Research article

Twin Transition: Synergies between Circular Economy and Internet of Things – A Study of Danish Manufacturers

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Handling Editor: Kris Hartley

Received: 11 October 2022 / Accepted: 7 November 2022

Abstract

The relation between digital technologies of the industry 4.0 agenda and the circular economy agenda is being coined as mutually beneficial in the twin transition agenda. However, the agenda is in a pre-paradigmatic stage where the dual relationship is primarily discussed at a conceptual level. At the same time, manufacturers are challenged in building sustained performance improvements from either transition. Therefore, this study adopts the multiple case study methodology for investigating the synergetic relation between the internet of things (IoT) and the circular economy (CE) in ten Danish manufacturers as representations of the constituting constructs of the twin transitixon agenda. Accordingly, this study proposes two empirically based propositions for the synergetic relationship between the two: IoT enables the circular economy engagement from the cumulative build-up of data capabilities and their connection to particular value propositions. At the same time, the value and purpose of digital technology are elevated to a strategic perspective when adopting circular economy as a design parameter.

Keywords: Industry 4.0; industrial sustainability; barriers; enablers; closed-loop supply chain; business model innovation; maturity; cumulative capability

1. INTRODUCTION

The combination of circular economy (CE) and industry 4.0 (I4.0), known as the 'Twin Transition', is argued to be vital in ensuring the competitiveness of European countries (European Commission, 2022). Companies pursuing the two agendas in conjunction are estimated to be "2.5x more likely to be among tomorrow's strongest performing businesses than others" (Ollagnier, 2020). The relation between the two industrial agendas lies in the complementing roles of CE as an economic model, while the I4.0 represent a lever to reach new levels of competitiveness. Therefore, the processual perspective underlying the twin transition builds on the idea of cumulative capabilities (known from, e.g. Flynn & Flynn (2004)). Cumulative capabilities are found when two or more capabilities build on each other and become mutually reinforcing, in this case, when the implementation of elements of CE and I4.0 benefits from one another and reach a higher level of performance, as called for in the EU report related to twin transition (European Commission, 2022).

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CE is a multi-faceted agenda addressing the entire organisational eco-system to de-couple economic growth from resource consumption (Kjaer et al., 2019). CE considers the internal company perspective (including the business model, product design, and operations), the external supply chain perspective (including the reverse logistics and collaboration with external partners), and the institutional context perspective (including the legislation, standards, and the potential financing options) (Uhrenholt et al., 2022b). I4.0 represents a series of intelligent technologies that serve as new levers for manufacturers in achieving competitiveness through the generation, analysis, and use of digital data to support and perform business processes (Colli et al., 2021b). In particular, the internet of things (IoT) is arguably the backbone of digital transformation due to its capability to enable the interconnectedness of systems through increased transparency (Haddud et al., 2017). Furthermore, the IoT enables improvements in collaboration and communication across supply chain partners (Zhu et al., 2018), which are becoming increasingly important in pursuing CE (Mishra et al., 2018). For this reason, this study refers to the relation between CE and IoT as the twin transition, as this link has been emphasised in literature (Colli et al., 2021b).

Recent research shows that manufacturers face challenges when implementing new agendas like IoT and CE. Garms et al. (2019) find that manufacturers achieve lower success rates in implementing IoT than other innovation projects (16% and 25%, respectively). The primary barriers hindering the successful implementation are reported to be negative or unclear business cases. Other findings suggest that manufacturers are too operational in evaluating IoT implementation while neglecting the tactical and strategic potentials enabled by its introduction (Colli et al., 2021a; Lassen & Waehrens, 2021). In the domain of CE, studies of barriers to implementation are prevailing in recent literature. The barriers are multiple and are hence clustered into varying groupings making the systemic nature of the agenda present. Ayati et al. (2022) reviews extant literature and find that the implementation of CE is challenged by seven groupings of barriers present in both the macro-, meso-, and micro-economic perspectives (Urbinati et al., 2021). Among the multitude of barriers to organisational implementation, the lack of data (Kirchherr et al., 2018), inadequate information and knowledge concerning product life cycle conditions (Agyemang et al., 2019; Ayati et al., 2022), and technology for integrating data and communication among stakeholders (Campbell-Johnston et al., 2019; Lindkvist Haziri et al., 2019) are widely acknowledged as primary constraints for the engagement into the circular resource loops and servitised business models.

While the twin transition argues that the simultaneous and synergetic implementation of IoT and CE will mitigate their individual barriers, the maturity of the academic discourse is at a pre-paradigmatic phase. As an example, the title of the agenda is not agreed upon, as it is referred to as the twin transformation (Ollagnier et al., 2020), the twin transition (Ortega-Gras et al., 2021), or mainly not coined at all. Furthermore, the extant literature presents a rather one-way relation, focusing on how IoT can enable the CE agenda (e.g. Rejeb et al., 2022) while enabling IoT based on CE remains unexplored, e.g. how analytics capabilities can enable CE (Kristoffersen et al., 2020). Accordingly, the calls for further research within this domain are plentiful. Most predominantly, calls are made for empirically based studies (Ayati et al., 2022; Kirchherr et al., 2018; Rosa et al., 2020) concerning the role of IoT in enabling circular resource flows, eco-design, and servitised business models (Kirchherr et al., 2018; Rejeb et al., 2022), the empirical studies within the domain further calls for research into the area of data management and analytical capabilities (Ingemarsdotter et al., 2020). To acknowledge these calls for research and to explore the twin transition agenda empirically, this study seeks to explore whether and how manufacturers are balancing and experiencing synergies between the IoT and the CE. This is explored through the following research question:

How do synergies between IoT and CE enable manufacturers to engage with the twin transition agenda?

The study aims to explore the synergies between the IoT capabilities and the CE strategies by identifying the synergies between the two halves of the agenda. Here, the aim is to enable and inspire other manufacturers to overcome the widely reported barriers of both IoT and CE implementation by adopting the twin transition agenda in their pursuit of increased and sustained competitiveness. From the academic perspective, the contribution of this study is to aid in maturing the novel domain of twin transition and theorising the mutually beneficial relationship between IoT, as a representative of digital technologies, and the CE.

The remainder of the paper is structured as follows: Section 2 reviews the extant literature, focusing on exploring the IoT capabilities and barriers, as well as the CE strategies, business model and barriers; Section 3 describes the research methodology; Section 4 presents the findings and the discussion, focusing on the synergies between IoT and CE along with their temporal perspective; Section 5 presents the concluding remarks of this study.

2. LITERATURE REVIEW

This literature review aims to identify the capabilities, barriers, and expected synergies in and between the IoT and the CE principles, as these provide the theoretical frame for analysing the empirical cases. The theoretical frame used for the analysis is summarised in Table 1 at the end of the section.

2.1 Internet of Things – IoT and analytics capabilities and barriers to implementation

Extant literature synthesising the capabilities and barriers for IoT and its implementation is plentiful. The questions of IoT capabilities concern what to achieve from utilising the newly acquired data, while the data analytics capabilities concern how to integrate the technology into the operations system. The IoT capabilities have been summarised by Ingemarsdotter (2019) regarding the usage of the technology; tracking, monitoring, control, optimisation and design evolution. Similarly, data analytics capabilities (Gartner, 2022) specify the information the data provide to stakeholders and the support the analytics provide for decision-making, i.e. descriptive, diagnostic, predictive or prescriptive. These capabilities are summarised and described in Table 1.

The barriers to IoT implementation are multiple (e.g. Singh, R. & Bhanot, 2020) have synthesised the various barriers identified in the literature and divided them into four groupings; Governance-, operational-, device-and data and architectural barriers. Among the many barriers hindering the implementation, the most predominant are those related to the operational perspective, concerning the business value and integration and operationalisation of data in existing operations. For example, Lassen & Waehrens (2021) finds that a vast majority of manufacturers working towards capturing the benefits of Industry 4.0 do so from a 'cost reduction' perspective, while only some organisations perceive the 'extended potential' of implementing I4.0 technologies, and very few work with these technologies with innovation as the primary strategic driver (Lassen & Waehrens, 2021). Consequently, Colli et al. (2021a) argue that managers should make a shift in mindset concerning the business case evaluation for investments into I4.0 (Colli et al., 2021a). They argue that the dimensions of the temporal (i.e. short vs. long-term value pay-back) and the locational value (i.e. direct vs. indirect applicability of learnings) should be determining in such investments rather than traditional X-year pay-back business cases. Hence, in transformational engagement, manufacturers are driven by capturing quantifiable value from their investments in the short-term while partially neglecting long-term strategic learning and development. Singh & Bhanot (2020) provide a synthesis of IoT barriers, as presented in Table 1.

2.2 Circular Economy – Strategies and barriers to implementation

The CE strategies are predominantly defined according to the notion of circular resource flows. For example, Bocken et al. (2016) defined ‘slowing, closing, and narrowing’ resource flows as extending product lifetime, taking products back, and using fewer resources in each product life cycle. Konietzko et al. (2020) later extended this, who added the ‘regenerating and inform’ strategies, referring to the use of clean energy and materials and the supporting use of data in optimising the other four strategies. For the theoretical frame, Ingemarsdotter (2019) defined six circular strategies within the ‘in-use’ and ‘looping’ categories, which propose a similar perspective, and are presented in Table 1. In addition to the emphasis on CE strategies, the business model innovation according to the CE principles is present in recent literature. Here, Tukker (2004) define eight archetypes of product-service systems, divided between three orientations; product-, use-, and result oriented. These are presented in Table 1.

As with IoT, CE initiatives have proven difficult to implement (Werning & Spinler, 2020). As a result, companies struggle to rethink business models through the lens of CE to harmonise environmental, economic, and societal agendas (Geissdoerfer et al., 2017). Several studies have identified barriers to CE (e.g. Guldmann & Huulgaard, 2020; Masi et al., 2018; Ormazabal et al., 2018; Werning & Spinler, 2020). These studies argue that barriers to CE appear on multiple levels, internally and externally (Urbinati et al., 2021), and can be categorised into several clusters (De Jesus & Mendonça, 2018). Aside from numerous barriers, their interrelatedness creates a complex interplay of uncertainties (Kirchherr et al., 2018), which causes companies to stick to linearity. To exemplify the multi-faceted nature of the CE barriers, Ayati et al. (2022) compile a comprehensive list of barriers within seven dimensions used for the theoretical frame and presented in Table 1.

Table 1 – Theoretical frame for case analysis

Area (author)	Levels	Definitions
IoT capabilities (Ingemarsdotter et al., 2019)	Monitoring	Information is available about a product's use, condition, or environment. This includes alerts and notifications.
	Tracking	Information available about a product's identity, location, or unique composition.
	Control	Product functionality can be controlled through software, based on predefined options. This includes pushing regular updates.
	Optimisation	Goal-based improvements of operations are supported by advanced algorithms.
	Design evolution	The design of a product or service can be improved based on data feedback from other lifecycle phases. This includes functional upgrades as well as the development of new products and services.
Data analytics capabilities (Gartner, 2022)	Descriptive analytics	What happened? I.e. Simple data visualisation
	Diagnostic analytics	Why did it happen? I.e. Data mining cross-referencing data
	Predictive analytics	What will happen? I.e. Probability is added to the data to predict outcomes or calculate uncertainties
	Prescriptive analytics	What should I do? I.e. Intends to calculate the best way to achieve an outcome
IoT barriers (Singh & Bhanot, 2020)	Governance	Long pay-back period, challenges in business model, regulatory and legal issues, lack of investment
	Operational	Issues of data centric, device management problem, need for talent and expertise, data handling, scalability issues
	Device	Problems of device standardisation, sensor calibration, issues of power efficiency of devices, issues of common software, device obsolescence, device flexibility, safety of physical devices
	Data and Architecture	Cyber Security, privacy, traffic characterisation and QoS support, lack of validation and identification, lack of internet infrastructure, network architecture
CE strategies (Ingemarsdotter et al., 2019)	Efficienct in use (In-use)	Energy, water, and other inputs are used more efficiently during a product's use phase.
	Increased utilisation (In-use)	Time periods during which a product is not used by anyone are identified and reduced.
	Product lifetime extension (In-use)	A products lifetime is extended by minimising wear, through predictive, preventive, or reactive maintenance and repair, or through updates.
	Reuse (Looping)	A product or component is identified, assessed, and transferred from one user to another. The process can involve maintenance steps, such as cleaning.
	Remanufacturing (Looping)	A product is inspected and treated to restore its original functionality, as a preparation for the next use cycle. The process can include reparations and replacements of worn parts.
	Recycling (Looping)	The constituent materials of a product or component are assessed, sorted, and treated so that they can be used again.

CE business models (Tukker, 2004)	Product oriented Use oriented Result oriented	Product related, advice and consultancy Product lease, -renting, and -pooling. Activity management, pay per service unit, functional result.
CE barriers (Ayati et al., 2022)	Technology	Compatible technology, quality assessment and control, tracking take-back initiatives, lack of mature technology for adopting a recovery approach, sorting and collecting EoL products, mature technology for integrating data
	Information, Knowledge and skills	Integrating data between entities, information about life use conditions, adopting a recovery approach, training workforces, public sector education, standards, reliable information, using feedback
	Economic and finance	Source/capability and incentive to invest, risk of low profits and long time to pass the break-even point, cost of circularity, final price of a recovered product, the low-cost penalties and surcharges
	Market	Take-back challenges from other companies, standards for recovered products, price gaps between un- and authorised market, the market for selling recovered EoL, unpredictable supply and demand, location of markets and consumers, brand issues and reputation, after-sale supports and lower lifecycle time
	Organizartion	Leadership and management, priority of the organisation, reliability along the supply chain, simultaneous transition, structure or communication methods, reluctancy, resource capacity
	Governments and regulations	Supportive regulations, legislating rules to define indicators and the evaluation system, policy to drive society and evaluate its partnership, integrity between governments and management systems in a country or a region, a lack of adopting circularity, the wrong focus of regulation
	Society and culture	Consumers' unwillingness to choose recovered products, price sensitivity, security and reliability to return the EoL product, public education, awareness, and any social norms

3. RESEARCH METHODOLOGY

According to the twin transition agenda, this study aims to explore the synergies between the IoT and CE in simultaneously pursuing the two. Due to this purpose's explorative nature and the novelty of the twin transition phenomenon, the case study methodology is considered suitable (Yin, 2009). Furthermore, case study methodology is not constrained by the limits of questionnaires and models for which the case study can provide new and creative insights while having high validity with practitioners (Voss, 2010). Multiple cases benefit this study, as they provide multiple, potentially varying perspectives of the phenomenon in question. Furthermore, the risk of observer bias is reduced by observing multiple cases, while the external validity is strengthened through multiple viewpoints (Karlsson, 2010). In summary, this is known as theory building through case studies, in which the purpose is to identify and describe variables and their linkages (Karlsson, 2010). To facilitate the validity and reliability of this study, a research protocol of the research design is developed, see Figure 1 based on the theoretical frame and used for the data collection and analysis (Yin, 2009).

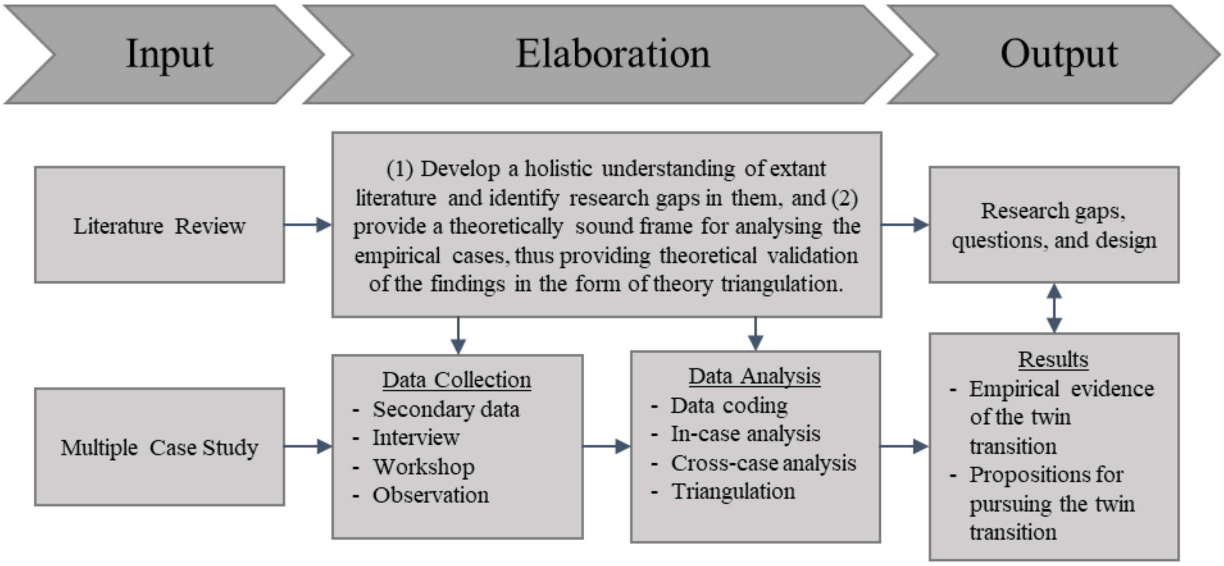

Figure 1 – Research design

The selection of appropriate cases is essential for case study research (Eisenhardt, 1989; Yin, 2009). The industrial cases identified for this study are selected according to purposive (also known as judgmental) sampling technique, meaning the cases provide a setting that enables the collection of the required information (Taherdoost, 2016). For this study, the following selection criteria have defined the selection of cases: case companies should (a) be manufacturing companies that have embarked on the twin transition agenda, (b) involving the introduction of IoT, (c) in the pursuit of performance improvements of products or processes that align with the principles of the CE. Furthermore, an element of convenience sampling technique is present in this study, as the selected cases are well-known to the authors due to their existing, and in most cases long-lasting, collaboration with the university. This relationship between the case companies and the research team provides a solid understanding of the industrial contexts.

Table 2 provides a descriptive overview of the case companies. While some companies (F, G and H) have substantially more employees, the studies have been conducted in a single business unit working with this agenda, suggesting a representative unit-of-analysis.

The industrial cases were engaged for over 3-6 months per case. The research team collected data during the project through company visits, interviews, and workshops. The company visits (two to three visits per company) allowed for an understanding of the company operations, specifically those within the scope of introducing IoT technology. The interviews were conducted with production and supply chain manager and lasted approximately one hour each. Two interviews were held for each company, one at the beginning and one at the end of the project period. These were guided by protocols framing semi-structured interviews concerning (a) the development of IoT capabilities and CE value proposition, (b) the barriers experienced in both the perspective of IoT and CE implementation, and (c) the relation and synergies between the IoT and the CE domains. In addition, three half-day workshops, with two to four company participants (CEO, CTO, production manager, supply chain manager), were held at each industrial case to facilitate a discussion of points a-c from the interviews. The first workshop explicitly focused on the operations mapping and analysis of the existing operations design. The second workshop concerned different operations design potentials according to the IoT solution and the required information flow to facilitate the design. The third and last workshop concerned the final technological solution and assessing the changed performance and criticalities in the operations. An elaboration of the workshop process can be found in Colli et al. (2021b).

Table 2 – Overview of selected case companies

Company	Employees Approx..	Industry (ISIC[1])	Product
A	100	Manufacture of other special-purpose machinery (2829)	Auto lifts
B	300	Manufacture of metal-forming machinery and machine tools (2822)	Automation manufacturing equipment
C	50	Manufacture of other pumps, compressors, taps and valves (2813)	Industrial Pumps for liquids and pulp (not water)
D	50	Manufacture of machinery for food, beverage and tobacco processing (2825)	Automation manufacturing equipment for fish processing
E	200	Manufacture of other general-purpose machinery (2819)	Industrial ventilation systems
F[2]	19.000	Manufacture of dairy products (1050)	Transport equipment for dairy manufacturing
G[3]	20.000	Manufacture of other pumps, compressors, taps and valves (2813)	Industrial and domestic pumps
H[4]	40.000	Manufacture of electric motors, generators, transformers and electricity distribution and control apparatus (2710)	Frequency converters
I	200	Manufacture of machinery for mining, quarrying and construction (2824)	Excavator buckets
J	50	Manufacture of motorcycles (3091) Manufacture of bicycles and invalid carriages (3092)	Cycles fitted with an auxiliary engine Invalid carriages with or without motor

[1] The International Standard Industrial Classification of All Economic Activities (ISIC)
[2] Focus is on their transportation equipment
[3] Study made for one product group
[4] Study made in one business unit

4. FINDINGS AND DISCUSSION

In order to explore the synergies between the two parts of the twin transition phenomenon, it is essential to investigate the capabilities, strategies, and barriers of the individual agendas that the case companies pursue and experience in their engagement with the agenda. Table 3 presents the findings of the individual cases, according to the theoretical frame presented in table 1. The cross-case analysis is presented in the subsequent sections (4.2, 4.3, and 4.4).

Table 3 - Findings from the ten cases according to the theoretical frame.

		Company A	Company B	Company C	Company D	Company E
IoT and Data Analytics	IoT capability (Ingemarsdotter et al., 2019)	Monitoring	Monitoring	Control	Monitoring	Control
	Data Analytics capability (Gartner, 2022)	Descriptive	Descriptive Diagnostic	Prescriptive (decision automation)	Descriptive	Prescriptive (decision automation)
	Long-term IoT strategy (Ingemarsdotter et al., 2019; Gartner, 2022)	Monitoring Predictive	Monitoring Predictive	Optimisation Predictive	Monitoring Prescriptive (decision support)	Optimisation Predictive
	IoT barriers (Singh & Bhanot, 2020)	-Need of talent and expertise -Data handling -Lack of investment -Issue of data centric	- Need of talent and expertise - Lack of investment - Data handling	-Need of talent and expertise -Data handling -Challenges in business model	-Need of talent and expertise -Data handling -Challenges in business model	-Data handling -Challenges in business model -Issue of data centric
CE strategy	CE strategy (Ingemarsdotter et al., 2019)	Increased utilisation	Increased utilisation	Increased utilisation Efficiency in use	Efficiency in use	Efficiency in use
	Long-term CE strategy (Ingemarsdotter et al., 2019; Tukker, 2007)	Looping Product lease	Looping Activity management	looping Functional result	Efficiency in use Functional result	Efficiency in use Functional result
	CE barriers (Ayati et al., 2022)	-Quality assessment and control -Lack of mature technology for adopting a recovery approach -Integrating data between entities -Information about life use -Adopting a recovery approach -Reliable information -Source/capability and incentive to invest -Risk of low profits and long time to pass the break-even point -Leadership and management -Reluctancy	- Information about life use conditions - Adopting a recovery approach - Source/capability and incentive to invest - Lack of mature technology for adopting a recovery approach	-Mature technology for integrating data -Information about life use condition -Adopting a recovery approach -Priority of the organisation	-Information about life use conditions -Reliable information -Integrating data between entities -Final price of a recovered product	-Mature technology for integrating data -Information about life use condition -Reliability along the supply chain -Adopting a recovery approach -Priority of the organisation

		Company F	Company G	Company H	Company I	Company J
IoT and Data Analytics	IoT capability (Ingemarsdotter et al., 2019)	Tracking	Monitoring	Control	Monitoring Tracking	Monitoring
	Data Analytics capability (Gartner, 2022)	Descriptive	Diagnostic	Prescriptive (decision automation)	Descriptive	Descriptive
	Long-term IoT strategy (Ingemarsdotter et al., 2019; Gartner, 2022)	Tracking Diagnostic	Optimisation Prescriptive	Optimisation Prescriptive	Monitoring Diagnostic	Monitoring Predictive
	IoT barriers (Singh & Bhanot, 2020)	-Long pay-back period -Issue of data centric -Issues of power efficiency of devices -Need of talent and expertise -Data handling -Network architechture	-IoT operating conditions -lack of customer interface	-Issue of data centric -Data handling	-Problem of device standardisation -Issue of data centric -Issues of power efficiency of devices -Challenges in business model -Need of talent and expertise -Data handling -Safety of physical devices -Lack of internet infrastructure	-Issue of data centric -Issues of power efficiency of devices -Need of talent and expertise -Data handling -Lack of investment
CE strategy	CE strategy (Ingemarsdotter et al., 2019)	Product lifetime extension	Efficiency in use	Efficiency in use	Product lifetime extension	Product lifetime extension
	Long-term CE strategy (Ingemarsdotter et al., 2019; Tukker, 2007)	Product lifetime extension Product renting/sharing	Looping Functional result	Looping Product leasing Functional result	Looping Advice and consultancy Product lease	Increased utilisation Product renting/sharing
	CE barriers (Ayati et al., 2022)	-Reliable information -Source/ capability and incentive to invest -Risk of low profits and long time to pass the break-even point -Final price of a recovered product -After-sale supports and lower lifecycle time	-Lack of mature technology for adopting a recovery approach -Quality assessment and control -Information about life use condition -Adopting a recovery approach -Cost of circularity -Priority of the organisation	-Tracking take-back initiatives -Information about life use conditions -Adopting a recovery approach -Final price of a recovered product -After-sale supports and lower lifecycle time -Leadership and management -Priority of the organisation	-Information about life use conditions -Adopting a recovery approach -Reliability along the supply chain	- Quality assessment and control - Integrating data between entities. - Information about life use conditions - Using feedback - Reliability along the supply chain - Structure or communication methods - Resource capacity - The wrong focus of regulation - Public education, awareness, and any social norms

4.1 IoT- and data analytics capabilities

Across the cases, one distinct difference is seen concerning the scope for which they are implementing IoT technology, which appears to be strongly influential on IoT- and data analytics capabilities. The cases approach the implementation of IoT from either a monitoring/tracking perspective (A, B, D, F, G, I, J) or a control perspective (C, E, H). In the monitoring/tracking perspective, the explicit scope of the IoT implementation is to improve an operational process, e.g. monitoring the use phase to increase efficiency and service operations. The control perspective concerns the direct performance of the product, such as actively changing the settings of the products based on the input to improve efficiency. Regardless of the scope, the IoT technology is designed and fitted onto the products using existing or retrofitted sensors. As presented in table 4, the monitoring/tracking versus control scope leads to specific data analytics capabilities being chased. A common denominator across all cases is the relative immaturity of the existing analytics capabilities. The process-oriented cases adopt simple descriptive visualisation of data and diagnostic correlation between few data sources, while the product-oriented adopt simple rule-based prescriptive analytics allowing their products to act according to simple measures of, e.g. liquid density (case C), humidity (case E), or weight (case H). From the long-term perspective, the cases intend to increase their analytics capabilities while they stay within the same IoT capability (case A^2, B^2, D^2, F^2, I^2, J^2) or move from the control capability to the more sophisticated optimisation capability (case C^2, E^2, H^2). Only case G^2 intends to make a drastic move from monitoring to optimisation.

Table 4 – Synthesis of correlation between IoT capabilities and data analytics capabilities (some cases appear twice due to multiple purposes from the same IoT device). X^2 represent the long-term ambitions of IoT and data analytics capabilities

		IoT capabilities (Ingemarsdotter et al., 2019)			
		Monitoring	Tracking	Control	Optimisation
Data analytics capabilities (Gartner, 2022)	Descriptive	A, B, C, D, I, J	F, I		
	Diagnostic	B, G, I^2	F^2		
	Predictive	A^2, B^2, J^2			
	Prescriptive	D^2		C, E, H	C^2, E^2, G^2, H^2,

In the implementation of the IoT technology, the case company reported a series of varying yet similar barriers that hinder the implementation or cause delays due to the need for additional analysis or the need to review the decision with stakeholders, as is presented in table 5. In summary, the two most frequently mentioned barriers originate from the novel need to treat and work with *data*- and *business*-related concerns. The *data*-related barriers concern the novel need for organisations to become more data centric, i.e. where data is used actively to guide operations development. Specifically, the cases express concerns about handling the data generated from the IoT device, e.g., linking the data inputs to the product application (case E). The *business*-related concerns involve the issue of investment, pay-back time, and the need to change the business model to capture the newly developed business potential. Among the challenges, the general immaturity of the industries is found to be limiting the customer buy-in for these solutions (e.g. case E). The remaining barriers are contextually dependent, e.g. for products and IoT devices that are not stationary, the cases expressed concerns for the devices' power efficiency and the fragility of the network architecture. At the same time, the smallest companies investigated expressed a lack of talent and expertise internally; these are summarised in table 5.

Table 5 – Barriers to the implementation of IoT technology

Barrier category	Barriers (Singh & Bhanot, 2020)	Case
Data	Data handling, Issue of data centric	A, B, C, D, E, F, G, H, I, J
Business	Lack of investment, Challenges in business model, Long pay-back period	A, B, C, D, E, F, I, J
Contextual	Need for talent and expertise	A, B, C, D, I, J
	Device specific (power efficiency, network architecture, device management, safety of devices, standardisation of devices, internet infrastructure)	F, G, I, J

4.2 CE strategies

All cases are currently pursuing the in-use CE strategies, focusing on optimising current products in the market, as in table 6. Across the cases, the individual company's choice of strategy aligns. For example, in the ambition of increasing utilisation, both case A and C initiated their introduction of IoT from the realisation that their current maintenance activities are inefficient (being unable to resolve issues immediately, going back and forth to customers, and excessive use of spare parts), from the lack of insight into the performance and health of the machinery at the customer. This results in increased customer downtime, as the companies cannot anticipate the maintenance and spare part needed before the breakdown. Case D introduced IoT to improve efficiency in pursuit of increased efficiency. Their machinery is processing high quantities, meaning that minor performance losses are costly in wasting potentially saleable products. Additionally, any breakdown in the machinery results in large amounts of waste, as any unprocessed product in the machinery must be discarded from a health and safety perspective. Pursuing an extended product lifetime, Case F provide the packaging and transportation equipment (i.e. roller cages) for the entire industry within their sector in Denmark. This means that the equipment leaves the company's control, while the ambition is that the natural flow of products and the supporting equipment will return to the company's custody. However, the company experienced a substantial loss, as a share of the equipment was never returned to their custody. In the long-term perspective, all cases, except case I^2, argue for moving away from the product-oriented business model. Many of these intend to do so through looping strategies (case A^2, B^2, C^2, D^2, G^2, H^2). Accordingly, they aim at de-coupling their resource consumption from their value creation through the provision of different value propositions.

Table 6 – Synthesis of CE strategies. X^2 represent the long-term perspectives of the CE strategies and business models

		CE strategies (Ingemarsdotter et al., 2019)			
		Efficiency in use	Increase utilisation	Product lifetime extension	Looping
CE business models (Tukker, 2004)	Product-oriented	C, D, E, G, H	A, B, C	F, I, J	I^2
	Use-oriented		J^2	F^2	A^2, H^2, I^2
	Result-oriented	D^2, E^2			B^2, C^2, G^2, H^2

Related to implementing CE strategies, the identified barriers can be clustered into four distinct categories: Business model/operations design, Data, Governance/risk averse, and Cost/value. These are presented in table 7. Relative to the IoT barriers, where the cases were varying in their perception of barriers, the cases are more aligned in their perception of barriers hindering their CE implementation. All cases report that they experience barriers in the categories related to the changes in the business model/operations design, the need for and use of data and information concerning the products in their lifecycle, and the governance of CE initiatives, including the lacking incentive from internal and external stakeholder to engage and prioritise the efforts in this agenda. However, the category concerning the cost and value of CE strategies is only present in a selection of the cases, which are the large case companies.

Table 7 – Barriers to the implementation of CE strategies

Barrier category	Barriers (Ayati et al., 2022)	Case
Business model / Operations design	Adopting a recovery approach, After-sale supports and lower lifecycle time, Lack of mature tech for adopting a recovery approach, Using feedback, Structure or communication methods	A, B, C, E, F, G, H, I, J
Data	Quality assessment and control, Integrating data between entities, Information about life use conditions, Reliable information, Mature technology for integrating data, Tracking take-back initiatives	A, B, C, D, E, F, G, H, J
Governance / Risk averse	Source/capability and incentive to invest, Leadership and management, Reluctancy, Priority of the organisation, Reliability along the supply chain, resource capacity, The wrong focus of regulation, Public education, awareness, and any social norms	A, B, C, E, F, G, H, I, J
Cost / Value	Risk of low profits and long time to pass the break-even point, Final price of a recovered product	D, F, G, H

4.3 Synergies between barriers and capabilities across the IoT and the CE

Similar to the relation between the IoT capability and the data analytics capabilities, a relation, although slightly weaker, is found between the IoT capability and the CE strategy pursued, as presented in table 8. All three cases that are pursuing increased efficiency in use through control capabilities are doing so from the product perspective, i.e. they are incorporating rule-based optimisation to their products to increase their efficiency when operating in their given environment. The same one-to-one relation is found between the tracking capability, which is only deployed in the pursuit of product lifetime extension, e.g. case F is tracking the movement of their transportation equipment to locate equipment that has been lost in the normal flow of the equipment, and hence they can re-collect the equipment rather than investing in new. Conversely, the monitoring capability is utilised for all three CE in-use strategies. While this is indicative of the industrial relevance of monitoring capabilities, especially considering that it has previously been reported as the most utilised capability in other studies (e.g. Ingemarsdotter et al., 2019), it may also be indicative of the low digital maturity of the industry, as this capability is to the least complex data analytics capabilities, as presented in table 8.

Table 8 – Correlation between IoT capabilities and CE in-use strategies

		IoT capabilities (Ingemarsdotter et al., 2019)		
		Monitoring	Tracking	Control
CE strategies (Ingemarsdotter et al., 2019)	Efficiency in use	D, G		C, E, H
	Increased utilization	A, B		C
	Product lifetime extension	I, J	F, I	

Across the cases, it is evident that a primary barrier to CE implementation is the need to gain insight into market products to enable the cases to engage in data-driven decision-making according to the circular principles. Specifically, most cases call for information about the products' life use conditions (case A, C, G, H, I, J) to enable the optimisation of their products directly when in the market (case C, E, H) or for optimising activities around the product, such as service and maintenance activities (case A, D, I, J). Subsequently, the need for technology for assessing and controlling the quality of products is present (case A, G, J), along with the concern for the reliability of data and information (case A, F, I). These barriers are all being addressed from the implementation of IoT technology, which is also well-recognised in the extant literature, e.g. see Rejeb et al. (2022) for a thorough review of the enabling role of IoT in the CE agenda. However, while the IoT is a catalyst for organisations to realise the need for this information, the barriers across the IoT and the CE implementation suggest a general immaturity in working with and making decisions based on data. The IoT barriers concerning the data handling (case A, C, E, F, H, I, J) and being data centric (case A, E, F, G, H, I, J) along with the CE barrier of the reliability of information (case A, F, I), suggests that the cases are not using data actively in their operations. Additionally, trust in data as reliable sources for decision making is low, e.g., case E expresses concern about how the data inputs can be translated to product application parameters.

Aside from the challenge of handling and incorporating data into the operations design, the primary barrier for the IoT implementation concerned the magnitude of business value, and its realisation, because of the newly generated insight and improvement potential from the data. For the investigated cases, it is observed that they engage in the twin transition from an operational perspective, i.e., the initial scope of the projects initiated by the cases frames specific problems that need solving. These problems negatively influence the current performance, creating a sense of urgency. This approach to adopting IoT reflects the findings of both Lassen & Waehrens (2021) and Colli et al. (2021a) that organisations adopt an operational approach in introducing digital technologies, limiting the realisation of tactical and strategic potentials from these.

However, once the case companies elevated their scope from the operational challenge they were facing, the perspectives of the discussion changed. The concern of the actual operational activity, e.g., the process flow of the maintenance activities and the traditional 2-year pay-back, was replaced with the strategic ambitions of adopting circular flows of products while de-coupling the resource consumption from the value creation through business model innovation. E.g., case I started from operational issues such as warranty claims and ended with future strategic ambitions of moving towards a serviticed business model, incorporating looping strategies (case A, B, C, D, H, G).

Using the terminology of Ingemarsdotter et al. (2019), Tukker (2004), and Gartner (2022), synergies between the IoT capabilities and the CE strategies can be shown in figure 2. The transformations of the empirical cases can be traced in figure 2, where the change in short-term and long-term twin tranistion scope for the empirical cases is plotted. Most transformations concern a cumulative build-up within the exploited IoT capabilities, in which the data analytics capability matures from simple descriptive and diagnostic analytics to predictive and prescriptive (both decision support and decision automation). This increase in data analytics maturity is linked to a change in the business model value proposition, in which the current product-oriented business model is developed into a use- or result-oriented one. Furthermore, most cases add the CE looping strategy to their current focus on in-use strategies. Accordingly, their strategic ambition is to de-couple the resource consumption from their value generation – as opposed to their current product-oriented business model in which the link is direct – through the business model innovation and to keep control of their products during their lifecycle through the looping strategy. E.g. A, B, and D all intend to move from the product-oriented business model using the in-use monitoring configuration, supported by descriptive analytics, towards a looping strategy governed by a use- or result-oriented business model. To operationalise this strategy, the companies are to increase their data analytics capabilities to the predictive and prescriptive level, in which advanced analytics are applied to the captured IoT data for suggesting and autonomously performing decision-making.

Accordingly, our findings align with the concept of maturity, as is discussed widely in both the digital (e.g. Colli et al., 2019) and circular (e.g. Uhrenholt et al., 2022a) domains. The general industrial transformation pattern remains the cumulative operational and slow build-up of capabilities confined to organisational silos. The longer-term strategic ambition in these cases is to gradually, as their maturity increase, adopt a wider spanning systems perspective (Checkland, 1999), including the cross-functional transformation of the entire organisation. As such, they initially induce little risk to their organisation by adopting the silo approach while generating insights into the novel capabilities and principles currently constrained by the barriers reported by the cases.

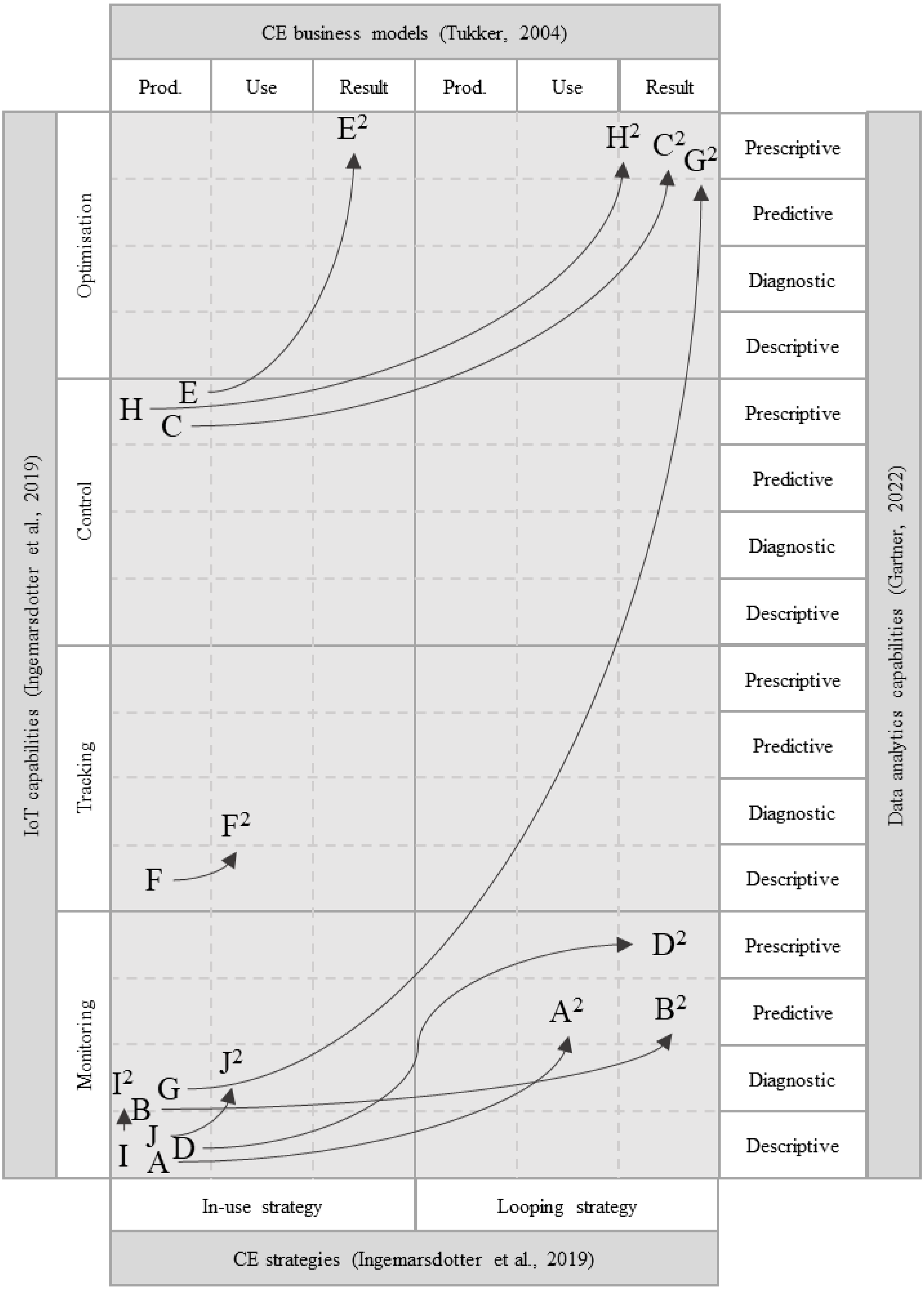

Figure 2 – Synergies between IoT capabilities and CE strategies in the Twin Transition

5. CONCLUDING REMARKS

The recent coining of the twin transition agenda makes promising propositions toward the dual relationship between the simultaneous pursuit of digital technologies and the CE principles. However, the agenda taps into a troublesome domain as manufacturers are challenged with implementing either of the two constituting constructs of the agenda (Ayati et al., 2022; Garms et al., 2019). Accordingly, the challenges faced in the industry and the academic immaturity of the agenda are evident from the multitude of calls for research to move beyond its conceptualisation (Ayati et al., 2022; Kirchherr et al., 2018; Rosa et al., 2020), and the explicit investigation of the relationship between its two halves (Kirchherr et al., 2018; Rejeb et al., 2022). This multiple case study has empirically investigated the relationship between the IoT (as a representative of the digital technologies) and the CE to uncover how their synergies enable the twin tranisition, thereby surpassing the barriers between the two agendas experiencing individually. Based on this investigation, we put the following two propositions forward. These propositions suggest specific synergetic relations between the two parts of the twin transition.

Proposition 1. *Data-driven decision-making in the CE context: The IoT technology provides specific lifecycle data of individual products, enabling the transformation to serviticed business models from the cumulative build-up of data and know-how of product performance, usage, and health.*

Our study finds that the CE-related barriers concerning data and the lack of insight into product use and health can be addressed with the introduction of IoT technology retrofitted to the products while in the market. Data is at the centre of the twin transition due to its role in unlocking new levels of competitiveness through digitalisation, automation, and organisation co-evolution. This emphasises the collection, integration, and utilisation of the data. For this, IoT is of specific interest to the notion that data can be generated from what is previously perceived as 'unintelligent' objects. IoT can enable monitoring of the health and actions of products (Pagoropoulos et al., 2017), enabling data-driven maintenance and service operations (Spring & Araujo, 2017). Similarly, the IoT can enable product life cycle management by integrating information across supply chain actors (Jensen & Remmen, 2017). Furthermore, the transparency generated, across the supply chain, from IoT enables organisations to align operations and react to changing supply and demand needs more flexibly (Birkel & Hartmann, 2020; Moeuf et al., 2018). Accordingly, engagement in data-driven service activities is an essential and enabling step toward use- and result-oriented business models for which data is central in orchestrating the value chain activities (Chen et al., 2022). However, regardless of the context in which the IoT is implemented, manufacturers are generally challenged to work actively and strategically with data to support and enable their decision-making process (Kashmanian, 2017; Singh, J. & Ordoñez, 2016). Accordingly, there is a need, both from the IoT and the CE perspective, for manufacturers to become data centric.

Proposition 2. *The strategic perception of IoT in the CE context: The CE context-related requirements must act as a design parameter for introducing IoT technology to ensure its technological potential's strategic and sustainable relevance – Hence relieving it from its cost-based constraints.*

Extant research argues that manufacturers adopt an operational perspective in investigating and implementing IoT technology while the tactical and strategical perspectives are neglected. Accordingly, the implementation of IoT in a manufacturing context is hindered by traditional cost-based evaluations (Colli et al., 2021a; Lassen & Waehrens, 2021). According to this study, the appreciation of IoT in pursuing CE principles puts the technology in a new light. When discussing the potentials of IoT implementation from the perspective of the CE principles, the tactical and strategic potentials in adopting a circular business model relieve the technology from the traditional pay-back-centred business case. From a short-term perspective, the IoT implementation optimises existing operations and products while providing product use and lifecycle data that manufacturers can utilise in exploring the CE principles, such as uncovering product EoL value (Bjerre & Parbo, 2021).

5.1 Implications, limitations, and future studies

From an academic point of view, this study addresses the gap in the literature concerning the synergetic relation between industry 4.0 (we focus on IoT) and the CE principles that make the founding argument for the twin transition. Based on the investigation of ten Danish manufacturers engaged, although in the early stages, in the twin transition, this study suggests that the two parts of the twin transition are indeed synergetic and even have elements of cumulative capabilities, where they become foundational for one another by bringing business purpose and technical capabilities together. The IoT provides the data required for gaining insights into product health and lifecycle according to the CE principles. At the same time, the perception and evaluation of IoT implementation are elevated from the operational perspective to the tactical and strategic perspectives when perceived in the CE context.

The implications of this study for practitioners concern the need for managers to build sustained competitiveness from their digital and sustainable transformation. This study provides empirical insights into the cumulative and synergetic nature of the build-up of and relation between IoT capabilities and CE principles, which managers can leverage in their organisational transformation.

The methodological choice of conducting this study as a cross-sectional study provides limited insights into the long-term engagement in the twin transition. Accordingly, the cumulative development of IoT capabilities and CE principles cannot be investigated in-depth from the lack of elapsed time. Furthermore, while this study provides empirical data on the pre-paradigmatic and highly conceptual agenda of the twin transition, the investigated cases represent a small industry sample. All ten cases are manufacturers of medium- and high-value products operating a product-oriented business model in the business-to-business market.

Derived both from the discussions of this paper and the research design limitations, the following suggestions for future research can be made. First, by adopting similar research designs, future studies should investigate the cumulative and synergetic relation of the I4.0 and the CE that makes up the twin transition agenda through longitudinal methodologies and investigate different industry sectors. Accordingly, future studies can provide valuable insights into the build-up of these synergetic capabilities along with the process, decisions, and risks. Similarly, the selection of contextually different cases may confirm or suggest different relations between the parts of the twin transition.

DECLARATIONS

Competing interests The author declares no competing interests.

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