Digital Twin-Enabled Circular Business Models

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Abstract
The transition to a Circular Economy within Industry 4.0 demands innovative approaches to integrate digital twin technology with business models. This PhD project investigates the value creation potential of digital twins in manufacturing and their implications for designing new circular business models. The first phase of the study focuses on analysing the interface between digital twins, business models, and Circular Economy to construct a theoretical framework and perform a cross-industry comparison of digital twins' value creation potentials in systems with varying complexity. The second phase of the research develops and validates digital twin-enabled circular business model patterns that can be applied across different industrial contexts. This study follows a Design Science Research approach including structured literature reviews, semi-structured expert interviews, case studies, and morphological analysis.

1. Introduction

1.1. Motivation and problem statement
The shift towards a Circular Economy (CE) becomes increasingly relevant, especially within the context of Industry 4.0 (I4.0), calling for conventional manufacturing processes to evolve into closed-loop and sustainable systems (He & Bai, 2021). This transformation involves rethinking product value chains and the development of circular business models (CBMs) that operate within circular value cycles (Behnert et al., 2024). Central elements to this transition are I4.0 technologies, data-driven mechanisms, and advanced digital infrastructures that support the generation, utilisation, and management of data across product lifecycles (Rosa et al., 2020). To cope with the resulting landscape, manufacturing firms are encouraged to reconsider their operational strategies and to increasingly adopt service-oriented business models (BMs), such as product-service-systems (PSS) (Thoben et al., 2017).
These developments also influence production planning and control (PPC) and the organisation of modern manufacturing systems, which are increasingly evolving towards autonomous and decentralised production networks (Antons & Arlinghaus, 2022a). Establishing the digital infrastructures required for such environments and addressing data-related challenges requires digital representations of physical products, equipment, and systems, namely Digital Twins (DTs). DTs enable the simulation, monitoring, and optimisation of products across their entire lifecycle, including design, manufacturing, distribution, use, and end-of-life stages (Tao et al., 2018). Through these capabilities, DTs support differentiation and new forms of value creation, positioning them, together with their associated business models, as potential enablers of CE strategies in the context of I4.0.

Despite the increasing attention given to DT technologies and their technical potential, a significant research gap remains regarding their implications for the design of new BMs within a CE context (Rosa et al., 2020). Existing studies predominantly analyse the technological capabilities of DTs, particularly their contributions to manufacturing optimisation and improved resource efficiency (Tao et al., 2018; He & Bai, 2021). However, these contributions are often examined from a technical perspective, leaving limited understanding of how DTs can be systematically embedded into BMs to enable circular value creation. Although the role of DTs in enhancing operational performance is widely recognised, their capacity to drive BM innovation across manufacturing industries from a CE perspective remains insufficiently explored. Consequently, research addressing the integration of DTs into specific BM configurations and analysing their economic, strategic, and operational implications for supporting the transition towards CE systems is still scarce.

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To address this gap, the overarching objective of the PhD research is to analyse the potentials of DTs for enabling value creation in manufacturing enterprises across different industry sectors, using the CE as the central analytical lens. Thus, the objective leads to the guiding research question: *How can digital twins enable value creation in manufacturing enterprises across different industry sectors?*

1.2. Theoretical background

1.2.1. Digital twins (DTs)

DTs depict their real-world counterparts, e.g. through detailed simulation models of the functional attributes of the physical object (Arlinghaus & Antons, 2022b). According to Tao et al. (2018), DTs are characterised by three core features: (1) real-time synchronisation with their physical counterparts; (2) interaction and convergence between the virtual and physical environments, including embedded devices and data flows; and (3) the capability for self-evolution through continuous data updates that enable progressive system improvement.
By providing real-time virtual digital representation of products throughout their lifecycle, DTs can enhance transparency and control over product use, maintenance activities, and end-of-life processes. This capability can consequently promote more efficient resource utilisation and facilitate circular practices such as reuse, recycling, and remanufacturing (He & Bai, 2021; Preut et al., 2021; Tao et al., 2018; Wang & Wang, 2019). Furthermore, DT-based data can generate valuable insights for diverse stakeholders, e.g. regarding environmental performance, to support decision-making processes, improve product design for longevity and recyclability (Lim et al., 2020; Tao et al., 2019), and foster innovative CBMs (Preut et al., 2021; Rosa et al., 2020).

1.2.2. Business models (BMs)

A BM depicts how an organisation creates, delivers, and captures value (Gassmann et al., 2014; Teece, 2018). In rapidly evolving digital environments, BMs play a fundamental role in translating the potential of emerging technologies, such as DTs, into economically viable value propositions (Geissdoerfer et al., 2017; Riesener et al., 2023; Teece, 2018). Technological innovations alone do not generate value unless they are embedded within fitting BM configurations. Hence, it is the alignment between technological capabilities and suitable BMs that drives new forms of value creation and competitive advantage (Riesener et al., 2023; Burger et al., 2023a; Burger et al., 2023b).

In this context, the shift towards servitisation, supported by the core elements of I4.0, such as decentralisation, real-time capability, and interoperability, plays a fundamental role in the CE transition (Ghobakhloo, 2020). This landscape transformation encourages firms to move from product-centric to service-oriented BMs, leveraging DTs and other digital technologies to offer innovative BMs, e.g. smart product-service systems (PSS), performance- and usage-based contracting, and manufacturing as a service (MaaS) (Ghobakhloo, 2020; Kohtamäki et al., 2020; Minerva et al., 2020).

1.2.3. Implications of DTs for BMs: prior research

Recent studies identify diverse industrial applications of DTs, particularly within manufacturing sectors (Enrique & Soares, 2022; Lim et al., 2020). In this context, DTs may enable diverse data-based service offerings (Qi et al., 2018; Stecken et al., 2019; Tao et al., 2018). One of the key value propositions associated with DTs lies in their capability to optimise products, processes, and services, which may consequently enable new BMs, such as equipment as a service or predictive maintenance (Klostermeier et al., 2018; Oettl et al., 2023). For example, Gain (2021) emphasises a synergy between digitalisation and business strategies, outlining data-driven strategies as primary drivers for transparency and flexibility in DT systems. Similarly, Stecken et al. (2019) describe a DT platform for data-driven services in product development processes.

DT technologies may also influence different components of BMs. Lim et al. (2020) argue that DT adoption can support more effective strategic resource allocation, enhance customer experience through intelligent product–service offerings, and stimulate innovation in manufacturing, procurement, and financial models aimed at increasing value creation. These developments may also contribute to CE strategies within I4.0 contexts. In particular, DT capabilities facilitate the transition from traditional product-centric offerings towards smart Product–Service Systems (PSS) (Enrique & Soares, 2022; Kampker et al., 2019; Uhlenkamp et al., 2020; Wilking et al., 2021).

However, despite these technological and operational potentials, the construction of BMs specifically designed around DT technologies remains hitherto insufficiently explored (Rosa et al., 2020). Thus, it is still unclear where DTs can generate the greatest value and how these benefits can be systematically linked to CE strategies (Lim et al., 2020; Timperi et al., 2023). Although lifecycle data generated through DTs are increasingly recognised as valuable, research efforts addressing how DT integration can support BM innovation across the entire product lifecycle is limited (Timperi et al., 2023; Zheng et al., 2018). From a CE perspective, particularly little attention has been given to the role of DTs in end-of-life (EoL) activities from a BM perspective (Lim et al., 2020).

1.2.4. Synthesis: the interface between DTs, BMs and CE

DTs have the potential to act as enablers in I4.0, offering real-time data integration, lifecycle management, and process optimisation, which are essential for achieving CE goals such as resource efficiency and waste reduction (Tao et al., 2018; He and Bai, 2021). However, the full potential of DTs can only be realised through their strategic incorporation into BMs designed to support circular practices. BMs may provide the structure through which the value generated by DTs is captured and scaled, particularly in transitioning from traditional product-based models to service-oriented ones like smart product-service systems (PSS) (Gassmann et al., 2014; Ghobakhloo, 2020). Despite the technological advancements of DTs, a significant gap exists in understanding their integration into BMs that directly facilitate CE (Lim et al., 2020; van der Veen et al., 2023). This synthesis underscores the need for research that bridges this gap, exploring how DTs can drive business model innovation in circular, automated, and smart manufacturing systems. This research includes a structured literature review to better understand this gap. The review confirmed the growing academic focus on the intersection of DTs, BMs, and CE but highlighted the need for deeper exploration of how DTs can be effectively integrated into BMs that promote CE practices.

2. Procedure and methods

2.1. Research design

This research follows a design science research approach, which enables the systematic development of solutions to complex real-world problems (Hevner et al., 2004). As illustrated in Figure 1, the research process combines knowledge development and empirical investigation in an iterative manner. Phase 1 focuses on building the knowledge base and analysing the industrial environment, while Phase 2 aims to design and validate digital twin-enabled circular business model (DTCBM) patterns.

2.1.1. Phase 1. Knowledge base development

The knowledge base is constructed through structured literature reviews following the guidelines of Sauer and Seuring (2023). First, initial structured literature reviews are carried out to explore key thematic intersections within the research topic, including i) DTs and BMs as well as ii) DTs and Data Spaces (DS). Additionally, an umbrella structured literature review is conducted to integrate and synthesise the broader bodies of knowledge on CE, BMs, and DTs. Combined, these reviews provide the necessary conceptual and theoretical foundation of the research by shedding light on the main interfaces between the core domains, identifying relevant research gaps, and supporting the development of the initial theoretical framework.

2.1.2. Phase 1. Analysis of the industrial environment

To complement the knowledge base with empirical insights, we adopt an exploratory multiple-case study design following Yin (2003), with integrated semi-structured expert interviews. Heterogeneous manufacturing firms are investigated as case studies, selected to capture different levels of product complexity, variant diversity, and product value. The case studies have an explorative nature and adopt a case-comparison approach. A multiple-case study is an effective approach for unexplored topics in which the main goal is to answer “how” research questions (Yin, 2003). The main units of analysis are manufacturing firms that 1) apply digital twin technologies and 2) employ CE-strategies at the product level. The units of observation are domain experts within these firms. To complement these cases, recycling or remanufacturing firms are included as external informants. They provide insights into CE implementation and collaboration with manufacturers, with a focus on product return, reuse, component recovery, remanufacturing, and data exchange requirements. The empirical data are analysed using the Gioia method (Gioia et al., 2013) to derive technological, organisational, and business model-related prerequisites for Digital Twin adoption. The results inform the development of a theoretical framework inspired by Kubicek (1976) and support the formulation of hypotheses and preconditions for DT adoption to enable CE strategies.

2.1.3. Phase 2. Research: development and validation of digital twin-enabled circular business model patterns (DTCBMs)

Building on the theoretical and conceptual foundations of DTs, BMs, and CE, we follow the approach of Gassmann et al. (2014) and integrate the approach of morphological analysis of Lüdeke-Freund et al. (2019) to construct the DTCBM-patterns in manufacturing. Morphological analysis helps to structure and examine multi-dimensional and complex cases (Lüdeke-Freund et al., 2019; Álvarez & Ritchey, 2015), making it ideal for understanding the intricate relationships between DTs, BMs, and CE strategies. The Business Model Navigator by Gassmann et al. (2014) complements this by offering a structured framework to innovate and explore new business model combinations. Considering the limited empirical evidence currently available on this research topic, the initial DTCBM patterns are developed through a deductive approach. While taxonomy approaches such as Nickerson et al. (2013) are useful for classifying existing business models, morphological

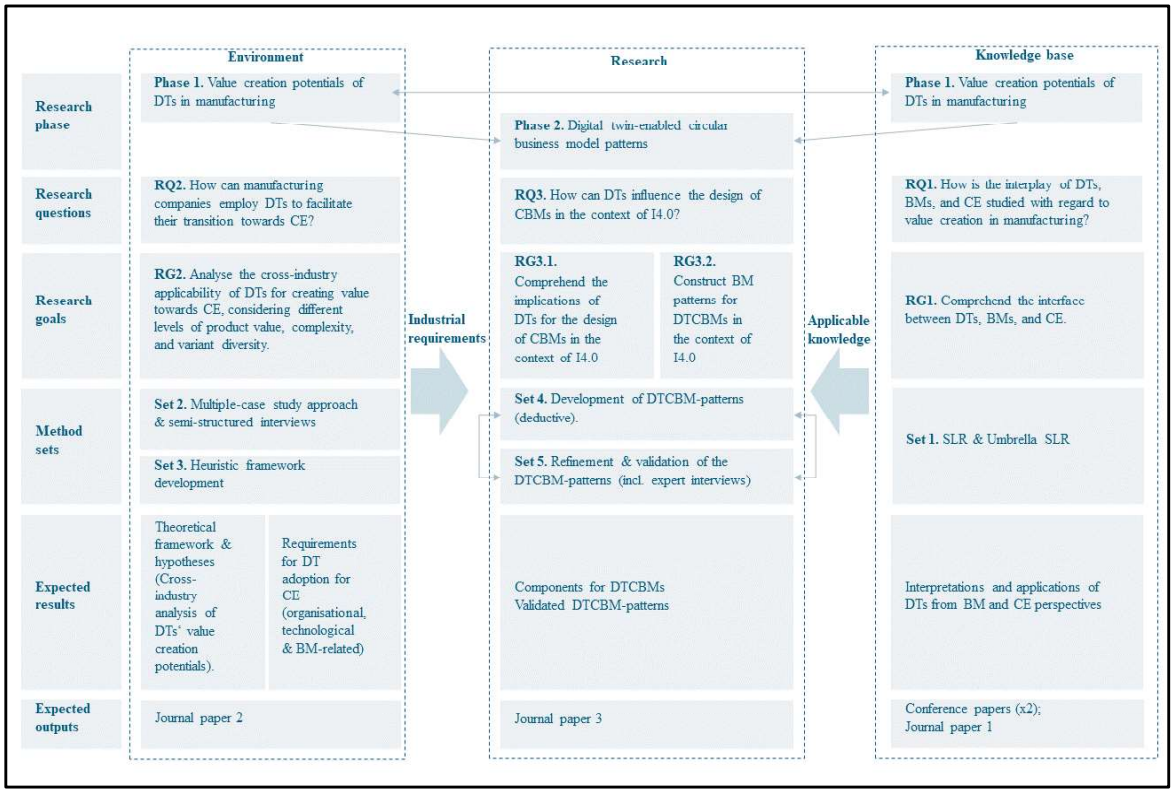

Figure 1: Research design of the PhD project

analysis enables the systematic exploration of possible configurations, fostering innovation while ensuring practical relevance through the Business Model Navigator framework.

3. Results and discussion

3.1. Value creation potentials of digital twins for business models

Initial results of the PhD project derive from a conference paper presented at the INCOM 2024 conference in Vienna, Austria (Torres Adelsberger et al., 2024). The study conducted a systematic literature review to explore the intersection of DTs and BMs within the context of Industry 4.0. We applied a CE lens to analyse 34 academic articles and derived eleven categories of potential digital twin-enabled business models: smart product-service systems, circular business models, smart maintenance, freemium with add-ons, smart manufacturing, performance- and usage-based contracting, data-driven digital services, collaborative business models, digital twin-based metaverse platforms, subscription, and urban digital twin-business models. To structure the derived categories, we drew upon the framework Business Model Navigator (Gassmann et al., 2014). Moreover, to refine the analysis of value creation potentials linked to the CE, we integrated insights from the Circular Ecosystem Patterns framework (Takacs et al., 2020).

These initial findings suggest that DTs have the potential to support servitisation by promoting the creation of tailor-made configurations of products and services across product lifecycles, which consequently may increase operational efficiency and customer satisfaction in manufacturing sectors (Torres Adelsberger et al., 2024; Thoben et al., 2017; Kampker et al., 2019; Enrique & Soares, 2022; Zheng et al., 2018). Furthermore, the results highlight data as a central resource that can be leveraged by DTs to create value within industrial settings (Torres Adelsberger et al., 2024; Uhlenkamp et al., 2020; Timperi et al., 2023; van der Veen et al., 2023). In other words, DTs may maximise data from products, machinery, and customers to execute effective industrial processes within complex I4.0 systems, promoting the creation of data-driven digital services (Torres Adelsberger et al., 2024; Uhlenkamp et al., 2020). Moreover, recurring challenges related to standardisation, interoperability, and issues of data ownership, sovereignty, privacy, and security continue to limit the practical implementation of the identified BMs (Torres Adelsberger et al., 2024; Kuenzel et al., 2019; D'hauwers et al., 2021).

3.2. Interaction between digital twins and data spaces

Building on the previous findings that identify data as a fundamental resource for DT-enabled value creation, we conducted an additional literature review to explore the potentials for promoting CE strategies emerging from the interaction between DTs and governance-based infrastructures for secure data exchange, such as data spaces (DS). This study was presented at the SysInt 2025 conference in Bremen, Germany (Torres Adelsberger et al., 2026). Specifically, we analysed

32 publications to explore how the integration of standardised digital twins, namely Asset Administration Shells (AAS), with DS may support circular value creation in manufacturing. We consequently derived a conceptual framework that identifies four key propositions:

1. AAS-DS integration enables digital product passports (DPP) through standardised product data and a secure infrastructure for data exchange
2. AAS-DS integration into manufacturing platforms enables CE by fostering cross-firm lifecycle data exchange, traceability, and collaboration
3. AAS-DS integration supports B2B marketplaces for manufacturing services and second-life components and materials by promoting secure data exchange
4. AAS-DS integration generates a trusted, regulated exchange environment that supports business model innovation via data-driven services

A critical imbalance appears between the conceptual rationale of DS and their practical implementation. Specifically, while DS are framed as decentralised infrastructures for sovereign data exchange, their actual value relies on the active participation of a sufficient number of players ready to share data under specific governance and access conditions. Thus, a participation dilemma may arise: broad participation is required to generate value, yet such participation remains difficult without already established value, trust, and incentives (Torres Adelsberger et al., 2026; Berg & Wilts, 2019; Jacoby et al., 2021; Otto et al., 2022). Additionally, aligned with the logic of shared production, data-driven BMs in the context of DS have the potential to go beyond pure financial transactions, e.g. by fostering the exchange of production tasks or (over)capacities to enable reallocation of underused resources across decentralised systems. Despite that conceptual synergies between AAS and DS are frequently mentioned, both domains continue to stay largely disconnected in the literature, with AAS research primarily focusing on product-level data models and DS research concentrating on cross-organisational data exchange infrastructures (Torres Adelsberger et al., 2026; Otto, 2022; Pettenpohl et al., 2022).

4. Limitations and conclusion

4.1. Next steps and expected results

As outlined in Section 2, this research builds upon a Design Science Research approach with an iterative nature (see Figure 1). In Phase 1 we develop the knowledge base and analyse the industrial environment in parallel, while in Phase 2 we focus on the design and validation of digital twin-enabled circular business model patterns. Complementing the achievements already presented in this paper, we expect the following results:

- Phase 1 – Knowledge base: interpretations and applications of DTs from BM and CE perspectives
- Phase 1 – Environment: a) theoretical framework and hypotheses for cross-industry analysis of DTs´ value creation potentials, and b) requirements for DT adoption for CE (organisational, technological, and BM-related)
- Phase 2 – Research: validated configurational patterns for digital twin-enabled circular business models

4.2. Research limitations and contributions

We acknowledge diverse limitations for this PhD project. First, we utilise a predominantly qualitative and exploratory research design based on literature reviews and conceptual development that relies extensively on expert-based insights. Second, our scope focuses on the manufacturing sector, thus, the applicability of the findings to other industries may remain limited. Third, the project deliberately chooses the perspective of manufacturing firms as the main unit of analysis, which may overlook relevant considerations from other actors within circular ecosystems.

With this PhD project we aim to contribute to both academia and industry. From a scientific perspective, the development of a theoretical framework integrating DTs, BMs, and CE perspectives may provide a foundation for further interdisciplinary research. From an industrial perspective, the identification of DTCBM-patterns aims to support manufacturing firms in exploring practical innovation opportunities for data-driven and circular value creation.

4.3. Concluding remarks

In this paper we present the research design and initial results of the ongoing PhD project investigating how digital twins can support circular value creation through business model innovation in manufacturing. The findings indicate that DT research still focuses predominantly on technical aspects, while their implications for business models and Circular Economy strategies remain comparatively underexplored. Moreover, the results highlight the central role of lifecycle data and data governance mechanisms for enabling data-driven services, servitisation, and circular value creation across product lifecycles.

From an exploitation perspective, the research aims to translate these insights into specific digital twin-enabled circular business model patterns and practical implementation guidance for manufacturing firms. These configurations are intended to support companies in identifying opportunities for data-driven services and circular value creation. Future research can therefore focus

on empirically validating the proposed concepts and further refining the business model patterns through industry case studies.

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