

However, there is a noticeable lack of studies that examine the fundamental concepts of digital twin across the entire product lifecycle. Instead, many existing methodologies and implementations are tailored to specific use cases, which highlights a gap in understanding the broader applicability of digital twin, particularly in the early lifecycle stages and the disposal phase. This gap suggests that important opportunities to leverage the full potential of digital twin across all phases of the product lifecycle may have been overlooked (Jones et al., 2020).

2.4.2 Digital Twin in Circular Economy

The relation between digital twin and sustainability is deeply embedded in their ability to provide detailed insights and control over manufacturing processes, which are crucial for implementing sustainable practices (Kamble et al., 2022). By enabling precise monitoring and management of resources, digital twin help in reducing waste, optimising energy use, and minimising the environmental impact of manufacturing activities. They also support the design of sustainable products and optimisation of supply chain operations, ensuring that sustainability is considered at every step of the product lifecycle. Kamble et al. (2022) also stated that digital twin involves deep integration with Industry 4.0 technologies such as IoT, AI, cloud computing, and cyber-physical systems. These integrations enable real-time data collection, analysis, and simulation that are crucial for sustainable operations.

Preut et al. (2021) discuss the potential contributions of digital twin to circularity in products and supply chain management. By decentralising information availability, digital twin enables processes such as reconditioning and corresponding supply chain management to be executed more efficiently and sustainably. This study presents a detailed exploration of how digital twin can facilitate the circularity of products and the management of circular supply chains, offering insights into the potentials and information requirements of circular supply chains for a digital twin.

In context of EEE, Wang and Wang (2018) highlighted that digital twin can be an enabler for manufacturers or remanufacturers to generate and obtain the data of product lifecycle in order to optimise efficiency and productivity and decreasing cost and minimising waste. The authors emphasised that product lifecycle information is often missing in production or interrupted by the users which then lead to data suspension in remanufacturing process. Thus, digital twin can play a role in creating a digitalised system to help stakeholders seamlessly share and collaborate data to support decision making in the end-of-life product while still maintaining security (Wang & Wang, 2018).

2.4.3 Digital Twin Capabilities

Currently, the manufacturing industry is at the forefront of exploring digital twin, which has been identified as a key driver of Industry 4.0 and Intelligent Manufacturing (Fuller et al., 2020; Li et al., 2020). Typically, a manufactured product undergoes four main stages: design, manufacture, operation, and disposal. digital twin are effectively utilised in all four stages to enhance productivity and efficiency (Jones et al., 2020). Li et al. (2020) studied how digital twin is applied in sustainable business model of home appliances, throughout the entire lifecycle of products.

In the design phase, digital twin allows designers to simulate and verify product designs in a virtual environment. This process enables the testing of multiple design iterations, helping to identify the optimal design that meets both performance and consumer needs. By leveraging real-time data from previous product generations, designers gain insights into features that perform well and those that need enhancement (Li et al., 2020). In addition, digital twin can also simulate the environmental performance and impact through life cycle assessment (LCA) resulting design for disassembly, recycling and remanufacturing (Wang & Wang, 2018).

In the manufacturing phase, digital twin aids in production planning by automating order execution and improving decision support through detailed diagnostics. It enables predictive maintenance by identifying potential system changes and their effects, thereby reducing downtime, and ensuring continuous operation. By simulating different manufacturing scenarios, digital twin helps optimise the production process, ensuring efficient use of resources and minimising waste (Li et al., 2020).

Furthermore, in the usage or operation phase, manufacturers can monitor the operational state of their products through digital twin, developing strategies for maintenance and service optimisation. For instance, Li et al. (2020) highlighted how digital twin can provide services such as energy consumption forecasting, user behaviour analysis, and predictive maintenance strategies through connection of digital twin platform network. They also showed that digital twin can enable the provision of customised services based on user data, enhancing the overall customer experience by tailoring products to specific user needs.

The final phase of the product, digital twin helps in the efficient recovery and remanufacturing of products by ensuring that valuable information is not lost when products are retired. For instance, Wang and Wang (2018) developed a digital twin-based system for the recovery of e-waste, supporting circular practices throughout the product lifecycle.

Overall, digital twin ensures a seamless and effective connection between the different phases of manufacturing (Li et al., 2020). As combination of virtual and real information between physical products, digital twin is highly advantageous in the manufacturing industry, positively impacting future products even before they physically exist. digital twin assist in various stages, including design, testing, process optimisation, predictive maintenance, product services, and the proper disposal of products. Additionally, digital twin enhances visualisation, which improves learning and decision-making, and fosters collaboration by allowing a wider range of professionals to work together with intelligent manufacturing. This results in a more comprehensive understanding of equipment and processes by everyone involved. Consequently, products are better designed, and processes become more efficient, saving time and resources.

2.4.4 Digital Twin Enabling Technologies

According to Fuller et al. (2020), digital twins are supported by several key enabling technologies that facilitate the integration of physical systems with their virtual counterparts. These technologies enhance capabilities in simulation, monitoring, and optimization throughout the product lifecycle. An overview of these enabling technologies is provided below.

Industrial Internet of Things (IoT)

At the heart of digital twin lies the Internet of Things (IoT) as one of the keys enabling technology, which involves the use of sensors and actuators connected by networks to collect data and monitor the connected object from the physical world (Fuller et al., 2020). These devices can be attached to almost anything, from machines on a factory floor to buildings or even broader infrastructure such as bridges and roads. Sensors gather data on various parameters such as temperature, pressure, motion, and more. This continuous stream of real-time data is crucial for the creation of a digital twin, as it provides the necessary information to mirror the physical state of the object accurately. In the context of CE, the information that are collected and generated by IoT can connect all the stakeholders across value chain. These connections among stakeholders can be the fundamental basis for evaluating the consequences from their action throughout product lifecycle (Pagoropoulos et al., 2017).

Cloud Computing

Once data is collected, it needs to be processed and stored. This is where cloud computing comes into play, offering the scalable computing resources needed to analyse large volumes of data. Cloud platforms enable the integration of data from diverse sources and facilitate complex simulations. Edge computing complements this by processing data closer to where it is generated, which can reduce latency and bandwidth use, especially critical for real-time decision-making processes in digital twin (Qi et al., 2021).

Augmented Reality (AR) and Virtual Reality (VR)

Digital twin is more effective when its insights are presented in 3D, but this shift requires moving from traditional 2D display methods to more advanced technologies capable of showcasing 3D, such as Augmented reality (AR) (Park et al., 2019). Virtual reality (VR), used within digital twin, creates a highly immersive environment that facilitates productive interactions with data (Malik et al., 2019). VR and computer simulations can be used to design a digital twin, enhancing the spatial awareness of robots without needing a physical counterpart. However, implementing AR and VR systems faces challenges such as a lack of training, insufficient knowledge of their potential, complex system integration, and the extensive time required for development (Kamble et al., 2022).

Big Data Analytics

Big Data Analytics (BDA) is the process of analysing large datasets generated by digital twin and collected in cloud platform. This process is crucial for identifying patterns, trends, and insights that later can help optimise performance and predict future states of the physical counterpart by creating algorithm to automate. In context of CE, BDA plays a significant role by uncovering pattern and the foundation for informed and data-driven decision-making in supply chain networks (Gupta et al., 2019). AI and its subsection, Machine Learning (ML) can enable digital twin by creating algorithm for computer based on collected data, where it gives ability to learn, act and predict outcomes without being directly programmed to do so (Fuller et al., 2020). These technologies enable digital twin in predicting maintenance of the machine and manufacture components and optimising production process to reduce waste and be more efficient. In contrast of BDA that deals with historical data to obtain insight and analyse what is happening, AI and ML are more on how to improve the product or the process and predicting the future based on collected data (Çınar et al., 2020).

Simulation and Modelling Tools

Taking consideration that there is no physical entity in the early stages, software tools such as computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE) are needed for creating accurate and dynamic models of physical assets. These tools allow for the simulation of various scenarios, helping in the design, optimisation, and predictive maintenance of the physical counterpart (Qi et al., 2021; Wang & Wang, 2018). Simulation and modelling tools are crucial for creating realistic, dynamic models of physical systems in the digital realm. By incorporating physical laws, operational data, and behavioural patterns into simulations, digital twin can predict how a system will respond under various conditions. This capability is fundamental for testing scenarios, optimising performance, and making informed decisions without the need to physically alter the system.

Distributed Ledger (Blockchain)

Lastly, Blockchain, an emerging technology that serve as pivotal tool in enhancing transparency through across external information exchange without infringement intellectual property. It serves as a serialised product identifier for tracking each product's unique life and ensuring accurate information management across its lifecycle (Andersen & Jæger, 2021). Later, the stored data can be shared in a controlled manner with other actors in the supply chain. This allows manufacturers to maintain control over their data while enabling access to necessary information for maintenance, repair, remanufacturing, or recycling.

Enabling technologies are the backbone of digital twin implementations, providing the necessary infrastructure, computational resources, and analytical capabilities to bridge the physical and digital worlds effectively.

2.5 Takeaways

Based on the literature review, it can be concluded that CE is crucial in addressing the environmental impact of the traditional linear economy, particularly in the EEE sector. However, the implementation of CE has been rather slow in this sector. Studies show that CBMs need to be implemented to accelerate the transition towards CE (Pollard et al., 2021). Despite this, sector-specific CBMs, especially in the EEE sector, require further exploration. Most existing studies focus on the end-of-life phase of the product lifecycle, commonly known as the WEEE sector, neglecting other crucial phases such as design, manufacturing, and use (Bressanelli et al., 2020). This literature review reveals a significant gap in the holistic view of CBMs in the EEE sector, highlighting the need to cover more aspects of the product lifecycle beyond just the end-of-life phase. Thus, this study will approach circularity from the perspective of the entire product lifecycle.

Throughout the literature analysis, it is shown that there is a lack of comprehensive studies that explore CBMs throughout the entire product lifecycle especially in EEE sector. Most existing research focuses on specific phases rather than providing a holistic view that integrates all stages from design to disposal. A more integrated approach is essential for realising the full potential of circular practices and achieving sustainability in the EEE sector.

Although there is no consensus on a single definition for digital twin, most of the literatures work concurs on their application and advantages. This includes the ability to obtain real-time data from assets currently in use and understanding the operational effects of those assets. Most of the literature discussing digital twin technology is linked to product lifecycle management, detailing the capabilities of digital twin and its enabling technologies at every stage of the lifecycle. Digital twin shows promising features to support CE by providing real-time digital representations of physical entities, optimising their use, maintenance, and recycling management. Digital twin enhances decision-making for CE strategies by facilitating better collaboration and information sharing across the supply chain. Its capabilities span the entire product lifecycle, from design simulation and production planning to real-time monitoring and end-of-life recovery. However, since digital twin is also an emerging topic, there are very few studies that discuss the integration of digital twin in CE, and even fewer that explore their role in CBMs within the EEE sector.

With the recent developments of Hybrid CBM-Tech framework by Tripodis (2023) which provides guidance on integrating Industry 4.0 technologies and circular strategies into CBMs across the value chain, there is a need for further development specific to industries and technologies. Therefore, certain established elements were incorporated into this study, adding more context-specific elements such as circular strategies and practices. Instead of focusing on the value chain, this study emphasises the product lifecycle to provide a better holistic view of each stage in the EEE sector and how digital twin technology can support them. By considering all three perspectives, strategies, product lifecycle, digital twin technologies, this study offers a comprehensive approach to understanding how circularity can be supported and enhanced in the EEE sector. This holistic view ensures that the implementation of CE principles is informed and effective, ultimately promoting sustainability and operational efficiency in this critical industry.

3 Methodology

This section discusses the research design and methodology that are used to collect and analyse the data, to meet the research objectives and to answer the research questions. To answer the sub-questions of research which were mentioned in the introduction part, a qualitative approach is proposed. The process begins with an extensive literature review aimed at understanding the CE in the context of the EEE sector. This foundational step involves defining CBMs specific to the EEE sector and exploring the various circular strategies employed within this industry.

Following the literature review, the research categorises these circular strategies along the product lifecycle, providing a comprehensive view on how CE principles are applied at different stages of product development and use. Concurrently, studies of digital twin capabilities and their enabling technologies within the EEE sector are reviewed to understand how digital twin can facilitate the transition to a circular economy.

The next phase involves generating a conceptual framework that integrates insights from the literature on CE, CBMs, and digital twin capabilities. This framework is then subjected to expert interviews for validation, where industry experts provide feedback to refine the framework. Identifying any missing points from the findings ensures a mature and comprehensive model. This iterative process of feedback and refinement helps in developing a validated conceptual framework that effectively addresses the research objectives and answers the main research question.

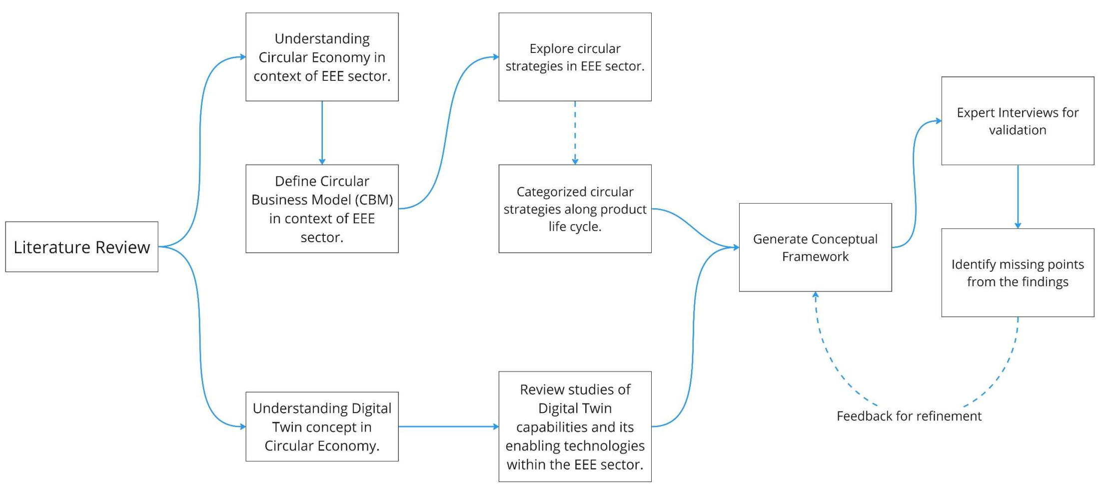

Figure 3.1 Research design overview.

3.1 Literature Review

Literature review was conducted to gather relevant academic knowledge from various sources such as academic papers, white papers, regulation, and industry reports. It serves as an essential foundation for research, ensuring its relevance, significance, and potential for contributing new knowledge to the field (Sekaran & Bougie, 2016). The criteria for the selection are focus on recent publications and documents from reputable sources that intersects to the topic of CE, BM, CBM, digital twin and EEE sector. Since the knowledge is relatively new and keeps developing in the time this research is conducted, the publication of was limited in a span of 10 years. The literature was gathered from journal articles using specific keywords, summarised in Table 6. The collected articles were assessed based on the number of citations they received and the relevance of their research perspective, as indicated by their titles and abstracts. The result of literature review was presented in Section 2.

Table 6 Overview of key themes and keywords of the literature review.

Database	Key Themes	Keywords
Scopus ScienceDirect Web of Science Google Scholar	Circular economy	*Circular strategies, circular practices, product lifecycle, CE in EEE*
	Circular economy business model(s)	*CEBM/CBM in EEE, CEBM/CBM in manufacturing, challenges, barriers, enablers, archetypes*
	Digital twin	*Digital twin definition, capability(s), enabling technology, digital twin in EEE, digital twin in manufacturing, digital twin and sustainability, digital twin and CE, digital twin business model*
	Electrical and electronic equipment	*Electrical, electronic, EEE, WEEE, e-waste, manufacturing*

In conducting the literature search, advanced search queries were designed to find articles intersecting the themes of digital twin, circular economy, and EEE manufacturing across multiple databases (see Table 7). Despite using broad and inclusive search terms, the results indicate a scarcity of literature in this area. After reading thoroughly the abstract, only 6 relevant papers for this research were identified (see Appendix I). This suggests that the intersection of these themes represents a relatively emerging field where academic discourse is still limited.

The limited number of papers reflects the novelty of combining digital twin technology with circular economy principles in the EEE manufacturing sector. This gap highlights the importance of this research in addressing an underexplored area, with the potential to contribute significantly to both the academic and industrial sectors.

Table 7 Result of search items on each database.

Database	Advance Search Items	General Filters	Result
Scopus	TITLE-ABS-KEY (digital AND twin* AND circular AND electronic* AND manufactur*)	• No sources older than 2014 • Free full text, Open Access via TU Delft license • Contain search terms in abstract, keywords, or title.	7
Web of Science	((ALL=(Digital Twin*)) AND ALL=(Circular*)) AND ALL=(Electronic Manufactur*)		35
ScienceDirect	Digital Twin AND Circular AND Electronic AND Manufacturing		29

3.2 Framework Development

The next phase is the creation of a comprehensive framework that integrates essential concepts from theoretical review, including circular strategies, circular business models value dimensions, product lifecycle stages, and digital twin capabilities. This phase builds on the insights gained from the literature and involves organising and structuring these concepts into a coherent framework. The development process began by gathering and analysing key publications related to circular practices, business model elements, and digital twin technologies. The methodology for structuring the framework draws inspiration from Preston et al. (2019) and Potting et al. (2017) which offers a systematic approach for combining circular economy principles and product lifecycle.

To develop this framework, the process was divided into four distinct phases: categorising circular practices, aligning them with product lifecycle stages and CBM components, and integrating digital twin capabilities to support the circular strategies, and lastly creating digital twin capabilities and CBM value element matrix. Initially, the circular practices identified in the literature were categorised according to their relevance and application within the EEE sector. This categorisation was crucial in laying the foundation for the framework by organising practices such as reducing, reusing, repairing, and recycling and other R-strategies into clearly defined clusters under specific circular strategies.

Following the clustering process, the categorised practices were aligned with the various stages of the product lifecycle. This alignment ensured that each circular strategy was effectively positioned within the lifecycle, from design to end-of-life, to guide firms in adopting sustainable practices. By mapping these strategies to lifecycle stages, the framework provided a clear roadmap for integrating circular economy principles into business operations. The final step in the framework development was the integration of digital twin capabilities. These technologies were linked to the identified circular strategies and lifecycle stages to enhance the efficiency and effectiveness of the practices. This framework was developed through a structured approach that involved categorising circular practices, aligning them with product lifecycle stages, and integrating digital twin capabilities. The resulting framework offers a comprehensive guide for the EEE sector to implement circular economy principles effectively, supported by advanced digital twin technologies.

3.3 Expert Interviews Validation

After developing the framework, expert interviews are conducted to validate the findings. These interviews aim to ensure the framework, which integrates digital twin technologies with circular economy strategies in the manufacturing industry, is both theoretically sound and practically applicable. Expert interviews provide valuable insights from individuals with specialised knowledge, especially in areas with limited literature, such as digital twin and circular economy practices (Bogner et al., 2009). By consulting experts, the study seeks to refine the framework based on real-world feedback, identifying gaps, challenges, and opportunities, and ensuring it meets current industry needs. This validation step enhanced the framework's credibility through external evaluation by knowledgeable professionals (Meuser & Nagel, 2009).

The validation process began by identifying and categorising relevant themes from the conceptual framework to guide the analysis. The first theme explores the role of digital twin in the CE. This theme examines the definition of digital twin within the context of CE and investigates how digital twin technologies contribute to the transition CE practices in the manufacturing industry. The second theme delves into digital twin capabilities and their effectiveness in supporting circular business value. This theme focuses on how digital twin can enhance value creation, delivery, and capture within circular business models, ensuring that these models are sustainable and aligned with circular strategies. The third theme addresses enabling technologies. Given that digital twin is conceptualised as a system comprising various interrelated technologies, this theme explores the specific technologies that enable digital twin to function effectively within the framework of CE, such as IoT, AI, and blockchain. The fourth theme identifies the challenges and barriers associated with implementing digital twin technologies within the context of CE. This theme is critical for understanding the practical difficulties, limitations, and potential obstacles that could hinder the successful adoption of digital twin and CE practices in the manufacturing sector. Finally, the fifth theme evaluates the overall framework. This theme assesses the comprehensiveness and applicability of the conceptual framework, as informed by expert feedback, and examines how well the framework aligns with industry realities and expert insights.

To systematically analyse the interview data and ensure a rigorous validation process, a detailed coding scheme (see Appendix II) was developed based on the literature review and framework elements. A coding scheme is a structured method used to categorise and interpret qualitative data by assigning specific codes to different segments of the text based on the identified themes. This approach is essential in qualitative research, as it allows for the organised and systematic extraction of relevant information from complex data sets. The coding scheme played a crucial role in the validation process by enabling the consistent application of codes across all interview data, ensuring that the analysis remained focused on the relevant aspects of the framework.

By applying the coding scheme, the study was able to identify common patterns, contradictions, and unique perspectives, which are critical for assessing the framework's validity. Moreover, the coding scheme facilitated the organisation of data into manageable segments, making it easier to conduct thematic analysis. This method allowed the study to validate whether the framework accurately reflects the realities of digital twin and CE practices in the manufacturing industry and, where necessary, to refine the framework based on expert feedback.

3.3.1 Unit of Analysis

In this study, the unit of analysis was the expert's opinion regarding the integration of digital twin technologies with circular economy strategies in the context of the manufacturing industry. The choice of unit analysis was critical in qualitative research as it defines the focus of the study and influences how data is collected and interpreted (Bogner et al., 2009). By focusing on expert's opinion, the study seeks to capture nuanced perspectives on how the developed framework can be applied in practice. The experts' views provided valuable insights into the feasibility, challenges, and potential benefits of integrating digital twin and CE practices across different stages of the product lifecycle. This focus allowed for an in-depth examination of the framework's applicability and relevance to real-world scenarios. Additionally, expert opinions can highlight industry-specific considerations that may not be immediately apparent in theoretical models. By analysing these opinions, the study aimed to validate and potentially refine the framework to better suit the needs of the EEE manufacturing sector.

3.3.2 Sampling Strategy

The sampling strategy for the expert interviews was needed to ensure that participants possessed the necessary expertise to provide valuable feedback on the developed framework. Given the focus on digital twin technologies and CE strategies in the EEE manufacturing industry, purposive sampling was employed. This non-probability technique selects participants based on their specific knowledge relevant to the research (Bryman, 2012). In this case, experts are chosen based on their substantial experience and understanding of digital twin and CE practices in EEE manufacturing. Given the time constraints and the emerging nature of the topics studied, a sample size of 8 experts is deemed sufficient. This number balances the need for diverse perspectives with the practical limitations of conducting in-depth interviews. Studies have shown that a sample of 6-12 experts can provide a robust foundation for qualitative research, offering enough variation in responses to identify key themes while allowing for manageable data analysis (Guest et al., 2006). By carefully selecting experts with relevant knowledge, the study aims to gather high-quality data that will contribute to the validation and refinement of the framework. The participants were selected using personal contacts and online professional platforms (i.e LinkedIn). Additionally, a snowball sampling method was used, where existing contacts served as a starting point to connect with other experts relevant to the study.

Table 8 Expert interview participant overview.

Expert ID	Role	Expertise	Years of Experience	Organisation
P1	CTO	Digital twin, circular economy business, manufacturing	15	European research institute specialising in technology innovation.
P2	Senior Researcher Manager	Digital twin, circular economy, manufacturing	16	European industrial research centre focusing on advanced manufacturing technologies.
P3	CEO	Digital twin, circular economy, circular business model	12	Mid-size, European IT services company specialising in digital twin.
P4	CEO	Digital twin, sustainability, manufacturing	8	Mid-size, global IT consultancy firm, specialising in enterprise solutions for digital transformation.
P5	Senior Consultant	Digital twin, sustainability, manufacturing	33	Global IT consulting and services provider, focusing on business process outsourcing and technology consulting.
P6	Senior Manager	Digital twin, circular economy, EV battery	30	European software development company with expertise in enterprise system integration and digital twin technologies.
P7	Lecturer	Circular economy, supply chain	20	Dutch academic institute
P8	Sustainability Product Manager	Circular economy, circular business model	7	Global automation and manufacturing technologies, with a focus on industrial machinery.

Eight experts were selected for the interviews where each brought a diverse set of perspectives based on their roles, years of experience, and organisational backgrounds. While the participants were not necessarily from the EEE manufacturing industry, they possessed substantial experience within the broader manufacturing industry. The diversity of expertise was considered valuable for the study, as the principles of digital twin and CE are applicable across various manufacturing sectors, providing transferable insights that can still inform the framework.

Although the industry-specific insights related to EEE manufacturing were limited, the decision to include these experts was based on the understanding that the underlying concepts of digital twin and CE have cross-industry relevance. The knowledge and experience of these experts about digital twin and CE are applicable to the broader manufacturing context. As such, their input remained highly relevant for validating the conceptual framework, which aims to integrate digital twin with CBMs.

3.3.3 Data Collection

Data for this study was collected through semi-structured interviews, which balanced guided inquiry with open-ended exploration. This method was well-suited for expert interviews, as it provided a framework for discussing key topics while allowing flexibility to explore areas of interest (Adeoye-Olatunde & Olenik, 2021). The interview guide focused on the key components of the developed framework, with open-ended questions designed to encourage detailed responses, allowing the experts to freely share their insights. Interviews were conducted via Micorsoft Teams, lasting between 60 and 75 minutes, and were recorded (with participant consent) to ensure accurate transcription and analysis. This method effectively captured rich, qualitative data to validate and refine the framework, accommodating the complexity of expert opinions (Smith & Osborn, 2003).

Each interview process was divided into two main stages. In the first part of the interview, the experts were asked open-ended questions related to the key themes extracted from the framework, including the role of digital twin in CE, digital twin capabilities in supporting circular business value, enabling technologies, and challenges and barriers in implementation. This part of the interview was conducted without presenting the developed framework to ensure that the experts' responses were based purely on their knowledge and experience, free from any potential bias introduced by the framework.

In the second part of the interview, the developed framework was introduced to the experts. During this phase, the experts were asked to evaluate the framework, offering feedback on its accuracy, applicability, and comprehensiveness. They were encouraged to validate the connections made within the framework and suggest any modifications or enhancements based on their professional experience. This step was crucial for assessing the alignment between the experts' earlier insights and the structure of the developed framework.

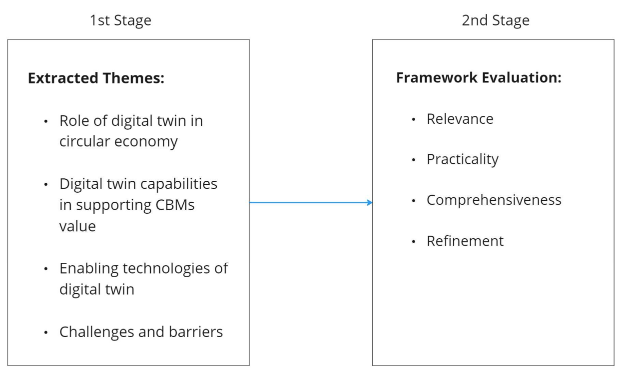

Figure 3.2 Stages of expert interviews

This two-stage approach within the interview sessions enabled a comprehensive exploration of the themes and provided a thorough validation of the framework. The feedback obtained from the experts, despite their varied industry backgrounds, was instrumental in refining the framework, ensuring that it is robust and applicable to the broader context of manufacturing, including but not limited to the EEE sector.

3.3.4 Data Analysis

The data from the expert interviews was analysed using thematic analysis, a method suited for identifying, analysing, and reporting patterns (themes) within qualitative data (Braun & Clarke, 2006). Thematic analysis provides a flexible yet systematic approach to analysing qualitative data, making it ideal for this study, where the goal is to validate and refine a complex framework. The interview data analysis was conducted to systematically interpret the insights gathered from the expert interviews, with the goal of validating and refining the conceptual framework. The process began with the meticulous cleaning of the interview transcripts. This involved removing any unnecessary content, such as irrelevant conversation or pauses, ensuring that the transcripts were clear and focused on the relevant discussions. Once cleaned, the transcripts were prepared for thematic analysis, which was carried out using both deductive and inductive approaches. Deductive codes were derived from the interview guide and framework, while inductive codes emerged organically from the data, capturing unanticipated insights (Fereday & Muir-Cochrane, 2006).

The deductive approach was guided by the coding scheme that had been developed prior to the analysis, based on the key themes extracted from the initial conceptual framework. This coding scheme included predefined codes corresponding to themes such as the role of digital twin in CE, digital twin capabilities in supporting circular business value, enabling technologies, and challenges and barriers. During the analysis, the established codes were systematically applied to the transcripts. Whenever a segment of the transcript aligned with one of these familiar themes, it was coded accordingly. This deductive approach allowed for a focused validation of the framework, as it directly linked the interview data to the key concepts that the framework sought to address.

In addition to the deductive analysis, an inductive approach was also employed to capture new insights that were not initially anticipated by the existing coding scheme. As the transcripts were analysed, any new themes or codes that emerged organically from the data were noted. These emergent themes were not predetermined but instead arose directly from the experts' responses. Once identified, these new codes were clustered and categorised to understand their relevance and relationship to the existing framework. This inductive process was critical for identifying gaps, expanding the framework's scope, and incorporating expert insights that might not have been captured by the original themes.

The combination of deductive and inductive approaches allowed for a comprehensive analysis of the interview data (Braun & Clarke, 2006). The deductive analysis validated the existing framework, while the inductive approach enriched it by incorporating novel insights from expert interviews. This dual approach made the framework more robust, aligning it with real-world practices of digital twin technologies and circular economy strategies in the manufacturing sector.

Through this thorough and systematic process, the study successfully validated the conceptual framework and integrated new themes, refining it to reflect both established knowledge and recent industry insights.

3.3.5 Validity & Reliability

Ensuring validity and reliability in qualitative research is critical for producing credible and trustworthy results. In this study, several measures was taken to enhance both the validity and reliability of the expert interviews. To ensure content validity, the interview questions were directly derived from the core components of the developed framework, ensuring that all relevant aspects are covered (Creswell & Miller, 2000). Before conducting the full set of interviews, the interview guide were reviewed by supervisors to obtain feedback and make necessary adjustments, further ensuring that the questions are clear and relevant. Reliability was addressed by maintaining consistency in how the interviews are conducted. All interviews were carried out by the same researcher, using a consistent approach to questioning and data recording, which reduces variability and enhances the reliability of the findings (Gibbs, 2007). Additionally, detailed notes were taken alongside the audio recordings to provide a rich context for interpretation. Triangulation, where the findings from the expert interviews were cross-referenced with the literature and other data sources, was also be employed to ensure the robustness of the conclusions drawn from the study.

3.3.6 Ethics Approval

Respecting individual autonomy and voluntary participation is crucial for ethical integrity in research. By choosing a sample of participants who are both available and willing, the research guarantees that participation is voluntary, and participants are able to give informed consent. This ethical approach builds trust and respect and protects the rights of participants throughout the research process.

The study received the approval of the Human Research and Ethics Committee (HREC) at TU Delft, confirming that all ethical requirements were met. All participants voluntarily agreed to partake in the study, affirming their informed consent and eagerness to contribute to the research. Additionally, the data steward at TU Delft approved the data management plan, ensuring that the data handling and storage protocols conformed to privacy and data protection laws.

The research was entirely conducted through online video calls using Microsoft Teams, offering a convenient and effective method for interaction between the researcher and participants. A strict distinction was maintained between the collection of experimental data and personal data during these sessions. This separation was crucial for protecting participant confidentiality and privacy, preventing any mixing of personal and experimental data. By adhering to these protocols and utilising online tools, the research was executed smoothly, maintaining ethical standards, ensuring data integrity, and protecting participant privacy.

4 Framework Development

This chapter synthesises the critical concepts reviewed in earlier chapters, including circular strategies, CBM dimension values, product lifecycle, and digital twin capabilities and technologies. First, building upon the comprehensive literature review based on Subchapter 2.3.1, this framework categorises various circular practices that are available and has been studied in context of EEE sector within clearly defined clusters of circular strategies. Then, as presented in Subchapter 2.3.3, these strategies are then aligned across the product lifecycle stages, ensuring that each strategy is appropriately positioned to give clarity in what stages of that these strategies are most suitable for firms to adopt in transitioning to CE approach in business.

As detailed in Section 2.3.2 of the literature review, the framework then connects circular strategies to the core elements of the CBM. This connection is structured to reflect the impact of each strategy on the business model's value-based components, including value proposition, creation, delivery, and capture (Bocken et al., 2016; Nußholz, 2017; Geissdoerfer et al., 2020). By aligning circular strategies with business model elements, the framework ensures that each strategy contributes effectively to the overall value creation and sustainability goals of the EEE sector (Pollard et al., 2021).

Finally, digital twin technologies are integrated throughout the product lifecycle, enhancing the application of circular strategies by providing detailed, real-time insights into product performance and resource utilisation. This integration is vital for enabling predictive maintenance, optimising resource efficiency, and extending product lifespan, thereby supporting the circular economy objectives. The connection between digital twin capabilities and circular strategies is made to ensure that digital tools are effectively utilised to enhance the sustainability of manufacturing processes.

4.1 Clustering Circular Practices under Circular Business Strategies

The clustering of circular practices within circular strategies in the EEE sector builds on existing literature that highlights the importance of closing material loops and minimising resource input (Geissdoerfer et al., 2017). Since the 10Rs offer practical actions to achieve circularity at various stages of the product lifecycle (Potting et al., 2017), they can be grouped and aligned with specific circular business strategies to form a coherent approach.

Greening Strategy

The greening strategy focuses on using renewable energy and regenerating natural ecosystems. In the 10R, refuse, rethink and recover principle aligns well with this strategy (Potting et al., 2017; Konietzko et al., 2020). Recover involves the extraction of energy from waste, which helps reduce reliance on non-renewable energy sources and contributes to more sustainable practices in the product lifecycle. Refuse and rethink support innovation in the product design phase by eliminating harmful materials and fostering systemic changes, such as integrating renewable energy sources into both manufacturing and product operation. The eco-design approach reduces the carbon footprint of products while contributing to a regenerative cycle, as highlighted by Bocken et al. (2016) and Konietzko et al. (2020). In the EEE sector, the recover principle is applied through the recovery of energy from non-recyclable e-waste, such as plastics and composite materials, that cannot be directly reused or recycled (Potting et al., 2017; Pan et al., 2022). This recovered energy can be utilised to power production facilities or other industrial processes, thus reducing the demand for non-renewable energy sources. Additionally, recovering valuable materials such as gold, silver, and palladium from e-waste also contributes to the regenerative cycle by conserving natural resources and reducing the environmental impact of mining.

Narrowing Strategy

The narrowing strategy focuses on reducing the usage of resources and energy consumption while still delivering value to consumers. In relation to the 10R framework of Potting et al. (2017), this involves practices such as refusing unnecessary products and packaging, which encourages both consumers and businesses to avoid items that generate waste or are resource intensive. Rethinking products and business models to use fewer resources is another key practice, which can include implementing service-based models instead of product-based ones, such as product-as-a-service. Additionally, reducing the use of raw materials in production and consumption is critical, achieved through designing products that require fewer resources and utilising alternative materials that are less resource intensive. Geissdoerfer et al. (2020) and Bocken et al. (2016) emphasise that narrowing resource loops through material reduction and dematerialisation can significantly reduce environmental impacts in resource-heavy industries similar to electronics. In the EEE sector, narrowing strategies can be implemented by encouraging consumers to avoid unnecessary electronic devices and single-use electronics (Pan et al., 2022). Designing multifunctional devices that serve multiple purposes reduces the need for separate devices, while using fewer rare earth elements and focusing on material efficiency are critical practices (Berwald et al., 2021).

Extending Strategy

The extending strategy aims to reduce the rate at which resources are consumed and waste is generated by increasing the useful life of products. The characteristics of this strategy align with reuse, repair, refurbish, remanufacture, and repurpose. Potting et al. (2017) explain reusing products multiple times in their original form without significant reprocessing is a primary practice under this strategy, encouraging consumers and businesses to continue using products as long as they remain functional. Repairing products to extend their lifespan also becomes crucial, which includes providing repair services and designing products that are easy to repair. Refurbishment involves restoring old products to a like-new condition, including cleaning, repairing, and updating components to prolong the product's life. Remanufacturing goes further by rebuilding products to meet original specifications using a combination of reused, repaired, and new parts, involving disassembly and inspection. Repurposing modifies products to serve new functions, creatively reusing them for purposes other than what they were originally designed for (Potting et al., 2017). Bocken et al. (2016) highlight that slowing resource loops through reuse, repair, and remanufacturing is key to reducing environmental impacts and conserving resources. Pan et al. (2022) systematically explore these practices in the EEE sector include promoting the reuse of electronics through second-hand markets and donation programs, providing easy access to repair services, and designing electronics that are easy to repair. Offering refurbished electronics as a viable alternative to new products and remanufacturing electronic devices to meet original specifications using a mix of new and reused components are also important. Creative repurposing of electronic components in new applications, such as using old phone parts for educational kits, further extends the life of these products.

Cycling Strategy

The cycling strategy focuses on creating a continuous flow of materials by ensuring that products and components are reused, repurposed, refurbished, remanufactured, recycled, and recovered, thereby keeping them in circulation for as long as possible before they reach the waste stream. Repurpose, reuse, refurbish, remanufacture, recycle, and recover principles align with this strategy. In the EEE sector, repurpose can involve giving new functions to outdated electronics, such as using old smartphones for home automation or media devices, thus delaying their entry into the waste stream. Reuse and refurbish programs, such as those offering second-hand smartphones or restored laptops, play a key role in extending product life, as noted by Pan et al. (2022) who emphasise the importance of these strategies for reducing e-waste. Remanufacture, commonly applied in industries such as office equipment and printers, ensures that products are restored to like-new condition using a combination of reused and new parts, allowing companies to capture additional value from returned products, as outlined by Bocken et al. (2016) and Berwald et al. (2021). Finally, recycle and recover are critical for handling materials at the end of their life cycle, with advanced recycling processes recovering valuable metals such as gold, copper, and palladium from e-waste. Pan et al. (2022) stress the need to increase recycling rates in the EEE sector to maximize resource recovery, while energy recovery from non-recyclable components helps reduce the environmental impact of waste disposal. This comprehensive approach ensures that materials are circulated through multiple life stages, reducing the need for virgin resources and minimising waste generation.

Intensifying Strategy

The intensifying strategy, which focuses on maximising the value derived from resources by increasing their utilisation, efficiency, and productivity, is supported by the rethink principle from the 10R framework. Rethink encourages businesses to innovate and explore new business models that allow for greater product efficiency, such as leasing or sharing platforms. Geissdoerfer et al. (2020) argue that intensifying the use of products through business model innovation is critical for industries that consume high levels of resources, such as the EEE sector. This strategy strengthens the argument that resource productivity can be improved by rethinking how products are consumed and used. In the EEE sector, the intensifying strategy is exemplified by companies offering leasing models for office electronics such as printers and servers. This ensures that these devices are used more intensively over their lifespan, reducing the need for new products and lowering the overall material footprint Pan et al. (2022) provide evidence that rethinking the use of electronics through leasing or product-sharing models can significantly reduce the environmental impact of the sector by ensuring products are fully utilised before being replaced.

The overview of clustering the circular practices under these circular strategies can be seen in the following Table 9.

Table 9 Circular practices under circular strategies in EEE sector.

Circular Strategy	Circular Practices (10R Framework)	Application in EEE Sector
Greening	**Refuse:** Avoiding the use of harmful materials and unnecessary products (Potting et al., 2017; Konietzko et al., 2020). **Rethink:** Innovating product design and manufacturing processes to use renewable resources (Potting et al., 2017; Konietzko et al., 2020; Bocken et al., 2016). **Recover:** Recovering energy from non-recyclable materials and waste streams (Potting et al., 2017).	- EEE manufacturers avoid using hazardous materials like lead and mercury (Pan et al., 2022). - Product design incorporates renewable energy use (e.g., solar-powered devices) (Potting et al., 2017; Konietzko et al., 2020; Bocken et al., 2016). - Energy recovered from non-recyclable plastics and composite materials can power production facilities (Pan et al., 2022).
Narrowing	**Refuse**: Avoiding unnecessary products (Potting et al., 2017; Geissdoerfer et al., 2020). **Reduce**: Minimising material use (Potting et al., 2017; Bocken et al., 2016). **Rethink**: Shifting to service-based models (e.g., product-as-a-service) (Potting et al., 2017; Bocken et al., 2016).	- Avoiding unnecessary electronic devices and single-use products (Pan et al., 2022). - Designing multifunctional devices (e.g., smartphones) to reduce the need for multiple devices (Berwald et al., 2021). - Product-as-a-service models for leasing electronics (Bocken et al., 2018; Pan et al., 2022).
Extending	**Reuse**: Using products multiple times (Potting et al., 2017; Bocken et al., 2016). **Repair**: Fixing broken products (Potting et al., 2017; Bocken et al., 2016). **Refurbish**: Restoring products (Potting et al., 2017; Pan et al., 2022). **Remanufacture**: Rebuilding products (Potting et al., 2017; Bocken et al., 2016). **Repurpose**: Finding new uses for old products (Potting et al., 2017; Pan et al., 2022).	- Reuse through second-hand markets and donation programs (Pan et al., 2022). - Modular designs (e.g., smartphones) enable easy repairs (Pan et al., 2022). - Refurbishing laptops and remanufacturing office equipment and printer cartridges (Pan et al., 2022). - Repurposing old electronic components for new applications (e.g., educational kits) (Pan et al., 2022).
Cycling	**Repurpose**: Finding new uses for products (Potting et al., 2017; Pan et al., 2022). **Reuse**: Extending product life (Potting et al., 2017; Pan et al., 2022). **Refurbish**: Restoring products (Potting et al., 2017; Pan et al., 2022). **Remanufacture**: Rebuilding products (Potting et al., 2017). **Recycle**: Extracting valuable materials (Potting et al., 2017). **Recover**: Recovering energy from waste (Potting et al., 2017).	- Repurpose outdated electronics (e.g., old smartphones used as home automation devices) (Pan et al., 2022). - Reuse and refurbish programs extend product life (e.g., second-hand laptops) (Pan et al., 2022). - Remanufacturing office equipment (Bocken et al., 2016; Berwald et al., 2021). - Recycling valuable materials (e.g., gold, copper) (Pan et al., 2022).. - Energy recovery from non-recyclable components (Pan et al., 2022).
Intensifying	**Rethink**: Innovating business models to increase product utilisation (Potting et al., 2017; Geissdoerfer et al., 2020).	- Leasing models for office electronics (e.g., printers and servers) (Pan et al., 2022). - Sharing platforms for electronics to improve utilisation rates (Pan et al., 2022).

The circular strategies and 10R framework are deeply interconnected, as they both provide structured approaches to transition from a linear to a circular economy. While circular strategies focus on changing the business model to better capture value from sustainability, the 10R framework provides the specific actions needed to implement these strategies at each stage of the product lifecycle. By combining the two, businesses can build robust systems that reduce waste, conserve resources, and generate long-term value in the transition toward circularity.

4.2 Circular Strategy and Circular Business Value

As Nußholz (2017) stated, the aim of CBM is to create, deliver and capture value while implementing circular strategies that can prolong the useful life of products and parts and close material loops. Based on literature review in Section 2.3.2, each strategy has been further explored in context of EEE sector with corresponding value dimensions of CBMs. Table 10 presents the overview and guide for the manufacturer's CBM of how implementation of circular strategies affecting Richardson's (2008) value logic. This table is also intended to contribute to an EEE manufacturer's developmental process in the design of a CBM that is specifically relevant to the EEE sector. Furthermore, it offers an opportunity for manufacturers to consider the potential for integrating circularity in their value proposition, delivery and capture.

Table 10 Circular business values of each circular strategy for EEE sector

Circular Strategy	Value Proposition	Value Creation and Delivery	Value Capture
Greening (Regenerate)	Provides sustainable solutions that enhance the natural environment and meet economic needs (Konietzko et al., 2020).	Development and use of processes that restore (Konietzko et al., 2020) or enhance ecosystem health, embracing eco-design for product circularity across product lifecycle (Pollard et al., 2021).	Monetisation of sustainable practices, such as using renewable energy to reduce costs and possibly earn revenue or credits (Konietzko et al., 2020).
Narrowing	Offers products and services that require fewer resources, appealing to consumers and organisations aiming to minimize ecological footprint (Bocken et al., 2016).	Innovative design and efficient resource use reduce raw material and energy consumption (Konietzko et al., 2020); design products that use fewer inputs and promote waste-minimising behaviours (Bocken et al., 2018).	Differentiating products as sustainable alternatives in the market, creating ongoing revenue streams through models such as pay-per-use (Bocken et al., 2018).
Extending (Slowing)	Reduces the need for frequent replacements, minimising waste and associated intangible benefits (Bocken et al., 2016; Konietzko et al., 2020).	Designing products for longevity and developing business models to maintain product value over time (Nußholz, 2018); ensuring accessibility and effective integration of durable products and extended services into consumer lives (Pollard et al., 2021)..	Capturing value through subscriptions or ongoing service fees for prolonged product use and service models (Nußholz, 2018).
Cycling (Closing)	Provides a sustainable solution to electronic waste management by enabling recovery and reuse of materials (Islam & Huda, 2018; Pollard et al., 2021).	Development of efficient recovery processes, product designs conducive to recycling, and effective reverse logistics systems (Cucchiella et al., 2015; Islam & Huda, 2018); ensuring technological advancements in recycling processes (Tong et al., 2018).	Triple bottom line benefits: economic gains from secondary materials, enhanced corporate responsibility, and reduced ecological impact (Schreck & Wagner, 2017; Arya & Kumar, 2020; Pollard et al., 2021).

Circular Strategy	Value Proposition	Value Creation and Delivery	Value Capture
Intensifying	Promotes sharing and repeated use to decrease overall demand for new products, offering lower ownership costs (Geissdoerfer et al., 2018).	Integration of ICT platforms into business operations for enhanced customer interactions and optimised usage among participants in an ecosystem (Pollard et al., 2021; Bocken et al., 2018).	Generates recurring revenues through rental services, leasing options, and remanufacturing; reduces total cost of ownership and operation (Pollard et al., 2021).

4.3 Positioning Circular Strategies across the Product Lifecycle

Once the circular practices are clustered under their respective strategies, as outlined in Section 2.3.3, the next step is to position these strategies across the various stages of the product lifecycle. Mapping circular strategies to specific lifecycle stages ensures that each stage, from design and manufacturing to use and end-of-life, incorporates sustainable practices that align with circular principles. This approach provides businesses with a clear roadmap, guiding them to integrate circular strategies seamlessly into their operations. This positioning is based on the literature findings in Section 2.3.3 and the framework proposed by Preston et al. (2019), which established connections between circular strategies and the product lifecycle.

During the design phase, strategies focus on minimising resource use and planning for product longevity, repairability, and recyclability. According to Preston et al. (2019), narrowing strategies are particularly important in the design phase, as they involve rethinking product designs to reduce material consumption and prioritize renewable or recyclable materials. As emphasised by Chioatto et al. (2024), circular input-based innovations—such as the use of bio-based or recyclable materials and designs that reduce material and energy usage—are critical for reducing environmental impact from the outset. In the EEE sector, narrowing strategies in design can be implemented by reducing the use of rare and hazardous materials. Moreno et al. (2016) support this by highlighting the importance of designing for durability, repairability, and disassembly to extend product life and ensure circularity from the beginning.

In the manufacturing phase, the emphasis shifts to resource efficiency, waste minimisation, and preparing products for future recycling and repurposing. Potting et al. (2017) emphasise cleaner production strategies, such as implementing material-efficient manufacturing processes and minimising waste. Chioatto et al. (2024) further support this by proposing input-based circular innovations, advocating the use of renewable energy and secondary raw materials to reduce the environmental footprint. Greening strategies also play a critical role, as Preston et al. (2019) highlight the need to integrate renewable energy sources into manufacturing processes, while Pavel (2018) recommends modular manufacturing to ease future upgrades, repair, or disassembly.

in the distribution phase, circular strategies should focus on minimising the environmental impact of logistics and enhancing the efficiency of product delivery systems. Preston et al. (2019) argue that narrowing strategies, such as optimising logistics to reduce fuel consumption and emissions, are critical here. Moreno et al. (2016) support the idea of localised production and distribution networks, which further reduce the carbon footprint and ensure alignment with circular economy principles.

In the use phase, circular strategies aim to maximize the product's lifespan and ensure efficient use while preparing for eventual end-of-life recovery. Chioatto et al. (2024)

emphasise the role of Product-Service Systems (PSS), which extend product life through leasing, sharing, or pooling models. These intensifying strategies ensure that products are used more intensively, thus reducing the demand for new products and conserving resources. Reike et al. (2018) also stress the importance of repair, reuse, and refurbishment during the middle stages of the lifecycle, helping to extend product life and reduce waste. Extending strategies, such as offering extended warranties and easy access to spare parts, further support this phase by encouraging users to maintain and repair their electronic devices rather than replacing them.

At the end-of-life phase, the focus is on recovering value from products through recycling, remanufacturing, and repurposing. Preston et al. (2019) describe closing strategies that facilitate a circular flow of resources by recovering materials at the end of the product lifecycle and reintegrating them into the production cycle. Potting et al. (2017) also highlight take-back schemes and reverse logistics as critical enablers for closing the loop, ensuring that products and materials are returned for recycling and recovery. Chioatto et al. (2024) similarly advocate for end-of-life innovations, such as upcycling, remanufacturing, and energy recovery from non-recyclable waste, ensuring that valuable materials are extracted and reintegrated into the production cycle.

By positioning circular strategies across the product lifecycle, businesses can ensure that each stage, from design to end-of-life, incorporates sustainable practices. This approach not only aligns with circular economy principles but also draws on the work of Moreno et al. (2016), Potting et al. (2017), Preston et al. (2019), and Chioatto et al. (2024) to establish a comprehensive framework for integrating circular strategies into the EEE sector.

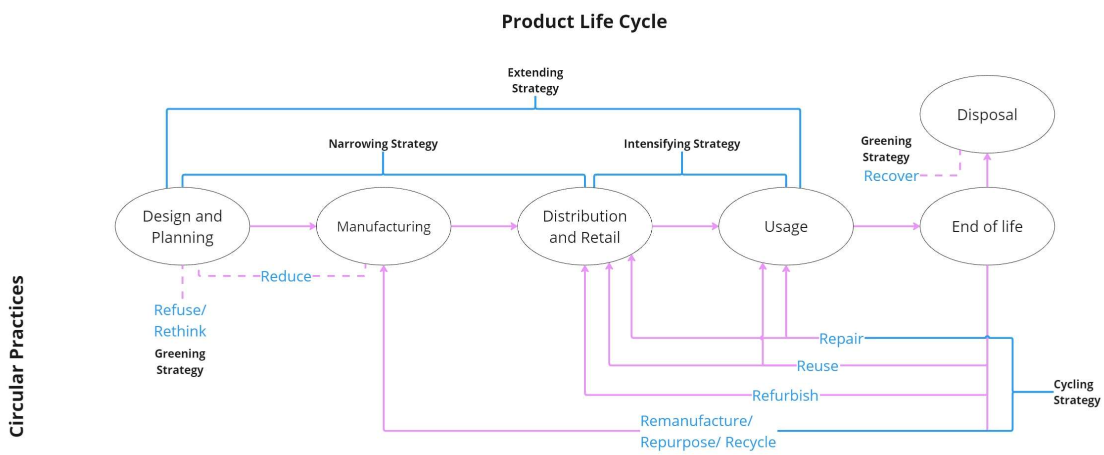

Figure 4.1 Mapping illustration of circular strategies and practices along the product lifecycle (simplified).

4.4 Connecting Digital Twin Capabilities and Enabling Technologies with Circular Strategies

The following phase involves integrating digital twin capabilities and enabling technologies with the identified circular strategies. Digital twin technology, with its ability to provide real-time digital representations of physical assets, plays a crucial role in enhancing the implementation of circular strategies. This phase ensures that the technological infrastructure supports and amplifies the benefits of circular strategies, leading to more resilient and sustainable business models in the EEE sector. According to Kritzinger et al., (2018), digital twin evolves across different stages of the product lifecycle, serving distinct purposes at each phase. This development step attempts to connect the digital twin with the enabling technology while considering the evolution of the digital twin itself across the product lifecycle.

In the design phase, the product does not yet exist physically. Instead, it is represented as a digital model, which provides a virtual replica of the product's intended structure, behaviour, and lifecycle characteristics (Kritzinger et al., 2018). Digital models allow engineers to simulate various aspects of the product, such as material selection, durability, and environmental impact, making them essential for circular strategies such as narrowing (resource efficiency) and greening (sustainability through eco-friendly materials and processes). Wang and Wang (2018) demonstrate that in this phase, CAD and CAE tools, integrated with cloud computing, are key enabling technologies that allow manufacturers to simulate the environmental impact of different design choices, perform lifecycle assessments (LCA), and develop products that are easier to recycle and repair. Moreover, the integration of VR into this phase adds an immersive dimension to the design process. As Rocca et al. (2020) explain, VR enhances the interactivity of digital twin models by allowing designers and engineers to collaborate in real-time, visualise the product in a 3D environment, and make design adjustments based on sustainability goals. This capability is particularly important for improving design for disassembly, where components can be visualised and optimised for easier end-of-life recycling.

As the product moves into the manufacturing phase, digital twin plays a critical role in monitoring, controlling, and optimising both the product and the manufacturing assets used to create it. Unlike the design phase, where only a virtual model exists, the manufacturing phase involves a physical product, and the digital twin reflects the real-time state of this product and the associated manufacturing environment (Kritzinger et al., 2018). In more advanced implementations, digital twin allows for bi-directional communication between the physical system and its digital counterpart, enabling real-time adjustments and predictive actions. Rocca et al. (2020), while in small scale, were able to show how digital twin works in conjunction with other Industry 4.0 technologies to gather real-time data from the physical disassembly plant for WEEE. This data includes energy consumption, sensor readings, and system performance metrics, which the digital twin uses to make informed decisions that support circular strategies such as narrowing (resource efficiency) and greening (energy and resource optimisation), as well as cycling (bringing materials back into the loop). In relation to the extending strategy, the real-time data gathered by the digital twin is used to track and monitor various machine states which allows for the identification of inefficiencies and likely to experience fault (Rocca et al., 2020).

In the usage phase, full digital twin plays a pivotal role in the real-time monitoring of product performance, enabling continuous interaction between the physical product and its digital counterpart (Kritzinger et al., 2018). This phase is where the digital twin exhibits its fullest capabilities, including predictive maintenance, performance optimisation, and lifecycle management. By integrating IoT sensors, cloud computing, and AI-based analytics, full digital twin helps manufacturers and end-users gain insights into product health, anticipate malfunctions, and manage the product's operational lifecycle more effectively. This is especially important for extending the life of the product and ensuring optimal usage, thereby minimising waste and resource consumption which is aligns with intensifying strategy (Geissdoerfer et al., 2020). The digital twin continues to evolve based on input from the end-user. Users can update the digital twin through various methods such as scanning QR codes, RFID, or NFC, with information about repairs, upgrades, and changes to the product (Wang & Wang, 2018). As the product is used, its digital twin reflects any modifications, such as replacement of parts or changes in ownership. This ensures that the product's lifecycle data remains up to date, which is crucial for planning its end-of-life recovery. When a product is sold, the digital twin transitions from a universal model (for the product type) to a unique one that reflects the specific history and condition of that individual product. This individualisation supports personalised service during the product's later stages, such as specific repair or recovery needs (Wang & Wang, 2018). Digital twin can also act as platform that monitors product performance, identifying potential failures before they occur and enabling users to extend product life through timely repairs and maintenance. This reduces the environmental impact by extending the useful life of the products (Li et al., 2020).

In the end-of-life phase, the digital twin functions more as a digital shadow because it is mostly used to provide static data about the product without requiring real-time interaction or control (Kritzinger et al., 2018). However, this static data is crucial for guiding disassembly and recycling processes. During the end-of-life phase, this type of digital twin is primarily formed from data collected throughout the product's lifecycle. By the time the product reaches the end-of-life phase, its digital twin contains a comprehensive record of its design, manufacturing details, usage history, and maintenance records. This information is invaluable for determining the most efficient and sustainable approach to disassembling the product, recovering valuable materials, and reintroducing them into the production cycle. RFID, QR codes, and barcodes: these technologies help track and identify products and components as they move through the recycling and disassembly process. Each product or part can be tagged with an RFID chip or QR code, linking it back to the digital twin and providing detailed information about the materials it contains (Wang & Wang, 2018). Blockchain provides a transparent and immutable record of the product's entire lifecycle, including its origin, material sourcing, and maintenance history. This technology is useful in closed-loop recycling systems to ensure that recovered materials are traceable and can be reused or sold as verified resources (Tozanlı et al., 2020; Andersen & Jæger, 2021). AI algorithms can use data from the digital twin to optimize the disassembly process, identifying the most efficient way to extract valuable materials while minimising waste. AI can also suggest the best routes for recycling or repurposing the recovered materials based on real-time market data. Digital twin helps facilitate resource recovery by providing detailed insights into the materials and components used in the product. This data helps recyclers target the most valuable materials and ensure that they are extracted efficiently and with minimal waste. Furthermore, the digital twin supports closed-loop recycling by ensuring that materials are not lost during the recycling process and are reintroduced into the production cycle (Wang & Wang, 2018; Li et al., 2022).

This synthesis leads to Digital Twin Nexus Circular Business Model framework depicted in Figure 4.2, consisting of four layers: the product lifecycle, circular practices and strategies, and digital twin layer with its enabling technologies. This framework serves as a guide for determining which stages and enabling technologies of digital twin should be implemented. Table 11 provides an overview of the concept, detailing the capabilities of digital twin at each stage of the product lifecycle, their connection to specific circular strategies, and the enabling technologies that play a role at each stage.

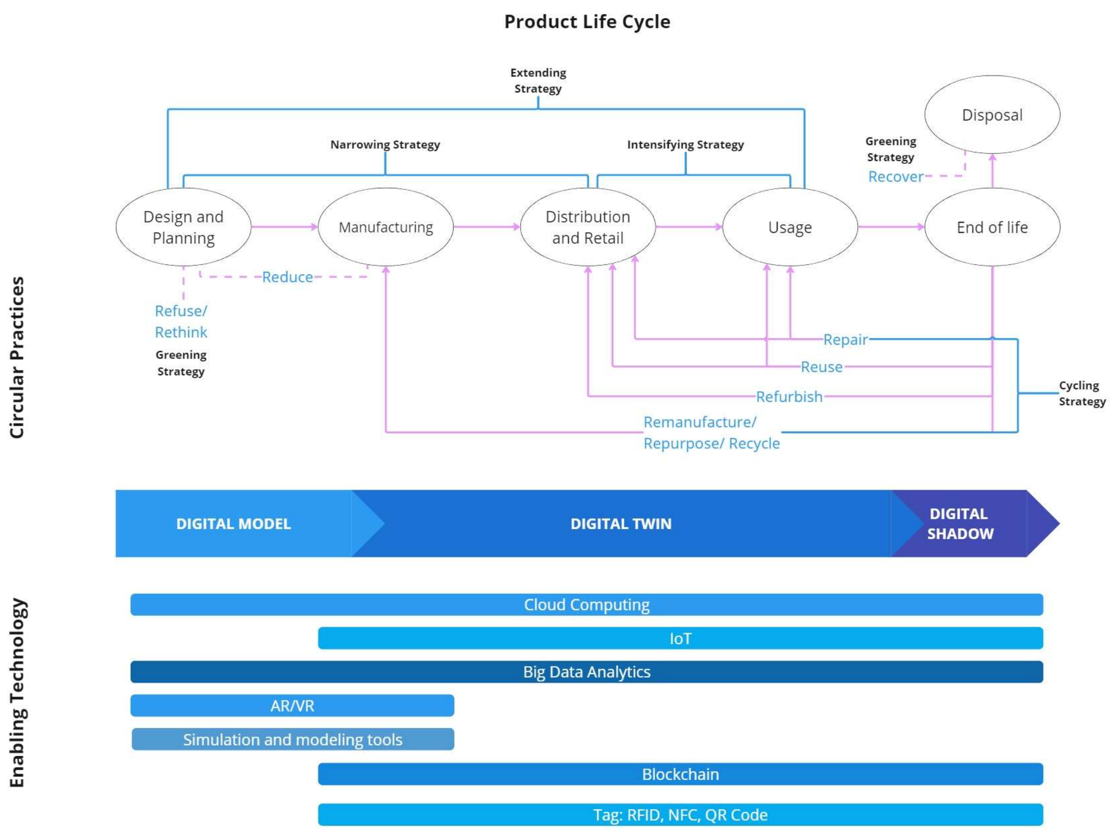

Figure 4.2 Digital Twin Nexus Circular Business Models.

Table 11 Overview of digital twin capabilities and its enabling technologies with circular strategies along product lifecycle.

Lifecycle Stage	Digital Twin Capabilities	Application in EEE Sector	Enabling Technologies	Circular Strategies
Design	• Simulate and verify product designs in a virtual environment (Rocca et al., 2020). • Test multiple design iterations to identify optimal design (Rocca et al., 2020). • Leverage real-time data from previous product generations for insights (Wang & Wang, 2018; Li et al., 2020). • Simulate environmental performance and impact through life cycle assessment (LCA) (Wang & Wang, 2018).	• Designing multifunctional devices to reduce the need for separate devices (Pan et al., 2022). • Using fewer rare earth elements and focusing on material efficiency (Pan et al., 2022). • Designing for disassembly, recycling, and remanufacturing (Wang & Wang, 2018).	Simulation and Modelling Tools, AR/VR Cloud Computing, AI, BDA	Narrowing, Extending
Manufacturing	• Aid in production planning by automating order execution (Rocca et al., 2020). • Improve decision support through detailed diagnostics (Rocca et al., 2020). • Enable predictive maintenance to reduce downtime (Rocca et al., 2020). • Optimise the production process by simulating different scenarios (Rocca et al., 2020; Tozanlı et al., 2020).	• Reducing resource consumption by optimising production processes (Rocca et al., 2020). • Incorporating renewable energy sources. • Establishing recycling loops within the production process (Wang & Wang, 2018).	IoT, Cloud Computing, BDA, Blockchain, Tags	Narrowing, Cycling, Greening
Operation/Usage	• Monitor the operational state of products (Li et al., 2020; Wang & Wang, 2018). • Develop strategies for maintenance and service optimisation (Li et al., 2020). • Provide services like energy consumption forecasting, user behaviour analysis, and predictive maintenance (Tozanlı et al., 2020; Li et al., 2020). • Enable customised services based on user data (Li et al., 2020).	• Providing easy access to repair services (Li et al., 2020). • Implementing product-as-a-service models to maximize utilisation (Pan et al., 2022). • Offering refurbished products as alternatives to new ones (Pan et al., 2022).	IoT, Cloud Computing, BDA, Blockchain, Tags	Extending, Intensifying

Lifecycle Stage	Digital Twin Capabilities	Application in EEE Sector	Enabling Technologies	Circular Strategies
Disposal/End-of-Life	• Facilitate efficient recovery and remanufacturing of products (Wang & Wang, 2018; Li et al., 2022). • Ensure valuable information is not lost when products are retired (Tozanlı et al., 2020; Andersen & Jæger, 2021). • Optimise each phase of the process from disassembly to end-refining (Wang & Wang, 2018; Li et al., 2022). • Enhance decision-making in trade-in strategies and end-of-life product recovery (Wang & Wang, 2018; Li et al., 2022).	• Establishing robust e-waste recycling programs (Wang & Wang, 2018). • Implementing waste-to-energy systems for non-recyclable electronic waste (Pan et al., 2022). • Remanufacturing electronic devices using a mix of new and reused components (Pan et al., 2022). • Repurposing electronic components in new applications (Pan et al., 2022).	IoT, Cloud Computing, BDA, Blockchain, Tags	Cycling, Extending

4.5 Digital Twin Capabilities and Circular Business Value

Building on insights from the Table 11 and previous literature in Section 2.4.3, digital twin capabilities can be categorised into five key areas: simulation and modelling, predictive analysis, tracking, monitoring, and control. This categorisation reflects the primary ways in which digital twin interacts with their physical counterparts (Kritzinger et al., 2018). Simulation and modelling allow for the creation of virtual models that simulate real-world processes, enabling testing and optimisation. Predictive analysis builds on this by using data to forecast future conditions and improve decision-making. Tracking ensures that digital twin is continuously updated with real-time data from their physical assets. Monitoring allows for the observation of key metrics and performance indicators in real-time, and control enables remote adjustments to physical assets through the digital twin, optimising their performance throughout their lifecycle.

Utilising the Digital Twin Nexus Circular Business Model framework, a matrix has been developed that extends the overview of how digital twin supports the circular business value of each strategy (Table 12). This matrix integrates digital twin capabilities with the value elements of each circular strategy as identified in the framework.

For the greening strategy, digital twin can support the value proposition through simulation and modelling by enabling the design of eco-friendly products (Wang & Wang, 2018). Furthermore, for value creation and delivery, digital twin simulates production processes that optimize the use of renewable resources, thus promoting sustainability (Wang & Wang, 2018; Rocca et al., 2020). Predictive analysis then ensures operational efficiency by managing renewable energy use, ultimately reducing costs and enhancing value capture (Rocca et al., 2020).

Similarly, for the narrowing strategy, digital twin drives value by minimising resource usage and environmental impact through advanced simulations (Wang & Wang, 2018; Rocca et al., 2020). During value creation, simulation tools optimize production with fewer resources, while predictive analysis helps forecast demand and reduce waste (Tozanlı et al., 2020). Additionally, control systems streamline processes, ensuring efficiency and reducing excess waste (Rocca et al., 2020). The combined effects of simulation and predictive analysis lead to lower production costs and improved resource utilisation (Tozanlı et al., 2020).

For the extending strategy, digital twin contributes to the value proposition by simulating and modelling products for longevity and durability (Wang & Wang, 2018; Rocca et al., 2020). For value creation and delivery, predictive analysis facilitates maintenance that ensures products remain in good condition over time, reducing downtime and extending product life (Li et al., 2020). Monitoring capabilities support timely upgrades and reduce the need for replacements. Value capture is achieved by profiting from maintenance services based on predictive maintenance, as well as enhancing customer loyalty through consistent product performance (Li et al., 2020).

The cycling strategy benefits from digital twin by enabling the value proposition of designing for disassembly through simulation and modelling (Wang & Wang, 2018; Li et al., 2022). This supports effective reverse logistics and recycling. For value creation and delivery, digital twin capabilities, including tracking and predictive analysis, help in designing products for easy recycling or repurposing, ensuring materials can be effectively reused. Value capture is achieved by reducing costs associated with new materials and creating new revenue streams from recycled products (Wang & Wang, 2018; Rocca et al., 2020).

Lastly, for the intensifying strategy, digital twin empowers companies to design products for shared use through simulations that enhance product adaptability for multiple users (Li et al., 2020). This capability enhances product adaptability for multiple users. Value creation and delivery are optimised through predictive analysis, which forecasts demand and usage patterns, and control mechanisms that ensure efficient resource allocation. Tracking ensures that shared products are used and maintained properly. Value capture is realised through dynamic pricing models based on usage patterns, as well as enhanced customer satisfaction and loyalty due to well-maintained shared products (Li et al., 2020).

Table 12 Digital Twin Nexus Circular Business Model values.

	Digital Twin Nexus Circular Business Models								
	Greening			Narrowing			Extending		
	Value Proposition	Value Creation & Delivery	Value Capture	Value Proposition	Value Creation & Delivery	Value Capture	Value Proposition	Value Creation & Delivery	Value Capture
Digital twin Capabilities	**Simulation and Modelling:** - Enable eco-friendly product (Wang & Wang, 2018).	**Simulation and Modelling:** - Simulate design and production with renewable resource (Wang & Wang, 2018; Rocca et al., 2020).	**Simulation and Modelling:** - Cost saving from renewable resource usage (Rocca et al., 2020). **Predictive Analysis:** - Reducing operational costs through efficient use of renewable energy (Rocca et al., 2020).	**Simulation and Modelling:** - Simulate design with minimal resource and environmental impact (Wang & Wang, 2018; Rocca et al., 2020).	**Simulation and Modelling:** - Enable production optimisation with fewer resources (Rocca et al., 2020). **Predictive Analysis:** - Forecasting demand and adjusting production to reduce waste (Tozanlı et al., 2020). **Control:** - Streamlining production processes and reducing waste through automation and decision support (Rocca et al., 2020).	**Simulation and Modelling:** - Reduce production cost from simulation and modelling (Wang & Wang, 2018; Rocca et al., 2020). **Predictive Analysis:** - Cost savings and efficient resource utilisation (Tozanlı et al., 2020).	**Predictive Analysis:** - Facilitating predictive maintenance that ensures products remain in good condition over time (Wang & Wang, 2018; Rocca et al., 2020; Li et al., 2020). - Reducing downtime and extending the product's useful life (Li et al., 2020).	**Simulation and Modelling:** - Simulate and model design for longevity and durability (Wang & Wang, 2018; Rocca et al., 2020). **Monitoring:** - Enabling timely upgrades and reducing the need for replacements with continues monitoring (Li et al., 2020).	**Predictive Analysis:** - Profits from maintenance services based on the predictive maintenance (Li et al., 2020). **Monitoring:** - Enhance customer loyalty by ensuring consistent product performance (Li et al., 2020).

	Digital Twin Nexus Circular Business Models					
	Cycling			Intensifying		
	Value Proposition	Value Creation & Delivery	Value Capture	Value Proposition	Value Creation & Delivery	Value Capture
Digital twin Capabilities	**Simulation and Modelling:** - Enable design for disassembly (Wang & Wang, 2018; Li et al., 2022). - Optimise best route for reverse logistics (Wang & Wang, 2018). **Tracking:** - Enabling effective reverse logistics and ensuring that products are returned for recycling or repurposing (Wang & Wang, 2018; Li et al., 2022).	**Simulation and Modelling:** - Designing products for easy recycling or repurposing, ensuring that materials can be effectively reused (Wang & Wang, 2018; Rocca et al., 2020). - Enabling closed-loop system with design for disassembly (Wang & Wang, 2018; Rocca et al., 2020). **Predictive Analysis:** - Forecasting the best times and methods for recycling and repurposing (Wang & Wang, 2018; Li et al., 2022).	**Predictive Analysis:** - Reducing costs associated with new materials (Rocca et al., 2020). - Creating new revenue streams from recycled products (Wang & Wang, 2018; Li et al., 2022).	**Simulation and Modelling:** - Designing products that are suitable for shared use and collaborative consumption (Li et al., 2020). - Enhancing product adaptability for multiple users (Li et al., 2020). **Monitoring:** - Ensuring that shared products are used and maintained properly (Li et al., 2020). **Tracking:** - Ensuring the products are efficiently distributed among users (Li et al., 2020).	**Predictive Analysis:** - Optimising the use of shared resources by forecasting demand and usage patterns (Li et al., 2020). **Control:** - Managing the orchestration of shared services and ensuring efficient resource allocation (Li et al., 2020). - Supports the creation and delivery of shared products by improving logistics and supplier coordination (Li et al., 2020).	**Predictive Analysis:** - Enabling dynamic pricing models based on forecasting demand and usage patterns (Li et al., 2020). **Monitoring:** - Enhances customer satisfaction and loyalty by ensuring that shared products remain in good condition (Li et al., 2020).

5 Findings

5.1 Validation

This section verifies that the findings effectively address the sub-research questions based on the themes derived from the Digital Twin Nexus Circular Business Model framework. It ensures that the insights are both grounded in the data collected and aligned with the theoretical framework established at the onset of this research.

5.1.1 Role of Digital Twin in Circular Economy

This section explores the diverse definitions and perceived roles of digital twin within the CE, highlighting both the commonalities and differences in expert perspectives. Experts consistently describe the digital twin as a virtual replica or digital replica of a physical entity, but their emphasis on specific features and its application in the CE differs. As one expert notes, digital twin is *"an integral part of all of these lifecycle elements of products,"* helping to *"predict how the product will be used and wear and tear"* it will experience (P1). This predictive capability allows companies to make products last longer by optimising usage and maintenance, reducing the need for replacements. Additionally, digital twin supports reuse and refurbishment by identifying when a product can still be effective in a less demanding context, even if it no longer meets high-performance standards. The expert explains, *"Very likely there is some other process...where that pump can still be effective".* Furthermore, digital twin enables the sharing of critical data across stakeholders, preventing waste and ensuring efficient use. They also support the transition to CBMs, such as product-as-a-service, by allowing for the management of product degradation and lifecycle performance (P1).

Another expert, P6, describes digital twin as *"the digital counterpart of a physical entity or product,"* emphasising their role in tracking and maintaining products throughout their lifecycle. This enables businesses to determine *"what's in it, how to maintain it, how to dismantle it"* (P6). P7 highlights a more traditional application of digital twin in supply chain planning and risk mitigation, using digital twin as simulation tools to replicate physical supply chain infrastructure and *"run scenarios based on the data used in daily business operations"* (P7).

A different perspective from P3 expands the definition as unique identifiers that contains necessary information that are available for stakeholder for each product, that later can be used to enhance and integrated to their business operations. As P3 stated*: "we add a digital ID to every individual unit of product, literally a universally unique identifier, with its own cloud space. This cloud space connects to different inputs, which could come from your ERP, CMS, CRM, or transport system. This brings all the scattered information into a relevant user experience for the different users that need to interact with your product."* In relation to CE, this expert explains that the digital twin is essential not only for regulatory compliance but also for enhancing product lifecycle management, asserting that it plays a critical role in *"extending product lifecycles"* and facilitating the transition to product-as-a-service models. As P3 mentioned *"...we cater to these need [regulatory compliance and enabling PaaS model] by making it easy to gather all information about products and workflows, making product interaction available to the different personas that need to interact with the product."*

Adding to these perspectives, P2 agrees that digital twin *"will help us acquire information to make decisions with proper data"* when it comes to extending the product's life or repurposing it. P2 emphasises the importance of product's information, stating that without it, *"...we might just throw it away, generating waste."* In the context of CE, P2 notes that *"Digital twin technology can help reduce this waste by providing the necessary information."* digital twin supports CE practices by acting as data collectors throughout the value chain, as highlighted by P5*: "This rethinking of the entire value chain is where circular economy principles come into play. Digital twin technology supports this by enabling better use of data collected over the years."* P7's perspective further reinforces the importance of strategically embedding CE principles within company operations to maximize the benefits of digital twin.

P8 introduces the concept of a *"Green Digital Twin,"* a specific application developed to estimate and improve the environmental performance of products. This digital twin incorporates the Bill of Materials (BOM) and environmental impact data to simulate a product's lifecycle and predict its ecological footprint. By using this approach, companies can better understand the environmental implications of their design choices early in the product development process. P8 explains, *"This tool is used to estimate the performance of the products we design, predicting the environmental impact based on the BOM and associated environmental data"* (P8). Despite the potential benefits, P8 notes that the application of digital twin in supporting circular economy strategies is still in its early stages.

5.1.2 Digital Twin in Supporting Circular Business Value

Digital twin technology supports multiple aspects of circular business value creation, particularly in the areas of extending, narrowing, and cycling strategies. The capabilities of digital twin—such as simulation, monitoring, control, predictive analysis, and tracking—are instrumental in enhancing these strategies. While most of digital twin's contributions to value creation are direct and evident in these strategies, their role in value capture is often more indirect, primarily through improved operational efficiencies, cost savings, and the creation of new revenue streams. This section discusses how digital twin capabilities drive these business values and explores the nuances of their direct and indirect impacts on value creation and capture within CBMs.

In terms of extending strategy, participants frequently mention that digital twin can facilitate prolonged product life by predicting maintenance needs, allowing companies to monitor and forecast when a product requires servicing or refurbishment, thereby extending its lifespan. For instance, P4 notes that *"we can predict the lifespan of machines by analysing the vibration signatures of their components,"* which aligns with the value of offering performance control and timely maintenance to prolong product use. Additionally, digital twin supports the creation of durable and adaptable products from the design stage, ensuring they can be maintained and upgraded throughout their lifecycle. P1 highlights the importance of designing for longevity, stating that *"we need to have a model to predict how long it will last,"* emphasising the role of digital twin in modelling and simulating product lifecycles to optimise durability. This is crucial for CBM that rely on offering long-lasting, high-quality products with upgradability options, as digital twin provides the necessary data to support these features. The value delivery aspect is also strengthened by digital twin, which enables efficient after-sale services and maintenance. P3 describes how unique identifiers on products such as washing machines can guide users and technicians through repairs and maintenance, providing personalised service and ensuring products remain in optimal condition. This supports the CBM goal of delivering high-quality maintenance services that extend product lifecycles. P8 adds digital twin can be used to create value by identifying critical points in the product lifecycle where intervention is needed to reduce environmental impact through its predictive capabilities: *"We then analyse what the results of the life cycle analysis model tell us. We might discover a "hotspot" or identify why a particular life cycle stage has a high impact, like during manufacturing or material procurement."*. P1 also highlights that data gathered from the physical entity through digital twin can help a company decide on the repurposing of a product, potentially leading to continued profitability. In terms of capturing value, P4 mentions that predicting maintenance for manufacturing machines can lead to indirect cost reductions, as machine breakdowns can halt production, resulting in significant profit losses. P3 emphasises the profit potential from maintenance services enabled by digital twin, noting that sharing maintenance data can create new business opportunities and enhance customer loyalty.

The second most frequently mentioned concept of CBM strategy by participants is cycling strategy. In this strategy, digital twin significantly contributes to creating and delivering value through enhanced traceability, reverse logistics and collaboration across the value chain. As noted by the participants, digital twin allows for the detailed monitoring of products post-use, which is crucial for remanufacturing and recycling processes. As stated by P2: *"The digital twin can represent data generated after use and monitor it. In logistics for remanufacturing electronics, digital twin technology should allow for traceability. This includes disassembly, inspection, cleaning, repairing, reassembling, testing, and tracking components that have been processed as waste or introduced into new products".* Furthermore, P6 discusses the importance of seamless information access provided by digital twin for tracking products throughout their lifecycle, which is essential for managing recycling and take-back systems: *"If you can define a way to pick, for example, a battery as an individual instance and request information about it from anywhere, it makes logistics and operations, such as repair or recycling, much easier".* This capability allows companies to track products from production through to end-of-life, ensuring they are recycled or remanufactured effectively. Moreover, P3 emphasises how digital twin facilitate take-back systems by providing digital IDs that allow for easy tracking and interaction with products throughout the supply chain: "*To ensure that packaging can be reused, you add a digital ID that is interactable and can be used as a digital channel to add services to it".* This approach ensures that products can be efficiently returned, refurbished, and reintroduced into the market, supporting the continuous cycling of materials. Digital twin support new revenue streams by facilitating the return and refurbishment of products, which can be resold or repurposed. P3 highlights the role of digital twin in streamlining the return process, which incentivizes consumers to return products for recycling or remanufacturing: *"Simplifying the return process: you just scan and get guided on how to easily return a certain package or product".* This ease of return not only enhances consumer participation in circular practices but also allows companies to capture additional value by reintroducing refurbished products into the market.

As for narrowing, experts agree that minimising waste has always been a priority for companies because less waste translates to lower costs and higher profits (P1, P4, P5). Digital twin can play a role in capturing the value of cost reduction by providing detailed insights through modelling, predictive analysis, and real-time monitoring, ensuring that resources are used as efficiently as possible. With the prediction capability, digital twin contributes to the value proposition by enabling the design of products and processes that require minimal resources. P2 emphasises the role of digital twin in reducing waste by providing crucial data that helps in decision-making: *"Sometimes we don't really know what's going on and if we can extend the life of our product or use it in another application. Without this knowledge, we might just throw it away, generating waste. Digital twin technology can help reduce this waste by providing the necessary information".* By leveraging digital twin, companies can design products that use fewer materials and ensure that resources are not wasted during production or throughout the product's lifecycle. P1 also discusses how digital twin is used during the design phase to model and optimise the production process, including its environmental impact: *"In the design phase, you're going to model... the production process and the efficiency of the production process, and the impact on nature* *(environment) that the production process will have".* The simulation also can be an insight for the organisation to decide of how they want to proceed with the design by considering the insights that is obtained from feedback loop of digital twin. This modelling capability allows companies to create more efficient production processes that minimize resource use and environmental impact.

Additionally, P4 highlights how digital twin is used for stock forecasting to minimize over-inventory and reduce raw material waste: *"We can do stock forecasting... so that the buffer stock in the warehouse can be minimised. Because if there is over-inventory, raw materials can be wasted".* By optimising inventory management through predictive analysis, digital twin helps companies reduce unnecessary resource consumption and improve overall efficiency. The value captured in the narrowing strategy through digital twin is realised via cost savings from reduced resource consumption and the creation of new revenue streams through innovative business models. P5 describes how companies are transitioning from traditional product ownership models to product-as-a-service (PaaS) models, supported by digital twin: *"Companies like Sulzer, which manufacture heavy pumps, used to sell the pumps but now sell them as a service... This approach includes elements of reusability and repairability, integral to the circular economy".* This shift not only reduces the burden of resource use on customers but also generates additional revenue through service-based offerings, capturing value by optimising resource use and extending product functionality. P4 also discusses how digital twin contributes to cost savings by optimising energy use in production facilities: *"For energy saving, we also have a smart lighting system where we save energy by adjusting the brightness of the lights".* This real-time optimisation of energy consumption reduces operational costs and enhances sustainability, further supporting the value capture aspect of the narrowing strategy.

The concepts that are similar to greening was less frequently mentioned during the interviews. Regarding the greening strategy, most of the digital twin capabilities contribute indirectly by simulating and predicting processes that lead to greater sustainability, thereby enhancing the company's reputation as a green business (P4, P5). P8 also adds that digital twin can do simulation of the environmental impact of various sourcing options, companies can choose suppliers that offer materials produced using renewable energy sources: *"if we find that sourcing a material, like aluminium from Supplier A, has a significant environmental impact based on our green digital twin simulation, we might discover from our global procurement discussions that there is another supplier offering aluminium produced with green electricity in a different country."* This capability enhances the decision-making process and aligns with the value capture strategy by balancing cost and sustainability, potentially improving the company's market position and reputation for environmental responsibility.

5.1.3 Enabling Technologies of Digital Twin

The validation of enabling Industry 4.0 technologies for digital twin reveals several components consistently recognised and aligned across multiple interviews. These technologies form the backbone of digital twin implementations, especially within the context of the CE.

In the early stages, when the physical entity does not yet exist, a digital model is created using simulation and modelling tools. As stated by P1: *"First, you need modelling tools to capture either physics knowledge or experience digitally into some kind of model."* Here, "modelling" refers to creating a 3D model using CAD/CAM tools during the design phase. However, participants often confused this with a computational simulation model. This type of model is an executable process that uses data and algorithms to produce outputs.

Although different from a 3D CAD/CAM model, computational simulation models can complement digital twin by enhancing predictive analysis at an early stage.

As the digital twin progresses from a conceptual model to a more detailed representation, the importance of data collection technologies, primarily through the use of IoT, becomes evident. These tools are widely acknowledged as essential for capturing real-time data from physical entities, which is crucial for the accurate functioning of digital twin (P1, P2, P4, P5, P6, P7). However, IoT is not the only tool for capturing data for digital twin; many other technologies exist. As P1 emphasised, *"For me, IoT is a means to collect data... but there are tens of other technologies out there that can also gather data."* For example, as P3 mentioned, data can also be collected through scanning embedded tags on products, such as QR codes, NFC, or RFID tags, which hold necessary information for CE practices. These tags are cost-effective, making them economically viable for certain products. As P3 stated, *“We can also work with other carriers like RFID or NFC, but the main reason we love QR codes is that they are low-cost and have a low threshold. For many products, it doesn't make economic sense to add a sensor.”*

After data is collected using various technologies, the next crucial step involves storing and processing this data effectively. Data storage, processing, and infrastructure are also critical enabling technologies, with cloud computing emerging as the primary method for managing the vast amounts of data generated by digital twin. Cloud platforms ensure that this data is accessible, scalable, and can be processed efficiently to support the dynamic needs of digital twin. P5 highlighted the importance of this by stating, *“Cloud-based storage systems have the capacity to handle this data, and various intelligent solutions can analyse it and provide actionable insights. This is a great help for the manufacturing community.”* Additionally, Big Data Analytics (BDA) and AI are crucial for interpreting the vast amounts of data collected by digital twin. These technologies support advanced functions such as predictive maintenance and operational optimisation. As a result, digital twin become highly valuable for both manufacturing and lifecycle management (P1, P2, P3, P4, P5).

Interoperability and standardisation are also crucial enabling digital twin. Several respondents emphasised the need to ensure that data formats and systems are standardised and interoperable. Interoperability refers to the ability of different systems and technologies to work together seamlessly, allowing digital twin to function effectively across various stages of the product lifecycle. This is particularly important when digital twin need to integrate with other systems or share data across different stakeholders. For example, P2 pointed out, *"We have data-related technologies like industrial data spaces that aim for data to be findable, accessible, interoperable, and reusable (FAIR principles)."* Blockchain technology is also needed to enable secure data sharing across stakeholders. As P2 highlighted, *“Blockchain can be part of it [digital twin], but it’s not the main technology. The data space itself should contain an embedded blockchain model.”*

Lastly, the concept of the digital thread, which is a communication framework that connects data and processes across the product lifecycle, emerged as a significant technological advancement in integrating digital twin. The digital thread connects multiple digital twin across the product lifecycle, enabling a more comprehensive and interconnected approach to data management and decision-making. P5 explained, *"The emerging approach is the digital thread, where multiple digital twins are integrated to bring collective intelligence together."* This integration is crucial for creating a cohesive view of the product lifecycle and ensuring that digital twins can deliver their full potential. P1 also added that *“So, you can create digital twins separately without having the digital thread. However, I think that if you apply the digital thread, it will become more valuable.”* This statement reveals that while digital twins can operate independently, failing to integrate them through a digital thread can lead to inefficiencies and missed opportunities for optimisation.

5.1.4 Challenges and Barriers

Through a series of interviews with experts, various themes emerged that highlight the complexities of implementing digital twin in real-world scenarios. These challenges are not isolated but often interlinked, reflecting the multifaceted nature of digital transformation and sustainability efforts in manufacturing sectors. This analysis synthesises the insights from these interviews, categorising the challenges into key themes: **technological challenges, organisational challenges, data governance and security, and regulatory challenges.**

Technological Challenges

A recurring theme in the interviews is the challenge of integrating the diverse technologies required to create and maintain digital twin. P2 emphasised that a digital twin is not a standalone tool but rather a *"conjunction of several bricks"* that together form a comprehensive system. This system includes sensors, actuators, simulation tools, cloud computing, and big data analytics, all of which must be effectively integrated to create a functional digital twin. The lack of modular and flexible integration frameworks aggravates these challenges, making it difficult to activate the appropriate tools for each use case within the digital twin framework.

Another significant technological challenge revolves around the collection and management of data necessary for populating digital twin models. P3 discusses the difficulties in gathering sufficient and relevant data in complex environments. The effectiveness of a digital twin relies heavily on the accuracy and completeness of the data it uses, and the challenge of *"filling that software with enough relevant data"* is crucial. This issue is compounded by the need to ensure that data collected from various stages of the product lifecycle can be effectively integrated and utilised within the digital twin system. P3 also highlights the technical difficulties in integrating digital identifiers, such as QR codes, into existing production workflows, which involves not only the physical implementation of these tags but also their incorporation into a broader digital ecosystem that includes data management and interaction systems.

A recurring theme across the interviews is the need for standardisation and interoperability in the development and implementation of digital twin technologies. P2 and P6 both stress the importance of creating standardised frameworks that can support the integration of digital twins across different systems and industries. The concept of industrial data spaces, which aim to make data *"findable, accessible, interoperable, and reusable,"* is critical for ensuring that digital twins can be effectively utilised for CBMs. However, achieving this level of data integration is technically challenging, particularly given the diverse range of industries and technologies involved.

The integration of digital twin technologies with existing systems, presents another layer of complexity. Some expert underlines the challenges associated with customising digital twin systems to meet specific needs, particularly in environments where companies rely on deeply ingrained existing systems (P4). The process of integrating digital twin with these systems is often complex and time-consuming, requiring careful management and adaptation. Additionally, there is a complexity in sourcing and integrating data from various systems, particularly when companies have multiple systems (P7).

P6 adds another dimension to this challenge by discussing the complexity of creating digital twins that effectively support CBMs. While developing a digital twin may be straightforward from an IT perspective, ensuring that it integrates seamlessly with the physical product's lifecycle and the circular economy is much more complex. For instance, P6 highlights the difficulty in designing products, such as batteries, in a way that supports easy recycling or repurposing—a critical aspect of the CE. The challenge is that while digital twin can theoretically track a product's entire lifecycle, the current state of technology does not fully support this in practice, particularly in terms of traceability. The lack of effective ways to track a battery's lifecycle once it is in use leads to a loss of valuable information, which in turn hampers the realisation of the full potential of digital twin in supporting CE goals.

Organisational Challenges

In addition to technological hurdles, organisational challenges also play a critical role in the successful implementation of digital twin technologies. These challenges revolve around issues of organisational alignment, change management, and the integration of new technologies into existing business processes.

Several interviewees pointed out the importance of having a clear organisational structure and alignment when implementing digital twin technologies. P1 and P2 argued that using digital twin should not be an end goal in itself; rather, the objective should be to achieve circularity while still creating value for the business. P5 and P7 emphasises that companies need to have a well-defined vision and organisational structure to support these initiatives: *"The overarching vision and mission need to be clearly articulated by the organisation. If the company hasn't implemented digital twins yet, they need to first articulate what they mean by digital twin and why they are going to use it."* (P5). Without this clarity, efforts can become fragmented, leading to inefficiencies and a lack of alignment with broader strategic goals.

Some experts (P3, P4, P8) also discusses the challenges of aligning different stakeholders within an organisation, noting that resistance to change and entrenched habits can significantly impede the adoption of digital twin. From internal side, P3 notes that multiple departments from production to customer service have different needs and perspectives regarding the implementation of digital twin. This can create significant hurdles in aligning these diverse interests towards a common goal. P3 and P8 emphasises the importance of top-level alignment to ensure successful implementation, stating, *"You need alignment at the top level to implement this successfully."* This highlights the complexity of managing cross-departmental collaboration, which is crucial for integrating digital twin technology into business operations. From external side, P4 describe the difficulties in convincing stakeholders of the value of digital twin, particularly when there is a lack of understanding or a reluctance to move away from established practices: *"Habit change and stakeholder resistance even though the vision is already [there]."*(P4). P8 also added: *"If there's already a strong understanding or awareness in the industry or ecosystem, it's usually easier to introduce new concepts."*

Another organisational challenge is the need for effective change management and skill development to support the adoption of digital twin technologies. P1 highlights the skills gap and unfamiliarity with digital twin as significant barriers, noting that *"…many companies lack the expertise and experience needed to implement and utilise digital twins."* This lack of familiarity extends to both the technology itself and the new way of working that digital twin necessitates.

Similarly, P4 points out the difficulties in teaching employees to use new digital tools, particularly in environments where workers may not be tech-savvy. They describe the challenge of transitioning from manual processes to digital ones, stating, *"Teaching them is extremely challenging...It's about teaching them to look at the information rather than manually inputting it."* This highlights the need for comprehensive training and support to ensure that employees can effectively use digital twin technologies. Moreover, P5 mentions that many companies are still in the early stages of becoming data-driven organisations. The transition to a data-driven model is essential for digital twin technology to be effective, especially in the CE context. However, achieving this transition requires significant investment in skills, infrastructure, and governance. P5 notes that *"many organisations lack this particular skill set,"* indicating a significant barrier in terms of the expertise required to manage and implement digital twin projects.

Data Governance and Security

Data governance and security emerged as critical themes across multiple interviews, with experts highlighting the importance of managing data effectively to ensure the success of digital twin initiatives. These challenges include issues related to data ownership, integrity, and the sharing of information across different stakeholders.

A key concern raised by several interviewees is the question of data ownership and the integrity of information within digital twin. P6 emphasises the importance of having a clear structure for who owns and manages the digital twin, particularly as the product moves through different stages of its lifecycle: *"Who governs the information? Who has the right to certify it and make official records?"* This challenge is further complicated by the need to protect sensitive business information while still sharing necessary data with external parties.

P3 also discusses the need for robust data governance frameworks to ensure that digital twin can operate effectively across different parts of an organisation. They highlight the risks associated with inaccurate or altered data, noting that *"if you provide a certificate saying, 'These are the official data' and then someone hacks it and changes some entries, the whole system becomes absurd."* This shows the need for secure data management practices to maintain the integrity and reliability of digital twin.

The sharing of information and the protection of intellectual property are also significant challenges in the implementation of digital twin technologies. P6 discusses the complexities of sharing information between different stakeholders, particularly when it comes to protecting competitive know-how: *"Building this digital twin in a standardised way and making this information accessible to everyone is important but without providing competitive know-how."* They highlight the difficulties in balancing the need for transparency with the need to protect sensitive business information, especially when multiple stakeholders are involved in the lifecycle of a product.

P6 repeats this concern, noting that the protection of intellectual property is a major barrier to the widespread adoption of digital twin for CE practices: *"If the government were allowed to look into my company's internal data, then it would be war."* This highlights the tension between the need for regulatory compliance and the protection of proprietary information, which is a significant challenge in industries where competition is fierce. P5 also raises concerns about the ethical implications of digital twin technology, particularly in terms of data privacy and security. They note that while digital twin offers significant potential for improving business operations and sustainability, they also pose risks related to the misuse of data and the potential for surveillance: *"Ensuring data security and privacy is a major challenge, especially when dealing with large amounts of sensitive information."*

Regulatory Challenges

Regulatory and legal challenges are another critical theme that emerged from the interviews. These challenges are particularly relevant in the context of the CE, where new regulations are being introduced to promote sustainability and transparency.

Several interviewees discussed the evolving regulatory landscape, and the challenges associated with complying with new laws and standards. P3 highlights the difficulty of justifying the costs associated with implementing digital twin technologies when the primary motivation is compliance, as opposed to value creation. They explain that while digital product passports, for instance, are driven by regulatory compliance, companies need to see beyond compliance to understand the potential value these technologies can bring to their business operations. *"If they only want to do it for compliance, it doesn't make sense at the moment,"* the interviewee asserts, suggesting that without a clear business case for value creation, companies may be reluctant to invest in these technologies.

P8 highlights regulatory challenges, noting that a conducive market environment with supportive regulations is essential for circular economy initiatives. The expert mentions specific regulations, such as the EU's Design for Sustainable Product Regulation (ESPR), which standardizes requirements to support CE or eco-design. P8 points out that regulations can help drive market demand and create the necessary conditions for circular economy practices to thrive: *"There must be supporting regulations...there needs to be a market landscape or conditions that are conducive."*

P6 highlights the introduction of laws the "battery pass," which aim to track the lifecycle of products and ensure their sustainability: *"The result of this battery law is to build this kind of organisation and neutral platform where everybody is forced to put the relevant information into this environment."* However, implementing these regulations is challenging, particularly because they require new infrastructures and platforms that are not yet fully developed.

5.1.5 Overall Framework

The proposed framework for integrating digital twin into CBMs has been met with insightful feedback from experts, revealing both its strengths and areas for improvement. The feedback shows the potential of the framework to support the transition from linear business model to CBMs but also emphasises the need for refinement to enhance its practical applicability. Each experts offered unique perspectives, emphasising the importance of expanding the framework's coverage of enabling technologies, including additional critical technologies such as the asset administration shell for better data management and interoperability. Furthermore, the professionals suggested the inclusion of real-world examples and business cases to validate the framework's effectiveness and its alignment with industry practices. The need for clearly defined success parameters, adaptability, and continuous improvement mechanisms was also mentioned, ensuring that the framework remains relevant in dynamic industrial environments. Additionally, considerations regarding data governance and ownership, particularly in the context of multiple stakeholders, were raised, suggesting the need for clear processes for managing data throughout the product lifecycle. Overall, these insights support the framework's potential while providing a roadmap for its improvement in further research, ensuring that it is not only theoretically robust but also practically actionable and relevant to the needs of industry professionals.

5.2 Framework Refinement

Building on the insights gained from the interviews, the framework has been refined to incorporate additional elements that will be thoroughly discussed in this section. These additions, coupled with the aspects covered in the literature review, have enriched the framework to better support manufacturing companies in adopting circular strategies. While the core components and perspectives of the framework remain consistent, the integration of digital twin capabilities, as highlighted in the interviews, has introduced new dimensions to the framework's structure and application. This enhancement will help other manufacturing companies by providing a balanced mix of academic literature and expert insights, facilitating their transition towards more sustainable CBMs.

One key refinement involves the extending strategy. The interviews highlighted the importance of predictive analysis for forecasting when products require servicing or refurbishment, a capability now emphasised in the framework. This enables companies to maintain products in optimal condition, thereby extending their lifecycle. Additionally, the framework now includes digital twin's role in providing decision-making support for repurposing products based on monitoring data. This ensures that products remain valuable and functional throughout their lifecycle, aligning with CBM goals of durability and longevity.

For the cycling strategy, the framework now emphasises the role of digital twin in facilitating take-back systems through the use of digital IDs. These IDs allow for seamless tracking and interaction with products throughout the supply chain, ensuring that products can be efficiently returned, refurbished, and reintroduced into the market. This refinement supports the continuous cycling of materials and opens up new revenue streams by making the return process simpler and more accessible to consumers.

In the context of the narrowing strategy, the refined framework now highlights the use of predictive analysis for stock forecasting to reduce waste. This capability is crucial in optimising resource use and minimising environmental impact, as it allows companies to manage inventory more effectively and reduce excess stock. Furthermore, digital twin's role in optimising energy use during production processes has been integrated into the framework, reflecting the importance of energy efficiency in cost reduction and sustainability efforts.

Although the concepts related to the greening and intensifying strategies were less frequently mentioned during the interviews, the framework still recognizes the indirect contributions of digital twin. For example, simulation and modelling are crucial for enabling eco-friendly product design and supporting regulatory compliance, such as with the Eco-Design Directive. Additionally, digital twin serves as a platform network under the intensifying strategy, enhancing the coordination and delivery of shared services, and ensuring efficient resource allocation.

In terms of enabling technologies, the refined framework recognizes two critical components that are essential for the effective implementation of digital twin within circular business models: the standardisation of data through Asset Administration Shell (AAS) and the integration of digital threads. These elements address foundational challenges in digital twin deployment, particularly in environments where multiple systems and data formats typically exist in isolation.

These refinements not only enrich the framework but also ensure its practical relevance and applicability in the context of contemporary manufacturing practices. The added elements based on interview insights provide a more comprehensive tool for companies looking to transition to circular business models, further bridging the gap between theory and practice.

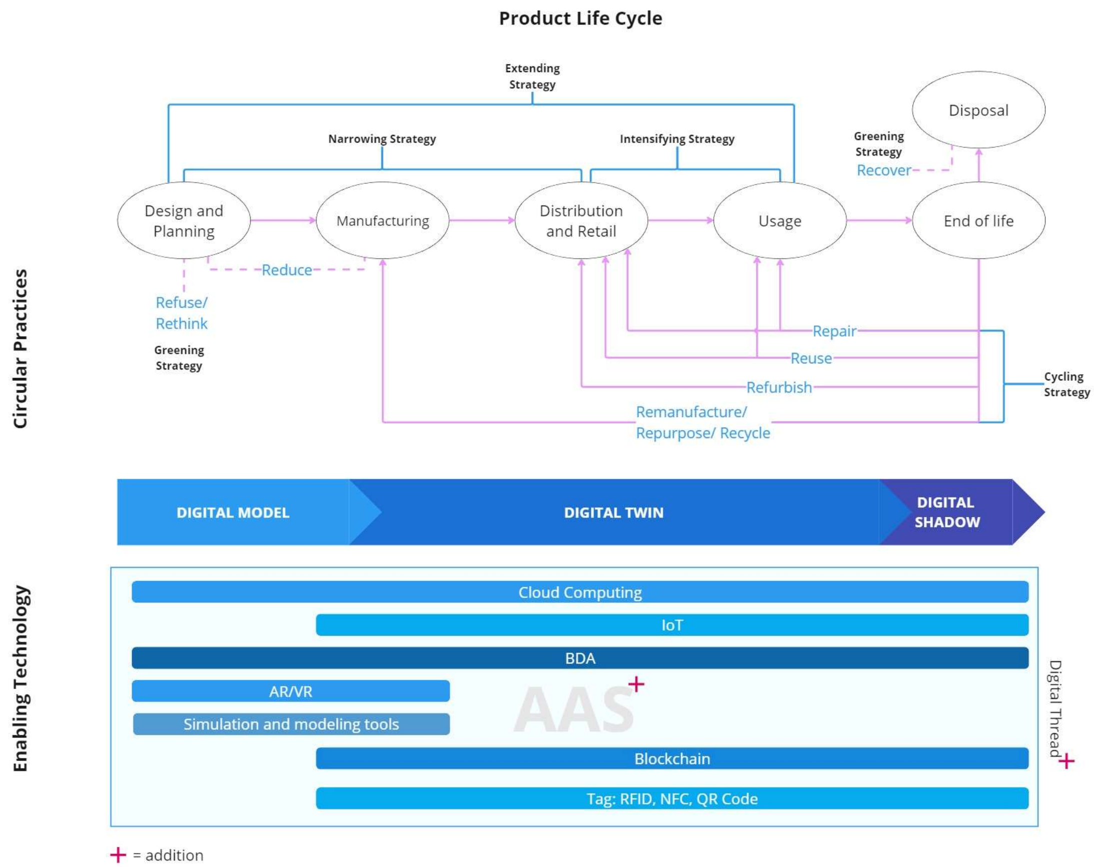

Figure 5.1 Digital Twin Nexus Circular Business Models (refined).

Table 13 Digital twin capabilities and its enabling technologies with circular strategies along product lifecycle (refined).

Lifecycle Stage	Digital Twin Capabilities	Application in EEE Sector	Enabling Technologies	Circular Strategies
Design	• Simulate and verify product designs in a virtual environment (Rocca et al., 2020). • Test multiple design iterations to identify optimal design (Rocca et al., 2020). • Leverage real-time data from previous product generations for insights (Wang & Wang, 2018; Li et al., 2020). • Simulate environmental performance and impact through life cycle assessment (LCA) (Wang & Wang, 2018). • Design based on the eco-design directive	• Designing multifunctional devices to reduce the need for separate devices (Pan et al., 2022). • Using fewer rare earth elements and focusing on material efficiency (Pan et al., 2022). • Designing for disassembly, recycling, and remanufacturing (Wang & Wang, 2018).	Simulation and Modelling Tools, AR/VR Cloud Computing, AI, Big Data, AAS	Narrowing, Extending
Manufacturing	• Aid in production planning by automating order execution (Rocca et al., 2020). • Improve decision support through detailed diagnostics (Rocca et al., 2020). • Enable predictive maintenance to reduce downtime (Rocca et al., 2020). • Optimise the production process by simulating different scenarios (Rocca et al., 2020; Tozanlı et al., 2020). • Stock forecasting to reduce waste. • Optimising energy-use • Monitoring machine and production assets.	• Reducing resource consumption by optimising production processes (Rocca et al., 2020). • Incorporating renewable energy sources. • Establishing recycling loops within the production process (Wang & Wang, 2018).	IoT, Cloud Computing, BDA, Blockchain, Tags, AAS	Narrowing, Cycling, Greening
Operation/Usage	• Monitor the operational state of products (Li et al., 2020; Wang & Wang, 2018). • Develop strategies for maintenance and service optimisation (Li et al., 2020). • Provide services like energy consumption forecasting, user behaviour analysis, and predictive maintenance (Tozanlı et al., 2020; Li et al., 2020). • Enable customised services based on user data (Li et al., 2020). • Predicting service requirement for product or alternative use. • Embedding necessary information for repair and maintenance through tag.	• Providing easy access to repair services (Li et al., 2020). • Implementing product-as-a-service models to maximize utilisation (Pan et al., 2022). • Offering refurbished products as alternatives to new ones (Pan et al., 2022).	IoT, Cloud Computing, BDA, Blockchain, Tags, AAS	Extending, Intensifying

Lifecycle Stage	Digital Twin Capabilities	Application in EEE Sector	Enabling Technologies	Circular Strategies
Disposal/End-of-Life	• Facilitate efficient recovery and remanufacturing of products (Wang & Wang, 2018; Li et al., 2022). • Ensure valuable information is not lost when products are retired (Tozanlı et al., 2020; Andersen & Jæger, 2021). • Optimise each phase of the process from disassembly to end-refining (Wang & Wang, 2018; Li et al., 2022). • Enhance decision-making in trade-in strategies and end-of-life product recovery (Wang & Wang, 2018; Li et al., 2022).end-refining. • Enhance decision-making in trade-in strategies and end-of-life product recovery. • Storing necessary information for returning and take-back systems • Monitoring of product post-use	• Establishing robust e-waste recycling programs (Wang & Wang, 2018). • Implementing waste-to-energy systems for non-recyclable electronic waste (Pan et al., 2022). • Remanufacturing electronic devices using a mix of new and reused components (Pan et al., 2022). • Repurposing electronic components in new applications (Pan et al., 2022).	IoT, Cloud Computing, BDA, Blockchain, Tags, AAS	Cycling, Extending

Table 14 Digital Twin Nexus Circular Business Model values (refined).

	Digital Twin Nexus Circular Business Models								
	Greening			Narrowing			Extending		
	Value Proposition	Value Creation & Delivery	Value Capture	Value Proposition	Value Creation & Delivery	Value Capture	Value Proposition	Value Creation & Delivery	Value Capture
Digital Twin Capabilities	**Simulation and Modelling:** - Enable eco-friendly product (Wang & Wang, 2018). - Support regulatory compliance e.g. ESPR	**Simulation and Modelling:** - Simulate design and production with renewable resource (Wang & Wang, 2018; Rocca et al., 2020)..	**Simulation and Modelling:** - Cost saving from renewable resource usage (Rocca et al., 2020). - Increase company reputation in terms of sustainability. **Predictive Analysis:** - Reducing operational costs through efficient use of renewable energy (Rocca et al., 2020).	**Simulation and Modelling:** - Simulate design with minimal resource and environmental impact (Wang & Wang, 2018; Rocca et al., 2020).	**Simulation and Modelling:** - Enable production optimisation with fewer resources (Rocca et al., 2020). **Predictive Analysis:** - Forecasting demand and adjusting production to reduce waste (Tozanlı et al., 2020). - Stock forecasting to reduce waste. **Control:** - Streamlining production processes and reducing waste through automation and decision support (Rocca et al., 2020). - Optimise energy use.	**Simulation and Modelling:** - Reduce production cost from simulation and modelling (Wang & Wang, 2018; Rocca et al., 2020). **Predictive Analysis:** - Cost savings and efficient resource utilisation (Tozanlı et al., 2020). **Control:** - Indirect cost reduction from energy saving.	**Predictive Analysis:** - Facilitating predictive maintenance that ensures products remain in good condition over time (Wang & Wang, 2018; Rocca et al., 2020; Li et al., 2020). - Reducing downtime and extending the product's useful life (Li et al., 2020). - Forecasting when a product requires servicing or refurbishment. **Unique Identifier:** - Providing necessary information for repairment to users and technicians. - Personalised service	**Simulation and Modelling:** - Simulate and model design for longevity and durability (Wang & Wang, 2018; Rocca et al., 2020). **Predictive Analysis:** - Decision-making support for repurposing product based on the monitoring data. **Monitoring:** - Enabling timely upgrades and reducing the need for replacements with continues monitoring (Li et al., 2020).	**Predictive Analysis:** - Profits from maintenance services based on the predictive maintenance (Li et al., 2020). - Reduce indirect costs by preventing machine breakdowns. **Monitoring:** - Enhance customer loyalty by ensuring consistent product performance (Li et al., 2020).

	Digital Twin Nexus Circular Business Models					
	Cycling			Intensifying		
	Value Proposition	Value Creation & Delivery	Value Capture	Value Proposition	Value Creation & Delivery	Value Capture
Digital Twin Capabilities	**Simulation and Modelling:** - Enable design for disassembly (Wang & Wang, 2018; Li et al., 2022). - Optimise best route for reverse logistics (Wang & Wang, 2018). **Tracking:** - Enabling effective reverse logistics and ensuring that products are returned for recycling or repurposing (Wang & Wang, 2018; Li et al., 2022). **Unique Identifier:** - Facilitates take-back systems by providing digital IDs that allow easy tracking and interaction with products throughout the supply chain. - Provide information for returning product where it simplifies the return process.	**Simulation and Modelling:** - Designing products for easy recycling or repurposing, ensuring that materials can be effectively reused (Wang & Wang, 2018; Rocca et al., 2020). - Enabling closed-loop system with design for disassembly (Wang & Wang, 2018; Rocca et al., 2020). **Predictive Analysis:** - Forecasting the best times and methods for recycling and repurposing (Wang & Wang, 2018; Li et al., 2022). **Monitoring and Tracking:** - Monitoring of products post-use.	**Predictive Analysis:** - Reducing costs associated with new materials (Rocca et al., 2020). - Creating new revenue streams from recycled products (Wang & Wang, 2018; Li et al., 2022). **Unique Identifier:** - Enhance customer participation in circular practices with easy information for return process.	**Simulation and Modelling:** - Designing products that are suitable for shared use and collaborative consumption (Li et al., 2020). - Enhancing product adaptability for multiple users (Li et al., 2020). **Monitoring:** - Ensuring that shared products are used and maintained properly (Li et al., 2020). **Tracking:** Ensuring the products are efficiently distributed among users (Li et al., 2020).	**Predictive Analysis:** - Optimising the use of shared resources by forecasting demand and usage patterns (Li et al., 2020). **Control:** - Managing the orchestration of shared services and ensuring efficient resource allocation (Li et al., 2020). - Supports the creation and delivery of shared products by improving logistics and supplier coordination (Li et al., 2020).	**Predictive Analysis:** - Enabling dynamic pricing models based on forecasting demand and usage patterns (Li et al., 2020). **Monitoring:** - Enhances customer satisfaction and loyalty by ensuring that shared products remain in good condition (Li et al., 2020).

6 Discussion

6.1 Framework Development

Digital Twin Nexus Circular Business Model framework developed based on the theoretical review with aims to give insights for practitioners showing the integration of circular business strategies with digital twin technologies to enhance sustainability within the EEE sector. This framework represents a novel approach by aligning various circular practices with specific product lifecycle stages and leveraging digital twin capabilities to optimize these practices. It explored further by developing the matrix between digital twin capabilities and the circular business values (value proposition, value creation and delivery, and value capture). This development was an effort to find a relation on how two emerging concepts are related, which in this case is digital twin and CBMs within the EEE sector.

From the framework development, several findings have emerged regarding the connections between circular business strategies and digital twin technologies throughout the product lifecycle. First, using a product lifecycle approach allows for a detailed analysis of how CBMs can be implemented at different stages of a product's existence. This approach helps pinpoint specific interventions that can enhance resource efficiency and minimize waste at each stage, providing valuable insights into how digital twin can drive circularity during various phases of a product's life. This aligns with the idea that digitalisation plays a crucial role in driving circular disruption of CBMs (Neligan et al., 2022). In contrast to the HCBMT framework (Tripodis, 2023) , which focuses on the value chain, the lifecycle approach is more relevant for companies seeking to understand where digitalisation can have the most significant impact in reducing resource use, extending product life, and optimising recycling or reuse. This lifecycle focus also accounts for the interconnected dynamics between companies (Neligan et al., 2022). By offering a detailed, stage-by-stage framework, this approach provides a more precise and effective method for achieving circular economy goals compared to the broader value chain approach, which tends to emphasise inter-company efficiency and cost reduction without the same level of detail regarding circularity at each stage of the product's life.

Second, by mapping digital twin across the product lifecycle, the framework establishes a clear connection between the type of digital twin, its level of integration, the corresponding lifecycle stage, and the enabling technologies required. For example, in the early design phase, a 'Digital Model' typically exists because there is no physical product yet to create a full digital twin. This digital model serves as a static representation that can be manually updated based on design changes or new requirements, using tools such as CAD/CAE systems. By identifying the capabilities of each type of digital twin at each lifecycle stage, the framework supports the corresponding circular strategies. For instance, in the design phase, products can be designed in a resource-efficient manner that aligns with the goals of the narrowing strategy, and they can also be designed using renewable materials, aligning with the greening strategy (Bocken et al., 2016; Konietzko et al., 2020). In the context of the EEE sector, digital twin capabilities can facilitate design for upgradability and reparability of electronic devices, thus supporting the extending strategy by making upgrades and repairs more accessible. To explore how digital twin support circular business models, a matrix was developed to identify the specific digital twin capabilities that enhance circular business values. The findings indicate that digital twin primarily contribute to the value creation process, while also indirectly influencing value proposition and value capture. However, due to constraints in resources and time, a more detailed analysis of the connections between these capabilities and business model elements at each stage of the product lifecycle was not possible, though it remains a potential area for further exploration.

Digital Twin Nexus Circular Business Model framework contributes to the theoretical understanding of CBMs by demonstrating how digital twin technologies can enhance the implementation of circular strategies. It provides a clear link between theoretical concepts and practical applications, showing how advanced technologies can drive sustainable practices in the EEE sector. For practitioners, the framework offers a roadmap for integrating digital twin into circular economy initiatives, highlighting specific actions and strategies that can be taken at each stage of the product lifecycle. However, its practical application requires careful consideration of technological readiness, resource availability, and data quality.

6.2 Framework Validation and Evaluation

In the process of validating the framework, several themes emerged as crucial to explore before evaluating the framework as a whole whilst answering the sub research questions.

6.2.1 Role of Digital Twin in Circular Economy

The first key theme revolves around understanding how digital twin is perceived by experts and what roles they play within the context of the CE. This theme is directly related to the first sub-research question:

How do different interpretations of digital twin technology influence its practical applications in supporting circular business models in the electrical and electronic equipment sector?

By exploring these perceptions, it becomes possible to discern the diverse ways in which digital twins are conceptualised and utilised, influencing their practical application and effectiveness in enhancing CBMs in the EEE manufacturing industry. Preut et al. (2021) introduced the concept of the digital twin for CE as a digitisation tool that ensures relevant product information is available to the right stakeholders at the right time. This study's findings support this view, particularly within the context of the CE. However, the role of digital twin in CE extends beyond merely decentralising information. The interviews conducted in this study reveal that digital twin can also transform this information into actionable insights that are critical for implementing sustainable CE practices. While the products discussed in these interviews were not exclusively EEE, the underlying concept aligns more closely with Wang & Wang's (2018) demonstration of digital twin's role in WEE recovery. In this context, digital twin acts as a bridge between the physical and digital worlds throughout the product lifecycle, from the early design stage to the end of life.

Digital twin enables a continuous flow of information at every stage of product lifecycle from beginning to end of product lifecycle and facilitates effective decision-making but also supports key CE strategies. The study also found that the application of digital twin at the end-of-life stage is rarely implemented or explored in depth. When it is addressed, the concept often differs in terms of synchronisation between the physical and virtual entities. At this stage, interaction with the product is typically limited to user actions, such as scanning a tag or digital ID, which connects the user to an application to update the product's status. This approach resembles more of a 'Digital Shadow' than a true digital twin, as changes in the digital state do not affect the physical state (Kritzinger et al., 2018).

With EU new regulations of Ecodesign for Sustainable Products Regulation (ESPR) (2024), this concept is more closely aligned with the Digital Product Passport (DPP). By acting as a digital ID, the DPP provides a centralised, accessible source of information for all stakeholders involved in a product's value chain. This supports better decision-making and ensures compliance with regulations. Moreover, the DPP can be a valuable complement to digital twin. While digital twin creates a dynamic representation of a product's lifecycle by syncing physical and digital data, the DPP provides a static but comprehensive overview of a product's sustainability credentials, materials, and compliance status. The information collected through the DPP can feed back into the design process, allowing companies to continuously improve products according to circular economy principles.

While many experts agree that digitalisation is crucial for advancing CE strategies, it is worth noting that digital twin is not a one-size-fits-all solution. Instead, digital twin should be seen as versatile tools that can be adapted to fit specific business needs, contexts, and sustainability goals. For some companies, digital twin might play a central role in monitoring and optimising every aspect of the product lifecycle, from design and production to end-of-life management. For others, especially those with less complex operations or limited resources, the benefits of implementing digital twin might not outweigh the costs or complexity involved.

6.2.2 Digital Twin in Supporting Circular Business Value

The second key theme, which is closely related to the second sub-research question, is:

How can the capabilities of digital twin technology be applied at various stages of the product lifecycle to enhance circular business models in the electrical and electronic equipment sector?

Understanding the capabilities of digital twin reveals how this technology can enhance various aspects of CBM strategies. Based on the interviews and literature review, it is evident that the capabilities of digital twins may vary depending on the type of digital twin being used. For instance, a digital model, which represents a physical entity that does not yet exist, has the capability to create a model and run simulations of a product before it is manufactured. On the other hand, a digital twin that fully represents a physical entity and is connected to it functions differently. In the usage phase, digital twins can monitor assets or products and detect when they are likely to experience faults. At the end-of-life phase, a digital shadow, which acts as a representation containing necessary data, can support CE practices by providing information that aids in recycling or repurposing efforts. This adds nuance to the previous study by Jones et al (2020), providing a deeper understanding of how different integrations of digital twins offer varying capabilities to support CE practices at different stages of a product's lifecycle.

The literature review and expert interviews reveal a range of capabilities associated with digital twins, including simulation and modelling, predictive analysis for maintenance and lifespan estimation, asset and product monitoring, remote control, and acting as a platform for information sharing among stakeholders. However, while digital twin can serve as platform networks to support sustainable business models (Li et al., 2020), this specific capability was not mentioned by the experts interviewed in this study. Therefore, further research is needed to explore this potential capability in more detail. According to Neligan et al. (2022), although digitalisation is a key driver of CBMs, digital technology is primarily used in the value creation process. This study supports this view, finding that the capabilities of digital twin mainly contribute to value creation, with only an indirect impact on value proposition and value capture. The interviews also reveal that digital twins are most often employed in the value creation of the narrowing strategy, a common approach for companies to reduce costs and increase profits by using resources more efficiently (Bocken et al., 2016). This strategy minimizes waste, which would otherwise lead to additional costs.

Overall, this study validates the concept of a structured framework that outlines how the capabilities of digital twin technology support the value components of CBMs. The findings demonstrate that digital twin enhances value creation by optimising resource use and extending product lifecycles, and they also indirectly impact value proposition and value capture. This framework helps to systematically understand the relationship between digital twin capabilities and CBM strategies, providing a comprehensive approach to leveraging technology for circular economy goals.

6.2.3 Enabling Technologies of Digital Twin

The capabilities of digital twin cannot be fully realised without supporting enabling technologies. This brings attention to the next key theme, which addresses the sub-research question:

How do enabling technologies facilitate the integration of digital twin with circular economy practices in the electrical and electronic equipment manufacturing sector?

Identifying these enabling technologies is essential for effectively implementing digital twin to support circular economy practices. Digital twin can differ in their level and type of integration, which means the necessary enabling technologies may vary depending on the specific application. The literature frequently highlights that digital twins are typically supported by Industry 4.0 technologies, with the IoT often identified as a core component. IoT facilitates the creation of digital representations of physical counterparts, which can be further enhanced by other technologies such as cloud computing, BDA, and AI (Kritzinger et al., 2018; Wang & Wang, 2018; Fuller et al., 2020). Although many experts recognize the role of Industry 4.0 technologies in enabling digital twins, some argue that specific technologies, such as IoT, are not always essential. What is critical is the ability to create a virtual entity that accurately represents the physical counterpart and performs necessary functions. This perspective suggests that the technologies used to enable digital twins can be flexible, as long as they achieve these fundamental objectives. This flexibility is crucial because it allows for a broader range of technological solutions to be adapted to various contexts within the EEE manufacturing sector. It highlights the importance of focusing on the functionality of digital twins rather than being restricted to specific technological components.

The findings from the study align with the proposed framework, showing that experts generally agree on the components needed to support digital twin technologies, such as data collection, data storage and processing, and data analytics. However, there is variation in how these technologies are implemented. As long as data can be effectively captured, processed, and shared, a digital twin can be developed. Moreover, for digital twins to provide maximum value across the entire product lifecycle, these technologies must be interconnected through a digital thread. This integration ensures that individual digital twins are linked, creating a cohesive system that benefits all stakeholders involved. Additionally, ensuring the secure sharing of collected data is critical, and technologies such as blockchain, or other security measures can play a crucial role in this aspect. The emphasis on interoperability and standardisation further highlights the need for a harmonised approach to maximize the potential of digital twins in supporting circular economy practices.

6.2.4 Challenges and Barriers

While digital twin offers a promising potential in supporting CBMs in EEE manufacturing sector, it also poses challenges the implementation. Thus, the next key themes and sub research question is:

What are the key challenges in implementing digital twin technology to support circular business models in the electrical and electronic equipment sector?

Through interviews there are several challenges that emerges when discussing implementation of digital twin CE purposes ranging from organisational to policy level. The findings indicate that the most prominent challenges lie in technological integration and data management. Experts consistently highlighted that successfully implementing digital twins requires a sophisticated technological infrastructure that integrates various components such as sensors, cloud computing, and big data analytics. This complexity reveals that digital twin ecosystems are not easily established; they require a modular and flexible integration framework to adapt to different use cases and systems effectively. This observation aligns with research by Qi et al. (2021) who argue that the lack of standardised frameworks for integrating diverse technologies complicates the development and implementation of digital twins. The difficulty in achieving seamless integration across these diverse technologies suggests that without standardised protocols and better interoperability solutions, the implementation of digital twins will remain fragmented and challenging.

Another significant challenge is organisational alignment and change management. The interviews reveal that deploying digital twin technologies successfully often depends on a clear organisational vision and strong leadership to guide the transition. This highlights the necessity for top-level alignment and strategic clarity; without these, efforts to integrate digital twins can become disjointed, lacking alignment with broader business objectives. Additionally, resistance to change from within the organisation, stemming from entrenched habits and varying departmental priorities, can significantly impede adoption. This shows that fostering a culture open to innovation and continuous learning is crucial for overcoming internal resistance and ensuring that digital twin initiatives align with the company’s strategic goals.

Data governance and security also emerged as critical challenges. Effective use of digital twins depends on the ability to manage data securely and responsibly, particularly when sensitive business information is involved. The need for robust data governance frameworks was emphasised by experts, who noted that issues related to data ownership, integrity, and the sharing of information across stakeholders must be carefully managed to maintain trust and reliability. This suggests that without stringent data governance practices, the effectiveness of digital twins could be severely compromised, as any unauthorised access or data manipulation could undermine their accuracy and reliability, as well as potentially expose proprietary information.

Lastly, regulatory challenges were identified as significant barriers to the adoption of digital twins for CBMs in the EEE sector. The evolving regulatory environment, particularly within the European Union, demands compliance with new laws and standards aimed at promoting sustainability, transparency, and resource efficiency. Directives such as the EU Waste Electrical and Electronic Equipment (WEEE) Directive (2018) and the ESPR (2024) set stringent requirements for the collection, recycling, and environmental performance of electronic products throughout their lifecycle. Digital twins have the potential to support compliance with these directives by providing accurate, real-time data on product use and lifecycle stages, facilitating better management of recycling processes and more efficient resource use.

However, integrating digital twin technologies to meet these regulatory requirements is not straightforward. The EU Circular Economy Action Plan and initiatives such as the DPP require enhanced product traceability and lifecycle transparency, which digital twins could theoretically support. But achieving this in practice involves overcoming substantial technical and organisational hurdles, such as developing new digital infrastructures, ensuring data interoperability, and protecting sensitive information across the supply chain. Additionally, the proposed EU Battery Directive (2006) emphasises the need for lifecycle tracking of batteries, presenting a clear use case for digital twins to monitor and optimize battery performance and recycling. Yet, as several experts noted, without a clear business case beyond compliance, such as reducing costs or enhancing product value, companies may be reluctant to invest in these technologies.

Overall, the findings from the interviews illustrate that implementing digital twin technology to support CBMs in the EEE sector is a multifaceted challenge. Addressing technological integration, fostering organisational readiness, ensuring robust data governance, and navigating regulatory landscapes are all crucial for realising the full potential of digital twins in driving circular economy initiatives. Developing strategies that holistically address these interconnected challenges will be key to successful digital twin adoption and utilisation.

6.2.5 Framework Evaluation

This brings to the last sub research question which is:

How can a framework be developed to guide electrical and electronic equipment manufacturing companies in integrating digital twin technology with circular business models across the product lifecycle?

This section further explores the developed framework that was initially discussed in section 6.1. Given the novel combination of digital twin technology and CBMs, expert interviews were conducted to validate the framework and assess its practical applicability.

In developing this framework, several limitations were identified that could impact its implementation in the EEE sector. Firstly, the reliance on digital twin technologies may pose a significant barrier for companies, especially those with limited technological capabilities or financial resources. Implementing advanced digital twin technologies requires substantial investment in infrastructure, training, and ongoing maintenance, which might not be feasible for all firms, particularly small and medium-sised enterprises (SMEs). This suggests that while the framework can be highly beneficial for large corporations with extensive resources, SMEs might struggle to adopt it fully due to these initial investment barriers.

Secondly, the framework assumes a high level of data availability and quality. In practice, however, data gaps, inconsistencies, or inaccuracies can undermine the effectiveness of digital twins, leading to suboptimal decision-making and reduced utility of the digital twin. The effectiveness of digital twins heavily relies on the accuracy and completeness of data throughout the product lifecycle. This assumption presents a significant challenge, as the data required may not always be readily available or of sufficient quality, particularly in companies that are not yet fully digitalised.

Additionally, while the framework categorises circular practices into distinct strategies, it does not account for the potential overlap and interaction between these strategies. In real-world applications, circular strategies may not be mutually exclusive; they often intersect and influence each other, requiring a more flexible and adaptive approach. The rigid categorisation could limit the framework's adaptability, as companies might need to implement a combination of strategies simultaneously to effectively transition to a circular economy model.

Feedback from the experts who reviewed the framework indicates that, overall, the proposed framework for integrating digital twin technology into CBMs is logically sound and offers a promising foundation for guiding EEE manufacturing companies. The experts acknowledged the framework's potential to facilitate a shift from linear business models to circular business models, highlighting its conceptual strength in bridging these two areas. However, experts also identified several areas for improvement to enhance the framework’s practical applicability. One of the key suggestions was to expand the framework’s coverage of enabling technologies. Experts recommended incorporating additional critical technologies such as the AAS, which plays a crucial role in data management and interoperability within digital twin systems. Including such technologies would enhance the framework's ability to handle diverse data sources and ensure seamless integration across different systems and stakeholders. Furthermore, experts emphasised the importance of incorporating real-world examples and business cases within the framework. This addition would help validate the framework's effectiveness and demonstrate its alignment with current industry practices. Real-world case studies could provide practical insights into the challenges and successes of implementing digital twins in CBMs, offering valuable guidance for companies looking to adopt the framework.

Another key area of feedback was the need for clearly defined success parameters and metrics to evaluate the framework’s effectiveness. Experts suggested that adaptability and continuous improvement mechanisms should be integral to the framework, ensuring it remains relevant in dynamic industrial environments. By establishing success criteria and enabling iterative improvements, the framework can better serve the evolving needs of EEE manufacturing companies as they navigate digital transformation and circular economy transitions. Additionally, considerations regarding data governance and ownership were raised, particularly in contexts involving multiple stakeholders. Clear processes for managing data throughout the product lifecycle are essential to address concerns about data security, privacy, and intellectual property. The experts pointed out that the framework should include guidelines for data governance to ensure that all stakeholders have a clear understanding of their roles and responsibilities in data management, thus enhancing trust and collaboration across the supply chain.

All in all, the expert insights support the framework’s potential as a foundational tool for integrating digital twin technology with CBMs in the EEE sector. However, these insights also provide a roadmap for future research and refinement, emphasising the need for the framework to be both theoretically robust and practically actionable. By addressing the identified limitations and incorporating the suggested improvements, the framework can be further developed to better meet the needs of industry professionals and facilitate more effective adoption of digital twins in the pursuit of circular economy goals.

7 Conclusion

7.1 Answering Main Research Question

The objectives of this study focused on developing a comprehensive understanding of how digital twin technology can support CBMs within the EEE manufacturing sector. Through a systematic approach that included an extensive literature review, the development of a conceptual framework, and validation through expert interviews, this research aimed to bridge existing gaps in both academic literature and industrial practice regarding the integration of digital twin capabilities into CBMs.

Beginning with a thorough review of existing literature, this study identified and analysed various applications of digital twin that support circular practices and CBMs. Although there is a growing body of work on both digital twins and circular economy principles, the intersection of these two areas remains poorly defined, especially regarding their practical implementation in EEE manufacturing from a business perspective. This ambiguity is partly due to the evolving nature of both digital twin technology and circular economy concepts. While there is still no universally accepted definition of a digital twin, this study was able to clarify and conceptualise how digital twins can facilitate CE practices throughout the product lifecycle. Addressing this gap is crucial for companies transitioning from linear to circular business models, as the role of digital technologies such as digital twins in this shift remains underexplored.

To address this challenge, a Digital Twin Nexus Circular Business Model framework was developed that specifically connects digital twin capabilities with CBMs strategy and its value elements. While several frameworks for CBMs exist, they often fail to incorporate the digital dimension that digital twins offer, especially beyond their basic simulation functionalities. Digital twins provide more than just simulation; they can exist throughout the entire product lifecycle and add value at each stage. With capabilities such as predictive analysis, sharing platforms, and product control and monitoring, digital twins can significantly reduce waste and extend product life. Additionally, existing frameworks typically fail to integrate these digital capabilities across the various stages of the product lifecycle, which is crucial for achieving a comprehensive circular approach. The developed framework links CBM strategies with the product lifecycle, incorporating digital twin technology based on the integration level and enabling technologies at each stage of the product's life. Digital twin capabilities were categorised and linked with the value elements of CBMs for each strategy. The framework was subsequently validated through eight expert interviews, demonstrating its applicability and alignment between theory and real-world scenarios and challenges in implementation. Key themes were identified using an inductive and deductive approach, followed by thematic analysis. Ultimately, the answers to the sub-questions provided a structured response to the main research question:

How can digital twin enable electrical and electronic equipment manufacturing firms to implement circular business models across the product lifecycle?

Digital twin technology enables the transition to CBMs in EEE manufacturing firms by providing a dynamic and integrated approach to managing products across their entire lifecycle. By creating a digital representation of physical assets, digital twins offer a comprehensive understanding of product behaviour, usage patterns, and environmental impacts, which are essential for implementing circular strategies. This technology facilitates circular strategies across various stages of the product lifecycle. During the design phase, digital twins allow companies to explore different configurations that prioritise material efficiency, durability, and recyclability. This ability helps firms design products that are easier to disassemble and recycle, directly supporting circular strategies such as closing and extending product lifecycles. In the usage phase, digital twins enhance product utilisation and lifecycle extension by enabling manufacturers to track and analyse how products are used over time. This capability supports strategies such as extending and intensifying, which aim to maximise the value and lifespan of products through better utilisation and maintenance informed by data gathered throughout the product’s lifecycle. Additionally, at the end-of-life stage, digital twins provide critical insights into the materials and components of a product, enabling more efficient recycling, repurposing, or remanufacturing processes. This optimises end-of-life strategies by ensuring valuable resources are recovered and reintegrated into the production cycle, reinforcing the closing strategy.

Beyond the individual product lifecycle, digital twins offer broader benefits across the value chain by enabling better collaboration and transparency among stakeholders. By creating a shared digital model accessible to suppliers, manufacturers, and customers, digital twins promote a more integrated approach to resource use and product lifecycle management, which aligns with the principles of a circular economy. Moreover, digital twins support the development of new business models and revenue streams, such as PaaS or leasing models, that keep products in circulation longer and reduce the need for new production, enhancing the firm's value proposition and long-term sustainability.

However, while digital twin technology offers significant opportunities for advancing circularity, its implementation comes with challenges. The complexity of managing large datasets and ensuring interoperability across different systems requires substantial investment in infrastructure and expertise. Furthermore, successful implementation demands a strategic vision that aligns digital twin capabilities with the company’s circular goals and fosters collaboration across the value chain to fully realise the technology’s potential in supporting circular business practices.

To enhance the understanding and application of digital twin technology in supporting CBMs, future research should focus on developing case studies and empirical research to validate the technology's effectiveness in real-world settings, particularly within the EEE manufacturing sector. Additionally, examining the comprehensive impacts of digital twin technology on the triple bottom line—economic, environmental, and social aspects—within the context of circular business models could also provide valuable insights for EEE firms. In conclusion, digital twin technology serves as a crucial enabler of digitalisation for EEE manufacturing firms seeking to transition to circular business models. By offering a holistic view of product lifecycles and supporting circular strategies, digital twins help firms enhance their sustainability practices and drive innovation in their business models.

7.2 Contribution to Research

This study provides a novel and comprehensive framework for understanding the role of digital twin technology within the circular economy from a business perspective, particularly in the EEE manufacturing industry. By addressing a significant gap in the literature, this research not only links digital twin technology with circular business models but also advances the field by offering a detailed and actionable framework that demonstrates how Industry 4.0 technologies, specifically digital twin, enable circular strategies across the entire product lifecycle.

While this research builds upon prior studies that explore digital twin and circular economy principles, it offers a unique perspective by integrating digital twin capabilities with the value elements of CBMs at each stage of the product lifecycle. Unlike the HCBMT framework, which overlook the comprehensive application of digital twin beyond simulation, this study presents an in-depth view of how digital twin functionalities, such as predictive analysis, resource optimisation, monitoring and control, supporting value creation, delivery, and capture within circular business strategies.

A central contribution of this study is the development of a Digital Twin Nexus Circular Business Model matrix that systematically connects digital twin capabilities with the value elements of CBMs. This matrix provides a clear, structured approach for companies looking to implement digital twin technology as a strategic tool for achieving circularity. It offers actionable insights into how digital twin capabilities can be harnessed at various stages of the product lifecycle to optimize resource efficiency, enhance product longevity, and reduce waste, thereby contributing to both economic and environmental sustainability goals.

Beyond the theoretical framework, this study offers a new lens through which to view the integration of digitalisation and sustainability, particularly in the context of Industry 4.0. By clarifying the role of digital twin in supporting CBM value elements, this research advances the understanding of digital twin's potential in business model innovation. Furthermore, the framework lays a solid foundation for future empirical research, providing a starting point for testing and refining the framework in real-world applications. Ultimately, this study contributes to the growing discourse on digital transformation in sustainable manufacturing, offering both academic and practical value.

7.3 Implications for Practice

The findings of this study have several implications for practitioners in the EEE manufacturing sector, particularly for those aiming to implement CBMs through the use of digital twin technology. Firstly, the developed framework provides EEE manufacturing firms with a strategic tool to better understand and implement digital twin technology in their pursuit of circularity. By clearly outlining how digital twin capabilities align with different stages of the product lifecycle and corresponding circular strategies, the framework enables companies to pinpoint where digital twin can most effectively support their specific circular goals. This allows for a more targeted approach to digitalisation, ensuring that investments in digital twin technology are closely aligned with the company's overall sustainability objectives. Secondly, the matrix connecting digital twin capabilities with the value elements of CBMs offers actionable insights that can guide decision-making processes. For companies considering the adoption of digital twin technology, this matrix serves as a practical reference for understanding the specific technologies needed at various stages of the product lifecycle. It also helps identify which circular strategies can be enhanced by digital twin, allowing companies to prioritize technological implementations that will yield the most significant sustainability benefits.

In conclusion, this study provides practical guidance for EEE manufacturing firms seeking to integrate digital twin technology into their circular business strategies. By adopting the framework and insights provided, companies can make informed decisions that support both their sustainability goals and their long-term business success.

7.4 Relevance to Management of Technology

This study is highly relevant to the Management of Technology (MoT) program, as it aligns with several key areas of the curriculum. Firstly, it demonstrates a comprehensive understanding of technology as a critical corporate resource, which is a central theme in MoT. Digital twin technology, as explored in this research, represents a significant innovation with the potential to drive sustainable practices and strategic business transformation. The study's focus on the integration of digital twin within circular business models (CBMs) highlight the practical application of technology in achieving corporate sustainability goals, which is directly relevant to the Technology, Strategy and Entrepreneurship course. This course emphasises the strategic use of technology to create and sustain competitive advantage, which is precisely what the adoption of digital twin within the circular economy (CE) aims to achieve.

Moreover, the study's exploration of digital twin technology as an emerging breakthrough aligns with the Emerging and Breakthrough Technologies. By examining the link between digital twin and circular business strategies, the study illustrates how cutting-edge technologies can enable new business models and catalyse industry-wide shifts towards sustainability. This is a key focus of the MoT curriculum, which seeks to equip students with the knowledge to identify, evaluate, and manage emerging technologies with transformative potential. The research methodology employed in this study reflects the rigorous application of qualitative research methods, which are covered in the Research Methods course. Furthermore, the study's insights into the implementation challenges and organisational alignment necessary for successful digital twin adoption directly relate to the Leadership and Technology Management course. This course emphasises the importance of leadership in driving technological change and managing the human and organisational aspects of technology adoption. The study highlights how leadership and effective management strategies are crucial for overcoming the barriers to digital twin implementation and achieving circular business objectives.

7.5 Limitations

Despite the promising insights generated by this study, several limitations must be acknowledged. First, the research is constrained by the emerging nature of digital twin and its application within the context of circular economy, particularly in the EEE manufacturing sector. This nascent stage results in a limited amount of existing literature and practical case studies, restricting the depth of theoretical exploration and empirical validation. Consequently, the literature review, while thorough, was constrained by the availability of comprehensive studies that fully integrate both digital twin and CE, especially in the manufacturing industry. This limitation may affect the robustness of the theoretical framework developed in this study.

Additionally, this study was conducted within a specific timeframe, which impacted the scope of data collection, analysis, and validation. Time constraints limited the ability to conduct longitudinal studies or gather a broader range of expert opinions, which could have provided deeper insights into the long-term impacts of digital twin on circular business models. Moreover, finding experts with in-depth knowledge in both digital twin and circular economy within the specific context of the EEE manufacturing sector proved challenging. As a result, the expert interviews, while insightful, were conducted with a small sample size, which may not fully capture the diversity of perspectives necessary for a comprehensive analysis. Additionally, some experts lacked direct industry-specific experience in the EEE sector, which may have led to findings that do not fully reflect the unique challenges and opportunities faced by manufacturers in this field.

The framework developed in this study has not yet been empirically tested in real-world settings, meaning that its practical applicability and effectiveness remain to be proven. There is a potential gap between the theoretical constructs proposed and the practical, operational realities of implementing digital twin technologies in manufacturing environments, which could vary significantly depending on the specific organisational context, technological maturity, and capabilities. While the framework integrates theoretical insights and expert opinions, its effectiveness in supporting circular strategies might vary when applied in different real-world scenarios, an aspect that this study could not fully account for.

Finally, the analysis may contain bias, as the interpretation of the data and the synthesis of findings were influenced by the researcher's perspective. These limitations suggest that the findings should be considered within the context of the study's constraints, and further research is needed to expand on the initial insights provided here.

7.6 Future Research

Given the limitations of this study, several rooms for future research are recommended to enhance and expand upon the current findings. First, the framework developed in this study could benefit from further refinement, particularly by incorporating the maturity levels of organisations as they transition to or begin operating within a CE. Understanding how different levels of organisational maturity affect the adoption and effectiveness of digital twin technology in CBMs would provide valuable insights. Additionally, future research should aim to establish a more standardised concept of digital twin, which is currently varied and lacks consensus. This standardisation could help in creating more consistent and comparable studies across different industries.

Moreover, future research should consider conducting case studies to further validate and refine the proposed framework. Case studies would provide practical insights and empirical evidence on how the framework performs in real-world scenarios, particularly within specific sectors such as the EEE manufacturing industry. Expanding the scope of empirical studies to include a larger and more diverse group of experts, ideally those with direct experience in both digital twin and CE within specific industries, would also enhance the robustness of the findings. Additionally, longitudinal studies could track the evolution of digital twin technologies and their impact on CE practices over time, offering a dynamic view of the relationship between these two fields. Finally, as digital twin and its enabling technologies continue to evolve, ongoing research should explore new technological advancements such as DPP and their potential to further enhance the sustainability and efficiency of CBMs.

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9 Appendices

Appendix I

Table 15 Overview of studies regarding digital twin capabilities in circular economy within EEE sector.

Author	Sample	Methodology	Digital Twin Capabilities	Enabling Technologies	PLC	Circular Practices	Limitations	Remarks
Wang, X. V. & Wang, L. (2018)	-	System development	• Serve as cyber-avatars for individual WEEE items, providing an integrated and dynamic representation of their status throughout their lifecycle, from design to recovery. • Facilitate personalised services and precise operations planning.	IoT, Cloud Computing, CPS, RFID, QR code	All	Rethink, Repair, Refurbish, Remanufacture Reuse, Recycle	• This approach heavily relies on stakeholder engagement, particularly from original producers who may be reluctant to share detailed product information. • The system requires robust security measures to protect data integrity and privacy.	No further research on the implementation.
Li, X. et al. (2020)	Haier Company in China	Single case study	• Enhance lifecycle management of product. • Real-time data integration and analysis across product life cycle. • Allows to predict, monitor, maintain and manage smart products and improve user experience. • Connects different layers of the business; from R&D and supply chain to manufacturing and customer service. • Allows mass customisation. • Resource optimisation through cross-border information sharing.	IoT, AI, Big Data, Cloud Computing	All	All	• Challenges in integrating diverse stakeholders and cultural elements into the digital twin framework. • Achieving full stakeholder integration and adapting the model to various cultural contexts are seen as areas needing further attention.	Only use single case study.

Author	Sample	Methodology	Digital Twin Capabilities	Enabling Technologies	PLC	Circular Practices	Limitations	Remarks
Rocca, R. et al. (2020)	Laboratory	Single case study, simulation	• Enables real-time monitoring and optimisation of WEEE disassembly processes through simulation tools.	AR/VR, IoT, CPS	MoL, EoL	Reuse, Repair, Refurbish, Recycle, Recover	The research notes that the real-time processing and simulation demands can require substantial computing resources, which may limit the scalability and feasibility in certain contexts.	Further research must be done with full scale and real-world scenario.
Andersen, T. & Jæger, B. (2021)	8 companies	Case studies	• Compliment transparent and secure data sharing across the product lifecycle in digital twin.	Cloud Computing, Distributed Ledger, IoT, Blockchain	All	Reuse, Repair, Remanufacture, Recycle	The research identifies the challenge of information fragmentation and the difficulty in ensuring consistent data sharing among various stakeholders. This affects the seamless application of the proposed model.	Need for more focused research and development to overcome the barriers to full integration and effectiveness of these technologies in promoting circular economy practices in the EEE sector.
Tozanli, Ö et al. (2020)	e-waste products	Discrete event simulation	• Enhances decision-making in trade-in strategies, optimises end of life product recovery through predictive analysis. It reduces uncertainties regarding the condition and lifespan of returned end-of-life electronic products, enabling better planning for repair, refurbishment, or recycling.	IoT, Blockchain	EoL	Repair, Refurbish, Repurpose Reuse, Recycle	There is complexities involved in technology integration and the unpredictability in assessing the quality of returned products, which could affect the efficiency of trade-in strategies.	While showcasing the potential benefits of digital twins in enhancing trade-in operations, the paper points out the necessity for further research to overcome the integration and predictive challenges for broader application success.
Li, J et al. (2022)	PCBs product	Case study and simulation	• Optimising each phase of the process from disassembly to end-refining. This approach allows for improved management and operation efficiency through the convergence of virtual and physical data.	Cloud Computing, IoT, Big Data Analytics, Simulations	EoL	Repair, Refurbish, Repurpose Reuse, Recycle	Complexity of integrating data from various sources and the need for significant computational power to handle real-time updates and simulations	Further research has to be done with full scale and real-world scenario.

Appendix II

The coding scheme derived from Table 12, which systematically categorizes and interprets data from expert interviews and literature reviews. The scheme was developed to facilitate structured thematic analysis, crucial for validating the research findings and ensuring their reliability. By referencing Table 12, this coding scheme directly links qualitative data to the quantitative analysis, highlighting the interconnectedness of digital twin technology applications within circular business models.

Table 16 Coding scheme

Aggregate Dimensions	2nd order Themes	1st order Themes
DT Nexus CBMs (Greening)	DT-Greening VP	Enable eco-friendly product (Wang & Wang, 2018).
	DT-Greening VCD	Simulate design and production with renewable resource (Wang & Wang, 2018; Rocca et al., 2020).
	DT-Greening VC	Cost saving from renewable resource usage (Rocca et al., 2020).
		Reducing operational costs through efficient use of renewable energy (Rocca et al., 2020).
DT Nexus CBMs (Narrowing)	DT-Narrowing VP	Simulate design with minimal resource and environmental impact (Wang & Wang, 2018; Rocca et al., 2020).
	DT-Narrowing VCD	Enable production optimisation with fewer resources (Rocca et al., 2020).
		Forecasting demand and adjusting production to reduce waste (Tozanlı et al., 2020).
		Streamlining production processes and reducing waste through automation and decision support (Rocca et al., 2020)
	DT-Narrowing VC	Reduce production cost from simulation and modelling (Wang & Wang, 2018; Rocca et al., 2020).
		Cost savings and efficient resource utilisation (Tozanlı et al., 2020).
DT Nexus CBMs (Extending)	DT-Extending VP	Facilitating predictive maintenance that ensures products remain in good condition over time (Wang & Wang, 2018; Rocca et al., 2020; Li et al., 2020).
		Reducing downtime and extending the product's useful life (Li et al., 2020).
	DT-Extending VCD	Simulate and model design for longevity and durability (Wang & Wang, 2018; Rocca et al., 2020).
		Enabling timely upgrades and reducing the need for replacements with continues monitoring (Li et al., 2020).
	DT-Extending VC	Profits from maintenance services based on the predictive maintenance (Li et al., 2020).
		Enhance customer loyalty by ensuring consistent product performance (Li et al., 2020).
DT Nexus CBMs (Cycling)	DT-Cycling VP	Enable design for disassembly (Wang & Wang, 2018; Li et al., 2022).
		Optimise best route for reverse logistics (Wang & Wang, 2018).

Aggregate Dimensions	2nd order Themes	1st order Themes
		Enabling effective reverse logistics and ensuring that products are returned for recycling or repurposing (Wang & Wang, 2018; Li et al., 2022).
	DT-Cycling VCD	Designing products for easy recycling or repurposing, ensuring that materials can be effectively reused (Wang & Wang, 2018; Rocca et al., 2020).
		Enabling closed-loop system with design for disassembly (Wang & Wang, 2018; Rocca et al., 2020).
		Forecasting the best times and methods for recycling and repurposing (Wang & Wang, 2018; Li et al., 2022).
	DT-Cycling VC	Reducing costs associated with new materials (Rocca et al., 2020).
		Creating new revenue streams from recycled products (Wang & Wang, 2018; Li et al., 2022).
DT Nexus CBMs (Intensifying)	DT-Intensifying VP	Designing products that are suitable for shared use and collaborative consumption (Li et al., 2020).
		Enhancing product adaptability for multiple users (Li et al., 2020).
		Ensuring that shared products are used and maintained properly (Li et al., 2020).
		Ensuring the products are efficiently distributed among users (Li et al., 2020).
	DT-Intensifying VCD	Optimising the use of shared resources by forecasting demand and usage patterns (Li et al., 2020).
		Managing the orchestration of shared services and ensuring efficient resource allocation (Li et al., 2020).
		Supports the creation and delivery of shared products by improving logistics and supplier coordination (Li et al., 2020).
	DT-Intensifying VC	Enabling dynamic pricing models based on forecasting demand and usage patterns (Li et al., 2020).
		Enhances customer satisfaction and loyalty by ensuring that shared products remain in good condition (Li et al., 2020).

Appendix III

Table 17 Thematic Analysis

Overarching Code	First Level of Code	Sub-Codes	Discussion Quotes
Digital Twin in Circular Economy	Enabler	- Building blocks	- "an integral part of all of these lifecycle elements of products" (P1) - "the digital twin is like a conjunction of several bricks that make up a complete house, although it's never fully completed" (P2)
		- Tool	- " digital twin itself is not an end; it's a tool. It helps in achieving something specific, such as remanufacturing or circularity. "(P2) - "This tool or software is used to estimate the performance of the products we design. It already includes the Bill of Materials (BOM) for the product and incorporates an environmental database related to the impact of each component within the product. This allows us to predict or calculate the environmental impact of the designs we create." (P8)
		- Data collection	- "help us acquire information to make decisions with proper data…Digital twin technology can help reduce this waste by providing the necessary information". (P2) - " Digital twin technology supports this by enabling better use of data collected over the years." (P5) - "We cater to these needs by making it easy to gather all information about products and workflows." (P3)
DT Nexus CBMs (Extending)	DT-Extending VP	- Predictive analysis to ensure the asset always in good condition	- "We can predict the lifespan of machines by analysing the vibration signatures of their components." (P4) - "We need to have a model to predict how long it will last." (P1) -" We then analyse what the results of the life cycle analysis model tell us. We might discover a "hotspot" or identify why a particular life cycle stage has a high impact, like during manufacturing or material procurement." (P8)
		- Personalised service through unique identifiers	- "Unique identifiers on products like washing machines can guide users and technicians through repairs and maintenance, providing personalised service." (P3)
	DT-Extending VCD	- Simulate and model design for longevity and durability	- " Because currently we're automating the construction of a pump, but we're not automating the deconstruction of the pump and reconstruction of the pump and if we want to do this at scale maybe we need to and here the twin comes in again. Design for refurbishments instead of design for sales." (P1)
		- Decision-making support for	- "I don't sell a pump, I sell throughputs and if my pump is degrading and I see this coming based on operational data, I'm going to schedule maintenance.

Overarching Code	First Level of Code	Sub-Codes	Discussion Quotes
		repurposing product based on the monitoring data	I'm going to take back this pump, replace it with another with high performance. And then once I take it back, there is a process for inspecting the quality, cleaning the pump. Maybe replacing certain parts to make it last longer, or to accept the degraded performance and to resell it to another company." (P1)
	DT-Extending VC	- Reduce indirect costs by preventing machine breakdowns.	- "However, when we talk about energy savings and the subsequent cost reduction [from predictive maintenance], the impact isn't immediately felt by them." (P4)
		- Enhance customer loyalty by ensuring consistent product performance	- "…brand benefits from customer loyalty, better tracking, and ensuring deposit returns. The retailer gains streamlined logistics processes. The washing facility gains new business from reusable packaging flows."(P3)
DT Nexus CBMs (Cycling)	DT-Cycling VCD	- Post-use monitoring	- "The digital twin can represent data generated after use and monitor it. In logistics for remanufacturing electronics, digital twin technology should allow for traceability." (P2)
		- Provide information for returning product	- "If you can define a way to pick, for example, a battery as an individual instance and request information about it from anywhere, it makes logistics and operations, such as repair or recycling, much easier." (P6) - "To ensure that packaging can be reused, you add a digital ID that is interactable and can be used as a digital channel to add services to it." (P3)
	DT-Cycling VC	- Enhance customer participation	- "Simplifying the return process: you just scan and get guided on how to easily return a certain package or product" (P3)
DT Nexus CBMs (Narrowing)	DT-Narrowing VP	- Modelling environmental impact	- "In the design phase, you're going to model... the production process and the efficiency of the production process, and the impact on nature (environment) that the production process will have." (P1)
	DT-Narrowing VCD	- Reducing resource consumption - Designing products and processes with minimal waste	-"Sometimes we don't really know what's going on and if we can extend the life of our product or use it in another application. Without this knowledge, we might just throw it away, generating waste. Digital twin technology can help reduce this waste by providing the necessary information." (P2)

Overarching Code	First Level of Code	Sub-Codes	Discussion Quotes
		- Stock forecasting to reduce waste	- "We can do stock forecasting... so that the buffer stock in the warehouse can be minimised. Because if there is over-inventory, raw materials can be wasted." (P4)
	DT-Narrowing VC	- Cost saving	-"For energy saving, we also have a smart lighting system where we save energy by adjusting the brightness of the lights". (P4)
CBM Values Greening Strategy	DT-Greening VP	- Support regulatory compliance	-"The concept is very close; what you call the greening strategy is like designing to be more eco-friendly, aligning with the Eco Design Directive. (P2)"
	DT-Greening VCD	- Simulate design and production with renewable resource.	-"if we find that sourcing a material, like aluminium from Supplier A, has a significant environmental impact based on our green digital twin simulation, we might discover from our global procurement discussions that there is another supplier offering aluminium produced with green electricity in a different country." (P8)
Enabling Technologies	Simulation and Modelling Tools	- 3D Modelling (CAD/CAM)	- "First, you need modelling tools to capture either physics knowledge or experience digitally into some kind of model." (P1)
	Data collection	- IoT - QR codes, NFC, RFID	- "For me, IoT is a means to collect data... but there are tens of other technologies out there that can also gather data." (P1) -" I think it's more in the Internet of Things (IoT). If you can measure the state of your products—like what's happening in the car industry or other industries—you can monitor them more closely. For example, you could detect if an engine needs repair before it breaks." (P7) - "We can also work with other carriers like RFID or NFC, but the main reason we love QR codes is that they are low-cost." (P3)
	Data storage	- Cloud computing	- "Cloud-based storage systems have the capacity to handle this data, and various intelligent solutions can analyse it and provide actionable insights." (P5)
	Data processing	- BDA - AI	- "...Similarly, AI is a tool to create models, but it is definitely not the only tool to create models. It's just one of the tools." (P1) - We recently published our Twin AI page, integrating new AI services. For instance, if you ask, "How do I repair this Miele device?" you get an answer. This makes your product a living object, providing relevant information." (P3) - "Analysing the data using business intelligence software, AI, and big data models. AI models, including GPT and LLM models, can enhance analytics, provided data security is maintained." (P5)
	Data integration	- AAS for standardised	- "An asset administration shell is a part of the digital twin, dealing with data

Overarching Code	First Level of Code	Sub-Codes	Discussion Quotes
		data formats	structure and formats. Standardisation ensures accessibility, findability, and interoperability, while regulations guide the usage and sharing of data among lifecycle partners.” (P2) - “Building this digital twin in a standardised way and making this information accessible to everyone is important…” (P6) - “But you have to put it into an environment capable of working with this digital twin, which sometimes involves huge data sets, accessible from everywhere but in a secure way.” (P6)
	Data security	- Blockchain	- "Blockchain can be part of it (digital twin), but it’s not the main technology." (P2)
	Connecting digital twins	- Digital thread	- "The emerging approach is the digital thread, where multiple digital twins are integrated to bring collective intelligence together." (P5) - "If you apply the digital thread, it will become more valuable." (P1)
Challenges and Barriers	Technological and technical challenges	- Integration issues	- “We have data-related technologies like industrial data spaces that aim for data to be findable, accessible, interoperable, and reusable (FAIR principles)... Standardisation ensures accessibility, findability, and interoperability, while regulations guide the usage and sharing of data among lifecycle partners.” (P2) - “Technical difficulties in integrating digital identifiers... into existing production workflows." (P3) - "Integrating digital twin with existing systems is often complex and time-consuming." (P4) -“ That’s the most challenging part because the data comes from all the different systems. It depends on how integrated your systems are because some companies have multiple ERP systems. The data is usually collected from these ERP systems.” (P7)
		- Insufficient relevant data	- “They have digital twin software in place, but the big problem is filling that software with enough relevant data.” (P3)
		- Design challenges	- "…by doing this, they are adding a lot of glue and other materials to the battery pack, making recycling extremely complex or even impossible. This means you can describe something with the digital twin, but when you want to operate, recycle, and put it into a circular economy, you might find that you can only burn the whole pack and cannot dismantle it to get the different pieces out." (P6)

Overarching Code	First Level of Code	Sub-Codes	Discussion Quotes
	Organisational Challenges	- Need for a clear vision and structure	- “First, establish a vision: "Our company will be headed this way. To make that happen, we need these innovations. This means your work will change in this way or that way." (P1) - "The overarching vision and mission need to be clearly articulated by the organisation." (P5) - “But more importantly, it [Circular Economy] should be part of the company’s strategy. This strategy must be backed by concrete programs and products that focus on how to change.” (P7) -“ Yes, once the top management has a clear vision, it can be communicated down the hierarchy.” (P8)
		- Organisational alignment	- "You need alignment at the top level to implement this successfully." (P3) - "Habit change and stakeholder resistance even though the vision is already [there]." (P4) - “If there’s already a strong understanding or awareness in the industry or ecosystem, it’s usually easier to introduce new concepts.” (P8)
		- Skills gap and unfamiliarity with digital twin	- "Many companies lack the expertise and experience needed to implement and utilise digital twins." (P1) - "Teaching them is extremely challenging...Teaching them to look at the information rather than manually inputting it." (P4) - "Many organisations lack this particular skill set." (P5)
	Data Governance and Security	- Data Ownership and Integrity	- "Who governs the information? Who has the right to certify it and make official records?" (P6) - "If you provide a certificate saying, 'These are the official data' and then someone hacks it and changes some entries, the whole system becomes absurd." (P3)
		- Balancing transparency with IP protection	- "Building this digital twin in a standardised way and making this information accessible to everyone is important but without providing competitive know-how." (P6) - "If the government were allowed to look into my company's internal data, then it would be war." (P6)
		- Data Security	- "Ensuring data security and privacy is a major challenge, especially when dealing with large amounts of sensitive information." (P5)
	Regulations Challenges	- Compliance cost	- "If they only want to do it for compliance, it doesn't make sense at the moment." (P3) - "The result of this battery law is to build this kind of organisation and neutral platform where everybody is forced to put the relevant information into this

Overarching Code	First Level of Code	Sub-Codes	Discussion Quotes
			environment." (P6)
		- Regulatory support	"There must be supporting regulations...there needs to be a market landscape or conditions that are conducive." (P8)
Evaluation	Practical Implication	- Feasible - Well defined - Support decision-maker	- “Sure, it's feasible and it's a way for decision-makers to decide what to implement. This is about deciding which components to use to build your new house. If you're focusing on operations and use, extending, or intensifying the lifecycle, you might not need RFID. This matrix helps to think about it.” (P2) - “I think this can be useful, but it needs to be focused. This framework is holistic, very comprehensive, which is amazing.” (P4) - “The way it has been depicted and aligned with the enabling technologies is very good. When we do these kinds of exercises, there is no end to delving into details, but sometimes it needs to be simplified to remain understandable and not too complex. So, it is quite good in that way.” (P5) - “Your framework shows that there are concrete benefits in designing, planning, manufacturing, and other stages. This helps people make decisions based on facts and benefits, rather than just reacting to regulatory pressure.” (P6) -“ It's interesting to see which technologies should be used at each life cycle stage and within each circular strategy” (P7) -“ I think it makes sense and is good.” (P8)
	Limitation	- Not self-explanatory - Not pragmatic enough	- “The framework should be explained with real-world examples to enhance understanding and make it more self-explanatory.” (P2) -“ If you want this framework to be useful from a business perspective, it should show how companies can use it. If a company knows what its circular strategy is, it should be able to relate that to what actions are needed at each life cycle stage” (P7) - “Usually, people in the industry want something pragmatic. Pragmatic in the sense that while they appreciate a holistic view, they also want to know what directly relates to their work.” (P4)
		- Maturity assessment	-“ Show the transition and maturity progression in areas like data, technology, process, people, and governance. This way, companies can see how their maturity in a linear economy context compares to a circular economy context.” (P5)
		- Ownership clarity	-“ in real life, the first question would be: on which server do you deploy your digital twin? You should have an answer for that. Perhaps it starts on the company's server and is then handed over to an official organisation. To

Overarching Code	First Level of Code	Sub-Codes	Discussion Quotes
			make your framework useful and applicable, you should at least address this kind of process." (P6)
	Improvement	- Use case	- "You should go a step further by showing real-world use cases or business cases in different markets. This will demonstrate that it works and provide a step forward to the community." (P2) - "Your framework will be more valuable if you add use cases in each enabling technology and its corresponding lifecycle stage" (P8)
		- Improve iteratively	"…never think that creating one system, one framework, or one product will be successful forever. That's impossible. There has to be something to serve as a reference for improvement. That's why the definition and success parameters also need to be tested and adjusted over time" (P4)

Appendix IV

Interview Protocol

I. Pre-interview Setup/Communication

1. Research Introduction: Begin by introducing myself and detailing the research's objectives and scope.
2. Overview of Research Questions: Provide a concise summary of the research questions and explain why the input from the interviewee is crucial to the study.
3. Confidentiality Assurance: Reassure the interviewee that their responses will remain confidential, and that any information gathered will be used exclusively for research purposes.
4. Consent Procurement: Secure the interviewee's consent to participate in the interview and to allow recording. An informed consent form will be sent to them a week before the interviews.
5. Setting Expectations: Describe the interview format, the expected duration, and any other relevant logistical details.

II. Interview Questions

Phase-1

1. **Introduction and Background**
    - Can you please introduce yourself and talk about your role in the place that you are currently working?
2. **Fundamental Understanding**
    - What is the first thing that comes to your mind when I say, 'digital twin' and 'circular economy'?
    - What are the core components/enabling technologies and functionalities/capabilities of a Digital Twin, in context of CE?
3. **Integration with Circular Strategies**
    - In your opinion, from business perspective, how can Digital Twin technology be integrated into the various stages of the product lifecycle (design, manufacturing, usage, and end-of-life) to enhance circularity?
4. **Business Perspectives**
    - How can Digital Twin technology transform business operations and strategies particularly in supporting the transition to Circular Economy?
5. **Expert Insights**
    - Based on your experience, what are the most important considerations when integrating Digital Twins with circular strategies?
    - Do you have any recommendations for practitioners looking to implement Digital Twin technology in their circular business practices?

Phase-2 Framework Validation

6. **Relevance:**
    - How applicable do you find the proposed Digital Twin framework for enabling Circular Business Models in the EEE sector?

7. **Challenges:**
    - What potential challenges do you foresee in implementing this framework within the EEE sector?

8. **Refinements:**
    - Are there any aspects of the framework that you think need further refinement or additional components?

9. **Integration:**
    - How well do you think the framework integrates Circular Strategies with Digital Twin capabilities across different lifecycle stages?

10. **Examples:**
    - Can you suggest any real-world examples or cases that align with the proposed framework?

11. **Barriers:**
    - What are the primary barriers to implementing Digital Twin technology in the EEE sector, especially for Circular Economy purposes?

12. **Additional Comments:**
    - Do you have any additional comments or suggestions for improving the proposed framework?
    - Is there anything else you would like to add regarding the role of Digital Twin technology in supporting Circular Business Models and Circular Economy principles?
    - Are there any other questions that you think I should have asked you?