Circular Strategies Enabled by the Internet of Things
Opportunities, Implementation Challenges, and Environmental Impact

Ingemarsdotter, E.K.

DOI
10.4233/uuid:9ac826a1-2203-4f23-b074-3d765abd73e3

Publication date
2021

Document Version
Final published version

Citation (APA)
Ingemarsdotter, E. K. (2021). *Circular Strategies Enabled by the Internet of Things: Opportunities, Implementation Challenges, and Environmental Impact*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:9ac826a1-2203-4f23-b074-3d765abd73e3

CIRCULAR STRATEGIES ENABLED BY THE INTERNET OF THINGS

OPPORTUNITIES, IMPLEMENTATION CHALLENGES, AND ENVIRONMENTAL IMPACT

CIRCULAR STRATEGIES ENABLED BY THE INTERNET OF THINGS

OPPORTUNITIES, IMPLEMENTATION CHALLENGES, AND ENVIRONMENTAL IMPACT

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, Prof.dr.ir. T.H.J.J. van der Hagen,
Chair of the Board for Doctorates
to be defended publicly on
Wednesday 24 February 2021 at 10.00 o'clock

by

Emilia Katarina INGEMARSDOTTER

Master of Science in Engineering, Chalmers University of Technology, Sweden
born in Partille, Sweden

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	Chairman
Prof. dr. A.R. Balkenende	TU Delft, promotor
Dr. E. Jamsin	TU Delft, copromotor
Independent members:	
Prof. dr. C.A. Bakker	TU Delft
Prof. dr. A. Bozzon	TU Delft
Prof. dr. M. Lindahl	Linköping University
Dr. A. Schroeder	Aston Business School
Prof. dr. P. Zwolinski	Grenoble INP

This research was conducted as part of the Circular European Economy Innovative Training Network Circ€uit, an action funded by the European Commission under the Horizon 2020 Marie Skłodowska Curie Action 2016, Grant Agreement 721909.

Keywords: Circular Economy, Digitalization, Circular Business Models, Sustainable ICT, Condition-Based Maintenance, Life Cycle Assessment
Printed by: Print en Bind, www.printenbind.nl
Front & Back: Helen Nieuweboer, www.helennieuweboer.com

ISBN 978-94-6366-369-4

An electronic version of this dissertation is available at
`http://repository.tudelft.nl/`.

CONTENTS

SUMMARY

THE CONCEPT of a ‘Circular Economy’ (CE) has been gaining traction in business, policy, and academia. It envisions an economy powered by renewable energy in which the value of products and materials are preserved for as long as possible. ‘Design for Circular Economy’ is emerging as a research field as well as a branch of sustainable design practice. Design strategies for the CE include energy and material efficiency, increased utilization, maintenance, repair, reuse, remanufacturing, and recycling.

As more and more products are equipped with digital functionalities and connected to the ‘Internet of Things’ (IoT), new opportunities arise for circular and sustainable design. However, research at the intersection between IoT and CE is still in an early phase and companies are only starting to explore what is possible. There is still a lack of research-based design guidance for companies aiming to use IoT to support ‘circular strategies’. In particular, little is known about the actual environmental impact of IoT-enabled circular strategies.

This thesis sets out to study how companies can use IoT to support circular strategies. By doing so, the aim is to provide guidance to companies who want to design and implement circular products and services. Focus is placed on understanding the opportunities for companies, as well as the implementation challenges and environmental impact of IoT-enabled circular strategies.

Towards this aim, four research questions are formulated and addressed:

- How have companies, to date, implemented IoT for circular strategies and how are these implementations distributed between the opportunities anticipated in literature? (Chapter 2)
- How can we explain the mismatch between the opportunities of using IoT for CE, as described in literature, and actual implementation in practice? (Chapter 3)
- Which challenges do companies face when trying to implement condition-based maintenance (CBM), and what solutions have they applied to address these challenges? (Chapter 4)
- Which factors are important to ensure a net reduction of environmental impact from IoT-enabled circular strategies? (Chapter 5)

The research conducted to answer these questions is mainly based on case studies with companies who, to some extent, have started to implement IoT-enabled circular strategies. First, a large set of cases from ‘grey literature’ is analyzed to reach an understanding of current practice and how it relates to the opportunities anticipated in literature (Chapter 2). In order to analyze the cases, a framework is developed which categorizes different types of IoT-enabled circular strategies. Thereafter, in-depth case studies are carried out (Chapters 3 and 4). By conducting semi-structured interviews with company representatives, qualitative insights are extracted about opportunities, implementation challenges, and solutions related to IoT-enabled circular strategies. Here, a second research framework is developed supporting the extraction of challenges faced by companies when implementing condition-based maintenance, which is one of the most commonly implemented IoT-enabled circular strategies to date. Finally, life cycle assessment methodology is used to evaluate the net environmental impact of using IoT for circular strategies in a particular case (Chapter 5).

This thesis presents five main capabilities brought about by the IoT: tracking, monitoring, control, optimization, and design evolution (Chapter 2). These capabilities can be leveraged to support six main circular strategies: efficiency in use, increased utilization, product lifetime extension, reuse, remanufacturing, and recycling. However, current practice is largely centered around IoT-induced efficiency in use and product lifetime extension. There are few examples of IoT-enabled reuse, remanufacturing, and recycling. Similarly, few examples can be found which describe ‘design evolution for CE’, i.e., the feedback of data from products-in-use to design, with the aim to improve product circularity in the design phase.

Results from the in-depth case studies (Chapters 3 and 4) display a wide range of challenges related to the design and implementation of IoT-enabled circular strategies. Chapter 3 highlights a lack of structured data management processes to ensure high-quality data collection and analysis, as well as difficulties in designing the software and hardware of IoT-enabled products for interoperability, adaptability and upgradability. Moreover, as asserted in previous research, financial uncertainty and limited consumer acceptance remain important challenges in relation to circular strategy implementation. Chapter 4 expands on Chapter 3 by extracting challenges in condition-based maintenance implementation. The challenges are categorized according to six types of ‘alignment’ between elements in the so called ‘work system’ that produces the IoT artefact needed for CBM. The work system is made up of the following elements: the product/service, customers, activities, participants, information, and technologies. For example, misalignment between ‘information’ and ‘activities’ manifests itself in the form of insufficient or irrelevant data collection, while misalignment between ‘activities’ and the ‘product/service’ includes unclear processes, roles, and responsibilities in the development of the IoT artefact.

The results from the LCA study (Chapter 5) show that, in order to reach net environmental impact reduction, it is important to consider the ability of the IoT solution to actually change the behaviour of different actors along the product life cycle.

Moreover, design decisions at the level of particular IoT components can have a considerable effect on the net impact. In order to facilitate additional studies about the environmental implications of IoT, there is a need for more detailed life cycle data about specific IoT components.

The research presented in this thesis can support companies in making effective and responsible use of IoT for circular strategies. By clarifying the opportunities, it can inspire companies to innovate and test new ideas. By elucidating implementation challenges, it enables companies to learn from the experiences of others. Finally, by providing insights into design factors which influence the net environmental impact of IoT-enabled circular strategies, it can help companies use IoT in a way that actually contributes to a more sustainable and circular economy.

SAMENVATTING

Het concept van de circulaire economie wint de laatste jaren aan populariteit in bedrijfsleven, politiek en wetenschap. Het idee van het concept is een economie die draait op hernieuwbare energie en waarin de waarde van producten en materialen zo lang mogelijk behouden blijft. 'Design for Circular Economy' (ontwerp voor circulaire economie) is in opkomst, als onderzoeksgebied en als tak van duurzaam ontwerp. Ontwerpstrategieën voor de circulaire economie zijn onder meer zuinigheid met energie en materiaal, intensiever gebruik, onderhoud, reparatie, hergebruik, herfabricage en recycling.

Nu er steeds meer producten worden uitgerust met digitale functionaliteiten en worden aangesloten op het 'internet der dingen' (IoT), ontstaan er nieuwe mogelijkheden voor een circulair en duurzaam ontwerp. Het onderzoek naar het snijvlak van IoT en circulaire economie staat echter nog in de kinderschoenen en bedrijven zijn nog maar net begonnen met onderzoeken wat er mogelijk is. Er is nog steeds een gebrek aan op onderzoek gebaseerde ontwerprichtlijnen voor bedrijven die het IoT willen gebruiken om circulaire strategieën te ondersteunen. Er is met name weinig bekend over de daadwerkelijke milieueffecten van op IoT gebaseerde circulaire strategieën.

In dit proefschrift wordt onderzocht hoe bedrijven met behulp van IoT circulaire strategieën kunnen ondersteunen. Het doel hierbij is om richtlijnen te geven aan bedrijven die circulaire producten en diensten willen ontwerpen en implementeren. De focus ligt op inzicht krijgen in de kansen voor bedrijven, de uitdagingen waar ze mee te maken krijgen bij de implementatie van circulaire IoT-strategieën en de milieueffecten van die strategieën.

Hiertoe hebben we vier onderzoeksvragen geformuleerd:

- Hoe hebben bedrijven tot nu toe IoT geïmplementeerd voor circulaire strategieën en hoe zijn deze implementaties verdeeld over de kansen die in de literatuur worden voorzien? (Hoofdstuk 2)
- Wat is de verklaring van de mismatch tussen de kansen bij het gebruik van IoT voor de circulaire economie, zoals beschreven in de literatuur, en de daadwerkelijke implementatie in de praktijk? (Hoofdstuk 3)
- Met welke problemen krijgen bedrijven te maken bij het implementeren van conditiegebaseerd onderhoud (CBM) en wat hebben ze gedaan om deze problemen op te lossen? (Hoofdstuk 4)

- Welke factoren zijn belangrijk om de netto milieu-impact van op IoT gebaseerde circulaire strategieën te verminderen? (Hoofdstuk 5)

Het onderzoek dat is uitgevoerd om deze vragen te beantwoorden is voornamelijk gebaseerd op casestudies van bedrijven die in enige mate zijn begonnen met de implementatie van op IoT gebaseerde circulaire strategieën. Ten eerste analyseren we een grote hoeveelheid casussen uit de 'grijze literatuur' om inzicht te krijgen in de huidige praktijk en te zien hoe deze zich verhoudt tot de kansen die in de literatuur worden voorzien (Hoofdstuk 2). Voor de analyse van de casussen ontwikkelen we een kader om de verschillende soorten op IoT gebaseerde circulaire strategieën te categoriseren.

Vervolgens worden vier casussen diepgaand onderzocht (Hoofdstuk 3 en 4). Door middel van semigestructureerde interviews met bedrijfsvertegenwoordigers komen we tot kwalitatieve inzichten over kansen, implementatieproblemen en oplossingen voor op IoT gebaseerde circulaire strategieën. Hierbij wordt een tweede onderzoekskader ontwikkeld om de problemen te kunnen benoemen waarmee bedrijven worden geconfronteerd bij de implementatie van conditiegebaseerd onderhoud —tot op heden een van de meest toegepaste op IoT gebaseerde circulaire strategieën. Ten slotte evalueren we in een specifiek geval met behulp van een levenscyclusanalyse (LCA) het netto milieueffect van op IoT gebaseerde circulaire strategieën (Hoofdstuk 5).

In dit proefschrift presenteren we vijf belangrijke mogelijkheden van IoT: tracking, monitoring, bediening, optimalisatie en ontwerpevolutie (Hoofdstuk 2). Deze mogelijkheden kunnen worden benut om zes belangrijke circulaire strategieën te ondersteunen: zuinigheid in het gebruik, intensiever gebruik, verlenging van de levensduur van het product, hergebruik, herfabricage en recycling. De huidige praktijk is echter grotendeels gericht op door IoT gecreëerde gebruiksefficiëntie en op verlenging van de levensduur van het product. Er zijn maar weinig voorbeelden waarin IoT wordt toegepast voor hergebruik, herfabricage of recycling. Eveneens zijn er weinig voorbeelden te vinden die de 'ontwerpevolutie voor de circulaire economie' beschrijven; hiermee wordt bedoeld dat gegevens van producten die in gebruik zijn, worden teruggekoppeld naar het ontwerp, met als doel de circulariteit van het product in de ontwerpfase te verbeteren.

De resultaten van de casestudies (Hoofdstuk 3 en 4) laten een breed scala aan problemen zien met betrekking tot ontwerp en implementatie van op IoT gebaseerde circulaire strategieën. Hoofdstuk 3 maakt duidelijk dat er een gebrek is aan gestructureerde processen voor gegevensbeheer om een goede verzameling en analyse van gegevens te waarborgen. Ook zien we hier welke moeilijkheden er zijn bij het ontwerpen van de software en hardware van IoT-producten met het oog op interoperabiliteit, aanpasbaarheid en upgradebaarheid. Bovendien heeft eerder onderzoek al uitgewezen dat financiële onzekerheid en beperkte acceptatie door de consument nog steeds belangrijke problemen zijn bij de implementatie van circulaire strategieën. Hoofdstuk 4 bouwt voort op Hoofdstuk 3 door een focus op de implementatie van conditiegebaseerd onderhoud. De problemen worden gecategoriseerd volgens zes soorten ‘afstemming’ tussen elementen in het zogenaamde ‘werksysteem’ dat het voor CBM benodigde IoT-artefact produceert. Het werksysteem bestaat uit de volgende elementen: product of dienst, klanten, activiteiten, deelnemers, informatie en technologie. Een verkeerde afstemming tussen ‘informatie’ en ‘activiteiten’ manifesteert zich in de vorm van onvoldoende of irrelevante gegevensverzameling, terwijl een verkeerde afstemming tussen ‘activiteiten’ en ‘product of dienst’ leidt tot onduidelijke processen, rollen en verantwoordelijkheden in de ontwikkeling van het IoT-artefact.

De resultaten van het LCA-onderzoek (Hoofdstuk 5) tonen aan dat het voor een netto vermindering van milieueffecten belangrijk is om te overwegen in hoeverre de IoT-oplossing het gedrag van de verschillende actoren gedurende de levenscyclus van het product daadwerkelijk kan veranderen. Bovendien kunnen ontwerpbeslissingen op het niveau van specifieke IoT-componenten een aanzienlijk effect hebben op de netto milieu-impact. Voor verder onderzoek naar de gevolgen van IoT voor het milieu is er behoefte aan nauwkeurigere levenscyclusgegevens voor specifieke IoT-componenten.

Het in dit proefschrift gepresenteerde onderzoek kan bedrijven ondersteunen bij een effectief en verantwoord gebruik van IoT voor circulaire strategieën. Doordat we verduidelijken welke kansen er zijn, kunnen bedrijven worden geïnspireerd om te innoveren en nieuwe ideeën te testen. Doordat we problemen bij de implementatie belichten, geven we bedrijven de kans om te leren van de ervaringen van anderen. En ten slotte verschaft het proefschrift inzicht in de ontwerpfactoren die het netto milieueffect van op IoT gebaseerde circulaire strategieën beïnvloeden, hetgeen bedrijven kan helpen om IoT te gebruiken op een manier die daadwerkelijk bijdraagt aan een duurzamere en meer circulaire economie.

1

INTRODUCTION

TECHNICAL CHANGE is a key driver for economic growth, and one of the most important parameters needed to understand past, current, and future human-induced effects on the natural environment (Grübler et al., 2002). Of particular importance are so called general-purpose technologies, i.e. technologies with far-reaching, and difficult to predict, effects on the economic system (Koomey et al., 2013). Today, it is almost impossible to imagine a world without, for example, the power grid or the internal combustion engine. Similarly, modern production and consumption systems are fundamentally shaped by the wide diffusion of information and communication technologies (ICT). After decades of continuous improvements in technical performance and economic efficiency (Koomey et al., 2013), ICT now forms an infrastructural backbone of most societies.

Moreover, ICT is increasingly making its way into products that are used to, for example, manufacture other products, transport goods and people, heat and cool buildings, or carry out household chores. A wide range of physical objects are being augmented with the capabilities of data collection, transmission, and processing - and connected to an ‘Internet of Things’ (IoT) (Porter and Heppelmann, 2014). This opens up new opportunities for companies to develop innovative products and services, reach new customers, and make processes more efficient and effective.

But the IoT is also surrounded by hype and confusion, leading to high expectations about opportunities, as well as legitimate concern about unintended consequences. Many reports highlight how IoT could help solve a range of complex global challenges, from climate change (Chandler, 2019) to food scarcity (German Federal Ministry for Economic Cooperation and Development, 2015). Others focus on risks, such as increased vulnerability to cyberattacks (Lee and Lee, 2015), privacy infringement (Dutton, 2014), and negative impacts on the environment (Finley, 2014). There is also an ongoing debate about the usefulness of IoT-connected consumer products (McPhail, 2018). Many early innovations did not succeed in creating real value for the user, and the internet is crowded with examples of ‘useless’ IoT gadgets (e.g., Coward, 2018; Rehabstudio, 2020; Wouk, 2019). Ultimately, the question is how to create policies that unleash the positive potential of the technology, while inhibiting negative effects (Hilty and Aebischer, 2015).

This thesis explores the potential for IoT to improve the environmental sustainability of products and services. More specifically, the research focuses on opportunities and challenges for companies to use the Internet of Things (IoT) to support ‘circular strategies’, i.e., product and service design strategies which are aligned with the vision of a Circular Economy (CE). The aim is to look ‘beyond the hype’, studying not only opportunities of IoT for CE, but also real-world implementation challenges and trade-offs. The thesis also explicitly addresses the net environmental impact of IoT-enabled circular strategies, including the potential benefits of using IoT as well as the added environmental impact from the technology itself. Apart from its scientific contribution, this thesis aims to provide knowledge and support for companies making strategic choices about when and how to implement IoT solutions to improve the circularity of their products and services.

The four studies making up this thesis build on previous work from several fields of research. The main part of this introductory chapter is thus dedicated to introducing these research fields, and to explaining how they relate to each other. Section 1.1 gives a short background to the wider topic of sustainable development and circular economy. Section 1.2 summarizes the evolution of the ‘Design for Sustainability’ field, as well as recent developments in ‘Design for Circular Economy’, while Section 1.3 introduces important aspects of IoT in the context of product and service design. Section 1.4 summarizes previous work on the topic of IoT-enabled circular strategies, and highlights the need for additional research. Following these background sections, Section 1.5 presents the aim and scope of this thesis and introduces the four studies.

1.1. SUSTAINABLE DEVELOPMENT AND CIRCULAR ECONOMY

The most commonly cited definition of sustainable development was put forward in 1987 by the Brundtland Commission as *“development that meets the needs of the present without compromising the ability of future generations to meet their own needs”* (United Nations, 1987). Since then, the human impact on the environment has become ever more obvious, and ‘sustainable development’ is now a natural part of any major policy document. Scientists have attempted to concretely define boundaries for human activities, beyond which there is a substantial risk that vital earth system functions, on which humanity depends, are irreversibly destabilized. Rockström et al. (2009) argue that the boundaries for climate change, rate of biodiversity loss, and the nitrogen cycle have already been surpassed, while the boundaries for ocean acidification and the phosphorous cycle are close within reach.

A prevalent description of sustainable development is that it should meet economic, social and environmental goals, often referred to as the ‘three pillars of sustainability’ (Purvis et al., 2019). However, perspectives differ about whether or not the three aspects can really be viewed separately, and how to treat trade-offs between them (Purvis et al., 2019). Some researchers argue that the three-pillars model should be reframed as a nested concept in which *“the global economy services society, which lies within Earth’s life-support system”* (Griggs et al., 2013). In this view, economic and social sustainability would not be possible without environmental sustainability. In 2015, the UN launched the 2030 Agenda for Sustainable Development, declaring 17 global sustainable development goals (SDGs) for 2030 (United Nations, 2015). The agenda is an attempt to integrate different aspects of sustainability, balancing economic, social, and environmental concerns. This has started a new academic debate regarding how to deal with trade-offs between the goals (Scherer et al., 2018), and whether the goals should be ordered in a hierarchy to support prioritization (Kumar et al., 2018).

Alongside the formulation of the SDGs, the growing global consensus about the need for large scale changes to the current system of production and consumption is visible both in international agreements, such as the Paris agreement (United Nations, 2015), and in surveys of public concern (e.g., Bedsted et al., 2015). The private sector is responding by launching increasingly ambitious sustainability programs, including, for example, stricter emission reduction targets for greenhouse gases (Gupta et al., 2019). Investors are now commonly evaluating environmental engagement as an indicator of business performance, with the implication that companies who fail to act in time might be left behind (Morgan et al., 2015). Still, going from ambition to action is challenging, and many companies struggle to meet their own targets (Plumer and Popovich, 2018).

In recent years, the concept of a 'Circular Economy' (CE), has been gaining traction within the sustainability discourse. In broad terms, the CE envisions an economy powered by renewable energy (Ellen MacArthur Foundation, 2013), in which products and materials are maintained for as long as possible, waste and resource use are minimized (European Commission, 2015), and, ultimately, resource consumption is decoupled from economic growth (Kjaer et al., 2018). The Ellen MacArthur foundation has been active in popularizing the term, framing the CE as an opportunity for businesses to simultaneously achieve economic benefit and act as a positive force for the environment (Ellen MacArthur Foundation, 2013). Several national governments are also promoting the CE concept (Korhonen et al., 2018). In 2015, the European union adopted an 'EU action plan for the Circular Economy' (European Commission, 2015), recently followed up by a new 'Circular Economy Action Plan' (European Commission, 2020) as part of the roll-out of the 'European Green Deal' (European Commission, 2019). China has had a CE strategy in place since 2002 (Su et al., 2013).

Having been mainly developed outside academia (Korhonen et al., 2018), the CE term still lacks a clear scientific definition (Kirchherr et al., 2017). Academically, the CE concept builds on multiple fields of research, including environmental and ecological economics (Boulding, 1966; Pearce and Turner, 1990), industrial ecology (Graedel, 1996), cradle-to-cradle design (Braungart et al., 2007), the performance economy (Stahel, 2010), and biomimicry (Benyus, 1997). Compared to 'sustainable development', CE tends to be interpreted with a stronger focus on reducing material resource use, mainly targeting economic actors in the search for solutions which can simultaneously benefit the economy and the environment (Geissdoerfer et al., 2017). While definitions of the CE concept generally do not include social aspects of sustainability, social benefits such as job creation are often highlighted as expected effects of the transition to a CE (e.g., Wijkman and Skånberg, 2015).

There is an ongoing academic debate regarding the need and adequacy of the CE concept. Some see a need for the CE term to make up for shortcomings of the SD term. SD is criticized, on the one hand, for being too vague and all-encompassing, making it impossible to operationalize (Kirchherr et al., 2017). On the other hand, 'sustainability', as carried out in practice, has been criticized for having a too narrow focus on incrementally reducing negative environmental impact (Murray, 2019), thereby not bringing about transformational change. In light of this, CE could be seen as an operationalization of SD (Kirchherr et al., 2017), emphasizing the business opportunities of intentional ‘by-design’ value retention of resources (Ellen MacArthur Foundation, 2013b). CE has also been promoted for its inspiring and easy-to-grasp framing (Korhonen et al., 2018). As argued by Blomsma and Brennan (2017), the CE serves as an ‘umbrella concept’ which articulates the capacity of different strategies related to waste and resource management, enabling a more meaningful discussion and debate among different actors. Recent reports have further argued that CE adds new perspectives to current climate change mitigation strategies by putting a more explicit focus on emissions driven by the demand for products and materials (Material Economics, 2018; Blok et al., 2016).

Critiques to the CE concept highlight the risk of over-simplifying complex sustainability issues (Korhonen et al., 2018). Specifically, authors have highlighted a sometimes over-optimistic view on decoupling in the CE discourse (Zink and Geyer, 2017). Korhonen et al. (2018), among others, see a need for more explicit assessment of environmental impact in CE literature. Moreover, the conceptual ambiguity of CE, caused by the lack of consensus about its definition, forms a risk for the long-term viability of the term (Kirchherr et al., 2017). The academic debate is to a large extent semantic, often focusing on what the CE term should and should not include, and how it is different from other related concepts. In an attempt to nuance the discussion, Geissdoerfer et al. (2017) studied how the CE concept is used in relation to SD. They concluded that the CE term is not as holistic as SD. Instead, CE can be seen as a subset of SD, representing *“one among several solutions for fostering a sustainable system”*.

In this thesis, I take a similar view of CE as a subset of sustainable development focused on achieving an environmentally sustainable production and consumption system. I present a set of ‘circular strategies’ including efficiency measure in the product’s use phase, increased product utilization, product lifetime extension, reuse, remanufacturing, and recycling. These strategies are treated as possible opportunities for reducing environmental impact, for which the actual impact reduction needs to be assessed on a case-by-case basis.

1.2. DESIGN FOR SUSTAINABILITY, CIRCULAR BUSINESS MODELS, AND PRODUCT-SERVICE SYSTEMS

Product and service design plays a fundamental part in the transition to a more sustainable production and consumption system. Decisions at the design stage largely influence the environmental impact of products and services throughout their life cycles. The ‘Design for Sustainability’ research field has developed over time, and has branched out into a diversity of philosophies, methods, and tools. Ceschin and Gaziulusoy (2016) proposed a framework which described this evolution: from a product-centric view, through a more integrative focus on product/service combinations, to systems-oriented approaches. On the product level, sustainable design approaches focus on improving existing products, or on developing new products with improved sustainability performance. On the product/service level, the scope is widened to include not only the product but also services related to the product, as well as business models through which the product/service is offered. On the system level, design approaches aim to enable larger societal shifts, for example by changing production systems as a whole, or by radically reinventing how needs are met. Ceschin and Gaziulusoy (2016) argue that design approaches at the different levels are complementary to reach sustainability. While sustainability challenges need to be addressed at the systems level, design considerations at the 'lower' levels cannot be overlooked (Ceschin and Gaziulusoy, 2016).

'Design for Circular Economy' has emerged as a field within the wider 'Design for Sustainability' community. 'Circular strategies' focus primarily on achieving product lifetime extension, reuse, remanufacturing and recycling (Geissdoerfer et al., 2017). So far, most circular design approaches cover the product and product/service levels, but recent research also include system-level circular design approaches (e.g., Konietzko et al., 2020). Specific product design strategies for CE have been formulated (e.g., Bakker et al., 2014), and a growing body of literature explores 'circular business models' (Bocken et al., 2016). This field is closely linked to research about service-oriented business models and Product-Service systems (PSS) (Tukker, 2015), in which focus is placed on the service made available to the user rather than the transaction of a physical product. Circular business models can, for example, enable sharing of products, and stimulate the producer to take products back after use, so that they can be reused, remanufactured or recycled.

1.3. INTERNET OF THINGS

Digitalization can today be seen as one of the strongest forces in product and service innovation (Yoo et al., 2010) and is thus expected to be of importance for sustainable and circular design approaches as well (e.g., Kristoffersen et al., 2020). Yet, many companies are only in the early phases of digitalization and much is left to learn about the associated industrial transformation (Lasi et al., 2014).

The term 'Industry 4.0' was first introduced as part of a German high-tech strategy for the industrial sector (Hofmann and Rüsch, 2017), but is now a popular term to generally describe the trend towards an increasingly digitalized and automated manufacturing system (Oesterreich and Teuteberg, 2016). A key technology within 'Industry 4.0' is the 'Internet of Things' (IoT) (Hofmann and Rüsch, 2017). While there is no clear consensus about how to define the IoT (Wortmann and Flüchter, 2015), it can be said to refer to wide-spread connectivity between physical things and between people and things. The lack of clear definition also means that the boundaries between different technologies are not obvious. It is clear, however, that IoT is closely linked to several related technologies, such as cloud computing and data analytics.

One proposed definition of the IoT, which is used throughout this thesis, is the following: *“a system of uniquely identifiable and connected constituents capable of virtual representation and virtual accessibility leading to an Internet-like structure for remotely locating, sensing, and/or operating the constituents with real-time data/informa-tion flows between them, thus resulting in the system as a whole being able to be augmented to achieve a greater variety of outcomes in a dynamic and agile manner.”* (Ng and Wakenshaw, 2017). While this definition clearly focuses on a system, attempts have also been made to define the ‘things’ being connected through the IoT. Kortuem et al. (2010) define ‘smart objects’ as *“autonomous physical/digital objects augmented with sensing, processing, and network capabilities”*. Porter (2015) conceptualize ‘smart, connected products’ as products made up of three core elements: physical components, ‘smart’ components, and connectivity components which enable communication between the physical product and the cloud. They use the example of a car, the physical components being, for example, the engine or the tires, the ‘smart’ components being, e.g., sensors, processors, and embedded software, and the connectivity components being, e.g., antennas. The smart, connected product connects to a ‘product cloud’ which contains data storage, analytics, and software applications (Porter, 2015). Together, the product layer, the connectivity layer, and the product cloud make up what Porter (2015) refer to as ‘the new technology stack’. In this thesis, ‘the new technology stack’ is used to represent the multi-layered nature of IoT artefacts.

The opportunities that IoT might bring to businesses have been explored in both academic literature and practice-oriented reports. On a general level, IoT can support better-informed decisions based on real-world data recorded by smart products in the field (Raynor and Cotteleer, 2015). More specifically, product and service design can be improved and customized continuously, based on data about real-world performance (Manyika et al., 2015). The IoT also has the potential to influence business models. In particular, IoT could support manufacturers to broaden their offerings beyond the physical product, to include the data itself, or services built on data (Porter and Heppelmann, 2014). For example, through access to data about how products are used by customers, tailored services can be offered to improve the customer’s operations (Rymaszewska et al., 2017).

As previously mentioned, the IoT also comes with risks and drawbacks. Important examples are the risks for cyber attacks and hacking of physical objects, the risk for surveillance and privacy intrusion, and for increased environmental impact from the production, use, and disposal of the additional electronic components needed. To increase the awareness about these risks, the design community has published ‘manifestos’ for responsible IoT design (Fritsch et al., 2018; iotmanifesto.com, 2015). Similarly, the World Economic Forum (2018) has published a set of ‘IoT guidelines for sustainability’. The design research community have also started to develop methods and tools which can support responsible design of IoT artefacts (e.g., Baldini et al., 2018; Bourgeois and Kortuem, 2019). This development is likely to continue as the IoT expands and matures.

1.4. IoT-enabled Circular Strategies

Both research and practice are starting to explore the opportunities that the IoT might bring to the transition to a circular economy. In a report from 2016, the Ellen MacArthur Foundation concluded that IoT can bring better knowledge about the location, condition, and availability of products, and that this information can enable 'extended use cycles', 'increased utilization', and 'looping/cascading' (Ellen MacArthur Foundation, 2016). Moreover, the report states that IoT can indirectly support de-materialization, through its ability to enable more service-oriented business models (Ellen MacArthur Foundation, 2016). Alcayaga et al. (2019) note that IoT could help fill information gaps in, for example, remanufacturing and recycling. Bressanelli et al. (2018) point out that IoT could support optimization of product usage, as well as product lifetime extension through predictive and preventive maintenance.

While these opportunities seem promising, research at the intersection between IoT and CE is still in an early phase (Cattelan Nobre and Tavares, 2017). At the moment of writing this thesis, a combined search in Scopus results in a total of 93 academic articles (on January 2nd, 2021), whereof 25 were published during 2020, see Figure 1.1. When this PhD project started in January 2017, only six of these 93 articles had been published, the oldest one in May 2015 (Reuter et al., 2015). In particular, few papers exist which empirically investigate, and evaluate in practice, the opportunities of IoT for CE (Antikainen et al., 2018; Cattelan Nobre and Tavares, 2017). Such a focus is important, since companies are only starting to explore the opportunities. More work is also needed to understand the barriers to implementation in practice (Okorie et al., 2018) and to develop tools and methods targeting companies who aim to implement IoT-enabled circulars strategies (Alcayaga et al., 2019).

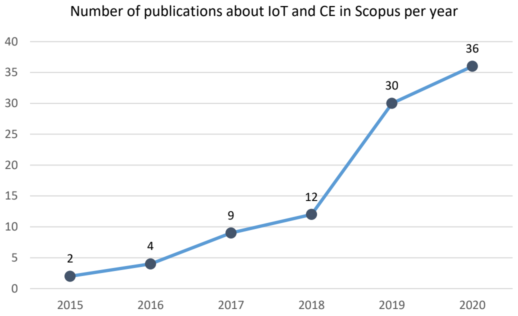


Figure 1.1: Number of articles listed in Scopus, per year, for the search query 'TITLE-ABS-KEY("Internet of Things" AND "Circular Economy")', as of January 2nd 2021. No publications before 2015. The number for 2020 includes one article with official publication date in 2021.

Challenges related to IoT implementation in general (i.e., not in the context of CE) have been studied to some extent, but this too is an emerging field. Identified challenges include the lack of interoperability between products (Westerlund et al., 2014), and the difficulty to derive real value from large amounts of data (Raynor and Cotteleer, 2015).

Moreover, IoT innovation might require changes to the organization, both in terms of which business functions are present and how they collaborate (Porter, 2015). This is also true for the implementation of circular strategies, which often requires integration of organizational functions, as well as involvement of additional stakeholders (Sousa-Zomer et al., 2018). Other challenges in circular business model implementation are, e.g., uncertainty about financial profitability (Linder and Williander, 2017) and a lack of customer acceptance (Sousa-Zomer et al., 2018). When attempting to implement IoT-enabled circular strategies, companies are thus likely to face a range of challenges. More research is needed to identify such challenges and explore possible solutions.

A specific challenge related to IoT-enabled circular strategies is to ensure that the efforts put in actually bring net environmental impact reductions. While IoT can enable circular strategies, the technology also comes with environmental risks. For example, wide-spread IoT implementation could lead to increased creation of electronics waste and higher levels of toxic chemicals entering the environment (Lewis, 2015). Another highlighted issue is the low durability of IoT devices. If IoT devices fail quickly, they might shorten the lifetime of the products in which they are embedded. Considering both opportunities and risks, it is a complex task to estimate the net environmental impact of IoT-enabled circular strategies.

So far, little research has been published in which environmental impacts of IoT-enabled circular strategies are explicitly assessed. However, literature from the field of sustainable ICT offers some support. As a way to structure the analysis of environmental effects of ICT, Berkhout and Hertin (2001) presented a framework which distinguishes between three levels of environmental impacts resulting from the use of ICT: direct effects, indirect effects, and structural/behavioral effects. Since it was first published, the framework has been developed by other authors, among others Hilty and Aebischer (2015), who have been important in the formulation of the research field ‘ICT for sustainability’. They define the following three impact levels: life-cycle impact, enabling impact, and structural impact.

Life cycle impacts are the direct impacts caused by production, use, and disposal of the ICT components themselves. Enabling impacts include information-aided process optimization, media substitution (e.g. electronic invoices replacing printed invoices) and behavioral or organizational changes in production and consumption. Structural impacts include changes to economic structures and institutions, policies, and social norms.

Life cycle impacts tend to be the easiest to quantify, and thus most environmental assessment studies of ICT have focused on this level (Williams, 2011). As the technology needed to build the IoT is developing quickly, more work is still needed to understand the direct life cycle impacts of components specific to IoT (e.g., sensors, actuators, antennas, and gateways). Moreover, while more complex and uncertain, enabling and structural impacts need to be understood in order to determine the net environmental impact of ICT solutions in general, and IoT solutions in particular.

1.5. AIM AND SCOPE

Based on the literature presented above, it is clear that the academic community is only just starting to understand the opportunities that IoT might bring to companies who aim to implement circular strategies. Moreover, previous work has not sufficiently addressed how companies could implement IoT-enabled circular strategies in practice. Lastly, there is a need for research about how to ensure net environmental impact reductions from IoT-enabled circular strategies.

The aim of this thesis is thus to study how companies can use IoT to support circular strategies. Towards this aim, the following three main topics are explored:

- Opportunities for using IoT to support circular strategies
- Challenges associated with implementing IoT-enabled circular strategies in practice
- The net environmental impact of IoT-enabled circular strategies

The focus of this research is on industrialized economies. Opportunities, challenges, or impacts specific to other settings are thus out of scope. In terms of assessing the sustainability of IoT-enabled circular strategies, focus has been on understanding their environmental impact. Any systematic analysis of social and economic impact is outside the scope of this thesis.

This thesis presents four studies, each focusing on a specific research question, as specified in Figure 1.2 and presented below.

In **Study 1**, the following research question is posed: *How have companies to date implemented IoT for circular strategies and how are these implementations distributed between the opportunities anticipated in literature?* To answer this question, literature in the fields of CE and IoT is reviewed to identify categories of IoT-enabled circular strategies. A framework is developed that distinguishes between six types of circular strategies and five types of IoT capabilities, and subsequently used to map 40 cases from practice. Study 1 presents a need for more research to understand the current mismatch between the opportunities of IoT for CE, as anticipated in literature, and what is actually being implemented in practice.

Study 2 builds on Study 1 and asks the following research question: *How can we explain the mismatch between the opportunities of using IoT for CE, as described in literature, and actual implementation in practice?* This question is explored through an in-depth case study with a company in the process of developing a circular value proposition for supermarket lighting systems supported by IoT. Based on interviews with company representatives, the study extracts opportunities and implementation challenges as perceived by these actors. From this, a better understanding is developed about what is hindering the implementation of IoT-enabled circular strategies in practice.

In **Study 3**, the aim is to extract transferable lessons from the experiences gained by companies who have already started to implement IoT-enabled circular strategies. The following research question is posed: *Which challenges do companies face when trying to implement condition-based maintenance (CBM), and what solutions have they applied to address these challenges?* A multiple case study is carried out, focusing on condition-based maintenance (CBM) implementation at three original equipment manufacturers (forklifts, industrial robots, heat pumps). CBM is selected as the focus of this study for two main reasons. Firstly, Study 1 concluded that IoT-enabled maintenance is one of the most commonly adopted IoT-enabled circular strategies in practice. Secondly, Study 2 showed that manufacturers face a range of challenges when trying to implement IoT-enabled maintenance, and that these challenges are likely relevant also for other IoT-enabled circular strategies. While Study 2 focuses mainly on perceived opportunities and early-stage challenges, Study 3 details a range of implementation challenges as well as solutions that the companies have applied to address these challenges. Based on this, a set of actionable recommendations can be formulated for other companies aiming to implement CBM.

Finally, **Study 4** focuses on the net environmental impact from IoT-enabled circular strategies. The following research question is formulated: *Which factors are important to ensure a net reduction of environmental impact from IoT-enabled circular strategies?* To answer this question, Life Cycle Assessment (LCA) is used to assess the net environmental impact of one particular case (IoT-enabled heavy-duty truck tires). Through sensitivity analysis, it is possible to identify parameters which significantly influence the overall result, and translate these findings into learnings for design.

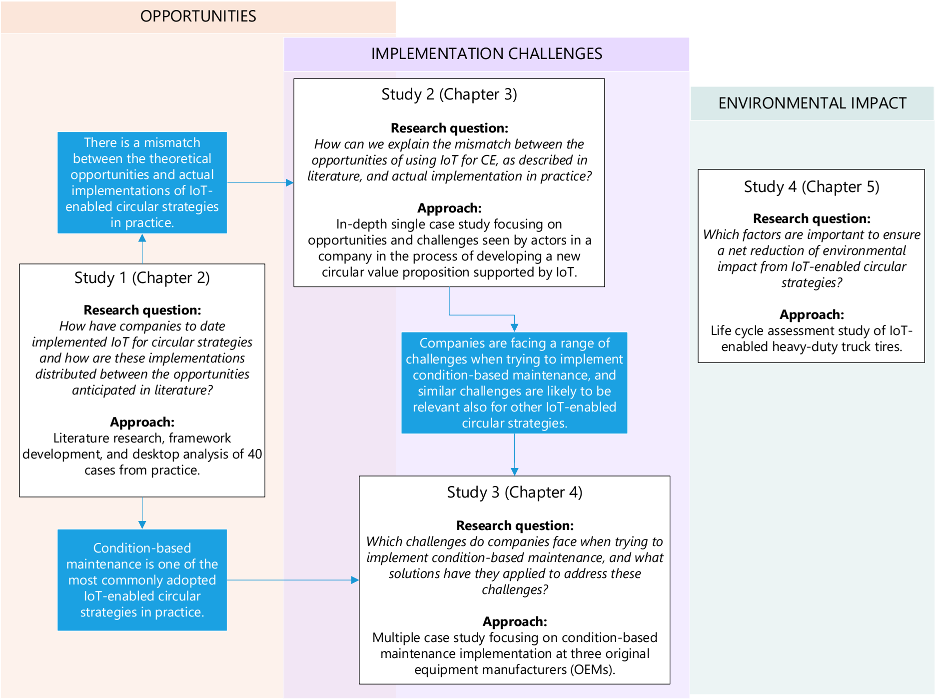


Figure 1.2: Studies in this thesis and how they relate to each other

REFERENCES

A. Alcayaga, M. Wiener, and E. G. Hansen (2019). Towards a framework of smart-circular systems: An integrative literature review. *Journal of Cleaner Production* **221**, 622.

M. Antikainen, T. Uusitalo, and P. Kivikytö-Reponen (2018), Digitalisation as an Enabler of Circular Economy, in *10th CIRP Conference on Industrial Product-Service Systems*, Linköping, Sweden.

C. Bakker, F. Wang, J. Huisman, and M. Den Hollander (2014). Products that go round: exploring product life extension through design. *Journal of Cleaner Production* **69**, 10.

G. Baldini, M. Botterman, R. Neisse, and M. Tallacchini (2018). Ethical Design in the Internet of Things. *Science and Engineering Ethics* **24**, 905.

B. Bedsted, Y. Mathieu, and C. Leyrit (2015), *World wide views on Climate and Energy*, World Wide Views Alliance. Available from: http://climateandenergy.wwviews.org.

J. Benyus (1997), *Biomimicry*, Harper Perennial, New York, NY, USA.

F. Berkhout and J. Hertin (2001), *Impacts of Information and Communication Technologies on Environmental Sustainability: speculations and evidence*, OECD. Available from: http://www.ictliteracy.info/rf.pdf/OECD-ICT-EnvrnmtImpct.pdf.

K. Blok, J. Hoogzaad, S. Ramkumar, A. Ridley, P. Srivastav, I. Tan, W. Terlouw, and M. de Wit (2016), *Implementing circular economy globally makes Paris targets achievable*, Circle Economy and Ecofys. Available from: https://www.circle-economy.com/.

F. Blomsma and G. Brennan (2017). The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *Journal of Industrial Ecology* **21**, 603.

N. M. P. Bocken, I. De Pauw, C. Bakker, and B. Van Der Grinten (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering* **33**, 308.

K. Boulding (1966). The economics of the coming spaceship earth. in *Environmental Quality in a Growing Economy*, edited by H. Jarrett. Resources for the Future/Johns Hopkins University Press, Baltimore, MD, USA.

J. Bourgeois and G. Kortuem (2019), Towards Responsible Design with Internet of Things Data, in *International Conference on Engineering Design, ICED19*, Delft, the Netherlands.

M. Braungart, W. McDonough, and A. Bollinger (2007). Cradle-to-cradle design: creating healthy emissions - a strategy for eco-effective product and system design. *Journal of Cleaner Production* **15**, 1337.

G. Bressanelli, F. Adrodegari, M. Perona, and N. Saccani (2018). Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies. *Sustainability* **10**, 639.

G. Cattelan Nobre and E. Tavares (2017). Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study. *Scientometrics* **111**, 463.

F. Ceschin and I. Gaziulusoy (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design Studies* **47**, 118.

S. Chandler (2019). How The Internet Of Things Will Help Fight Climate Change. *Forbes* Available from: https://www.forbes.com.

J. Coward (2018). Funny IoT Devices: Is This the Worst of the Internet of Things? *IoT World Today* Available from: https://www.iotworldtoday.com.

W. H. Dutton (2014). Putting things to work: Social and policy challenges for the Internet of things. *info* **16**, 1.

Ellen MacArthur Foundation (2013), *Towards the Circular Economy: Economic and business rationale for an accelerated transition*, Cowes, UK.
Available from: https://www.ellenmacarthurfoundation.org/publications.

Ellen MacArthur Foundation (2016), *Intelligent assets: Unlocking the Circular Economy Potential*, Cowes, UK.
Available from: https://www.ellenmacarthurfoundation.org/publications.

European Commission (2015), *COM(2015) 614: Closing the loop - An EU action plan for the Circular Economy*.

European Commission (2019), *COM(2019) 640: The European Green Deal*.

European Commission (2020), *COM(2020) 98: Circular Economy Action Plan - For a cleaner and more competitive Europe*.

K. Finley (2014). The Internet of Things Could Drown Our Environment in Gadgets. *Wired* Available from: https://www.wired.com/.

E. Fritsch, I. Shklovski, and R. Douglas-Jones (2018), Calling for a revolution: An analysis of IoT manifestos, in *CHI '18: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, Montreal, QC, Canada.

M. Geissdoerfer, P. Savaget, N. M. P. Bocken, and E. J. Hultink (2017). Review: The Circular Economy A new sustainability paradigm? *Journal of Cleaner Production* **143**, 757.

German Federal Ministry for Economic Cooperation and Development (2015), *Internet of Things: Using sensors for good: How the Internet of Things can improve lives.*

T. Graedel (1996). On the concept of Industrial Ecology. *Annu. Rev. Energy Environ.* **21**, 69.

D. Griggs, M. Stafford-Smith, O. Gaffne, J. Rockström, M. C. Öhman, P. Shyamsundar, W. Steffen, G. Glaser, N. Kanie, and I. Noble (2013). Sustainable developmnet goals for people and planet. *Nature* **495**, 305.

A. Grübler, N. Nakicenovic, and W. D. Nordhaus (2002). Induced Technological Change and the Environment: An Introduction. in *Technological Change and the Environment*, edited by A. Grübler, N. Nakicenovic, and W. D. Nordhaus, Chap. 1. Resources for the Future & International Institute for Applied Systems Analysis, Washington, D.C., USA & Laxenburg, Austria.

A. Gupta, A. Raghunath, L. Gula, L. Rheinbay, and M. Hart (2019), *The Decade to Deliver, a Call to Business - CEO Study on Sustainability*, UNGC & Accenture Strategy. Available from: https://www.accenture.com/us-en/insights/strategy/ungcceostudy.

L. M. Hilty and B. Aebischer (2015). ICT for Sustainability: An Emerging Research Field. in *ICT Innovations for Sustainability - Advances in Intelligent Systems and Computing*, edited by L. M. Hilty and B. Aebischer. Springer, Cham.

E. Hofmann and M. Rüsch (2017). Industry 4.0 and the current status as well as future prospects on logistics. *Computers in Industry* **89**, 23.

iotmanifesto.com (2015), IoT Design Manifesto: Guidelines for responsible design in a connected world, https://www.iotmanifesto.com [accessed 2020-10-13].

J. Kirchherr, D. Reike, and M. Hekkert (2017). Conceptualizing the Circular Economy: An analysis of 114 definitions. *Resources, Conservation and Recycling* **127**, 221.

L. L. Kjaer, M. Niero, D. C. A. Pigosso, N. M. Bech, and T. C. McAloone (2018). Product/Service-Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption? *Journal of Industrial Ecology* **23**, 22.

J. Konietzko, N. Bocken, and E. J. Hultink (2020). Circular ecosystem innovation: An initial set of principles. *Journal of Cleaner Production* **253**.

J. G. Koomey, H. Scott Matthews, and E. Williams (2013). Smart Everything: Will Intelligent Systems Reduce Resource Use? *Annual Review of Environment and Resources* **38**, 311.

J. Korhonen, A. Honkasalo, and J. Seppälä (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics* **143**, 37.

G. Kortuem, F. Kawsar, D. Fitton, and V. Sundramoorthy (2010). Smart objects as building blocks for the internet of things. *IEEE Internet Computing* **14**, 44.

E. Kristoffersen, F. Blomsma, P. Mikalef, and J. Li (2020). The Smart Circular Economy: A Digital-Enabled Circular Strategies Framework for Manufacturing Companies. *Journal of Business Research* **120**, 241.

P. Kumar, F. Ahmed, R. K. Singh, and P. Sinha (2018). Determination of hierarchical relationships among sustainable development goals using interpretive structural modeling. *Environment, Development and Sustainability* **20**, 2119.

H. Lasi, P. Fettke, and H. Kemper (2014). Industry 4.0. *Business & Information Systems Engineering* **6**, 239.

I. Lee and K. Lee (2015). The Internet of Things (IoT): Applications, investments, and challenges for enterprises. *Business Horizons* **58**, 431.

N. Lewis (2015), The environmental impacts from an increased use of connected devices: an argument for the need to implement a circular economy.

M. Linder and M. Williander (2017). Circular Business Model Innovation: Inherent Uncertainties. *Business Strategy and the Environment* **26**, 182.

J. Manyika, M. Chui, P. Bisson, J. Woetzel, R. Dobbs, J. Bughin, and D. Aharon (2015), *The Internet of Things: Mapping the value beyond the hype*, McKinsey & Company. Available from: https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/the-internet-of-things-the-value-of-digitizing-the-physical-world.

Material Economics (2018), *The Circular Economy, A Powerful Force for Climate Mitigation.* Available from: https://materialeconomics.com/publications.

J. McPhail (2018). Useful Or Useless? Identifying The Business Case For IoT. *Forbes* Available from: https://www.forbes.com.

J. Morgan, K. Levin, J. Song, and J. P. Osornio (2015), *Driving Transformative Change: the Role of the Private Sector in Advancing Short-Term and Long-Term Signals in the Paris Climate Agreement*, World Resources Institute. Working paper, Available from: https://www.wri.org/publication.

S. Murray (2019). The case for a circular world. *Financial Times*
Available from: https://www.ft.com.

I. C. Ng and S. Y. Wakenshaw (2017). The Internet-of-Things: Review and research directions. *International Journal of Research in Marketing* **34**, 3.

T. D. Oesterreich and F. Teuteberg (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry* **83**, 121.

O. Okorie, K. Salonitis, F. Charnley, M. Moreno, C. Turner, and A. Tiwari (2018). Digitisation and the Circular Economy: A Review of Current Research and Future Trends. *Energies* **11**, 3009.

D. Pearce and R. Turner (1990), *Economics of Natural Resources and the Environment*, Harvester Wheatsheaf, New York, NY, USA.

B. Plumer and N. Popovich (2018). The World Still Isn't Meeting Its Climate Goals. *The New York Times* Available from: https://www.nytimes.com.

M. E. Porter (2015). How smart, connected products are transforming companies. *Harvard Business Review* Available from: https://hbr.org/archive-toc/BR1510.

M. E. Porter and J. E. Heppelmann (2014). How smart, connected products are transforming competition. *Harvard Business Review*
Available from: https://hbr.org/archive-toc/BR1411.

B. Purvis, Y. Mao, and D. Robinson (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science* **14**, 681.

M. E. Raynor and M. J. Cotteleer (2015), *The more things change. Value creation, value capture, and the Internet of Things*, Deloitte Review.
Available from: https://www.deloitte.com/insights.

Rehabstudio (2020), The Internet of Useless Things, https://iout.rehabagency.ai/ [accessed 2020-08-19].

M. A. Reuter, R. Matusewicz, and A. Van Schaik (2015). Lead, zinc and their minor elements: Enablers of a circular economy. *World of Metallurgy - ERZMETALL* **68**, 134.

J. Rockström, W. Steffen, K. Noone, Å. Persson, F. Chapin, E. Lambin, T. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. Corell, V. Fabry, J. J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley (2009). A safe operation space for humanity. *Nature* **461**, 472.

A. Rymaszewska, P. Helo, and A. Gunasekaran (2017). IoT powered servitization of manufacturing-an exploratory case study. *International Journal of Production Economics* **192**, 92.

L. Scherer, P. Behrens, A. de Koning, R. Heijungs, B. Sprecher, and A. Tukker (2018). Trade-offs between social and environmental Sustainable Development Goals. *Environmental Science and Policy* **90**, 65.

T. T. Sousa-Zomer, L. Magalhães, E. Zancul, and P. A. Cauchick-Miguel (2018). Exploring the challenges for circular business implementation in manufacturing companies: An empirical investigation of a pay-per-use service provider. *Resources, Conservation and Recycling* **135**, 3.

W. R. Stahel (2010), *The Performance Economy*, 2nd ed., Palgrave Macmillan, Basingstoke, UK.

B. Su, A. Heshmati, Y. Geng, and X. Yu (2013). A review of the circular economy in China: Moving from rhetoric to implementation. *Journal of Cleaner Production* **42**, 215.

A. Tukker (2015). Product services for a resource-efficient and circular economy - A review. *Journal of Cleaner Production* **97**, 76.

United Nations (1987), *Report of the World Commission on Environment and Development: Our Common Future*.
Available from: https://sustainabledevelopment.un.org.

United Nations (2015), *Transforming our world: the 2030 Agenda for Sustainable Development*. Available from: https://sustainabledevelopment.un.org.

United Nations (2015), *Paris Agreement*. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

M. Westerlund, S. Leminen, and M. Rajahonka (2014). Designing Business Models for the Internet of Things. *Technology Innovation Management Review* **4**, 5.

A. Wijkman and K. Skånberg (2015), *The Circular Economy and Benefits for Society: Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency*, The Club of Rome.
Available from: https://clubofrome.org/publications.

E. Williams (2011). Environmental effects of information and communications technologies. *Nature* **479**, 354.

World Economic Forum (2018), *Internet of Things Guidelines for Sustainability*, World Economic Forum. Available from: https://www.weforum.org/.

F. Wortmann and K. Flüchter (2015). Internet of Things: Technology and Value Added. *Business and Information Systems Engineering* **57**, 221.

K. Wouk (2019). 6 Smart Home Devices that Are Totally Useless. *IoT Tech Trends* Available from: https://www.iottechtrends.com.

Y. Yoo, K. Lyytinen, R. Boland, N. Berente, J. Gaskin, and D. Schutz (2010), *The Next Wave of Digital Innovation: Opportunities and Challenges - Report on the Research Workshop: Digital Challenges in Innovation Research*. Available from: https://dx.doi.org/10.2139/ssrn.1622170.

T. Zink and R. Geyer (2017). Circular Economy Rebound. *Journal of Industrial Ecology* **21**, 593

2

CIRCULAR STRATEGIES ENABLED BY THE INTERNET OF THINGS —A FRAMEWORK AND ANALYSIS OF CURRENT PRACTICE

This chapter has been published as:
E. Ingemarsdotter, E. Jamsin, G. Kortuem, and R. Balkenende (2019) Circular Strategies Enabled by the Internet of Things—A Framework and Analysis of Current Practice. *Sustainability* **11**, 5689.

Abstract: This paper focuses on how the Internet of Things (IoT) could contribute to the transition to a circular economy (CE), through supporting circular business model and design strategies.While literature has highlighted the opportunities for IoT to support circular strategies in business, little has been published about actual implementations in practice. The aim of this study was therefore to understand how companies to date have implemented IoT for circular strategies, and how these implementations compare to the range of opportunities described in literature. To that end, a two-step approach was followed. Firstly, building on academic literature, a framework was developed which categorizes different IoT-enabled circular strategies. The framework recognizes tracking, monitoring, control, optimization, and design evolution as IoT capabilities. Efficiency in use, increased utilization, and product lifetime extension are distinguished as circular in-use strategies, while reuse, remanufacturing, and recycling are distinguished as circular looping strategies. The framework complements previously published work, as it adds additional detail to the categorization, and allows for easy mapping of diverse cases. Secondly, 40 cases from practice were analyzed and mapped to the framework. This way, practice-based insights were derived about the current distribution of IoT-enabled circular strategies implemented in practice. The results show that current implementation of IoT-enabled circular strategies mainly supports two strategies in the use phase: efficiency in use and product lifetime extension. Only a small number of the reviewed cases display IoT-enabled looping (reuse, remanufacturing, and recycling). Similarly, few cases describe 'design evolution' for CE, i.e., the feedback of data from products in use to support circular design. Based on these results, this study identifies the need for future research to further investigate why IoT-enabled looping strategies and design evolution for circular strategies have not been implemented to scale.

Keywords: Circular Economy; Digitalization; Sustainable Business Models; Product Service Systems

2.1. INTRODUCTION

The circular economy (CE) conceptualizes an envisioned global economy which is *"restorative and regenerative by design"* (Ellen MacArthur Foundation, 2013) and which simultaneously considers environmental impact, resource scarcity, and economic benefits (Lieder and Rashid, 2016). In practice, CE-related issues—such as the reduction of waste, emissions, and supply risk—are spurring innovations in business models, product designs, materials, and supply chain configurations. Circular business approaches focus on *"maintaining the highest level of economic value of products, components and materials for as long as possible, while at the same time ensuring that the environmental impact over time is as low as possible"* (Balkenende et al., 2017). In a CE, businesses need to find ways to make profit from *"the flow of materials and products over time"* in a system where products and materials are continually reused (Bocken et al., 2016). In particular, service-oriented business models, such as product service systems (PSS), are often mentioned for their potential to reduce environmental impacts (Qu et al., 2016), and support the CE (Tukker, 2015). PSS have been defined as innovation strategies that *"shift the business focus from designing and selling physical products only, to designing and selling a system of products and services which are jointly capable of fulfilling specific client demands"* (Manzini and Vezzoli, 2003). On the product level, circular design strategies prescribe a lifecycle perspective, targeting product features such as durability, upgradability, reparability, and recyclability (Balkenende et al., 2017).

The Internet of Things (IoT) has been described as a new paradigm in which everyday objects can sense and communicate (Atzori et al., 2010) leading to completely new possibilities for information exchange (Whitmore et al., 2015) and recent reports have emphasized the theoretical potential for IoT to support the transition to a CE (Ellen MacArthur Foundation, 2016; GESI and Accenture, 2016; Lacy, 2015). The IoT has been defined as a *"system of uniquely identifiable and connected constituents capable of virtual representation and virtual accessibility leading to an Internet-like structure for remote locating, sensing, and/or operating the constituents with real-time data/information flows between them, thus resulting in the system as a whole being able to be augmented to achieve a greater variety of outcomes in a dynamic and agile manner"* (Ng and Wakenshaw, 2017) [p. 6]. The IoT brings about the possibility to collect large amounts of data from products in use. The business opportunities of the IoT are thus linked to developments in other technologies such as real-time computing, machine learning, and big data analytics (Stankovic, 2014). The implementation of IoT in a company can support real-time data processing and optimized resource use which could lead to the development of more competitive products and more profitable business models (Li et al., 2015). As the IoT takes form and expands, with a growing number of smart and connected products (Porter and Heppelmann, 2014), physical objects are increasingly able to understand and react to their environment (Kortuem et al., 2010). This allows for improved visibility of assets in the field, with implications for CE. For example, manufacturers can gain knowledge about the current and predicted condition of products, and thereby build services based on actual performance and use (Baines and Lightfoot, 2013). Moreover, connecting products to the IoT can support monitoring of products and parts throughout their lifecycles, and provide decision support for companies implementing circular business models (Lieder and Rashid, 2016).

Previous research has categorized the opportunities of IoT for CE into 'smart' maintenance, reuse, remanufacturing, and recycling (Alcayaga et al., 2019). However, publications covering empirical work, and in particular case study research, are still limited (Cattelan Nobre and Tavares, 2017). Specifically, extant literature does not give an answer to how current practice compares to the envisioned opportunities of IoT for CE.

In this paper, we therefore aim to better understand how IoT is currently implemented for CE in practice, and how that compares to the literature about how IoT might support the CE. To this end, we aim to answer the following research question: How have companies to date implemented IoT for circular strategies and how are these implementations distributed between the opportunities anticipated in literature? To answer this question, we also pose the following sub-question: How can IoT-enabled circular strategies be categorized in a framework which enables mapping a variety of company cases?

To answer these questions, we first provide a brief overview of current literature on IoT-enabled CE (Section 2.2). Subsequently, we explore literature in the fields of IoT and CE to develop a framework that categorizes IoT-enabled circular strategies (Section 2.4). We then collect examples from practice of current IoT implementations for CE and map them to the framework (Section 2.5). The results are discussed in Section 2.6, and the methodology is presented in Section 2.3.

2.2. BACKGROUND

Existing literature about IoT within the context of CE is sparse but growing (Cattelan Nobre and Tavares, 2017). While there is a large pool of literature available in the fields of IoT and CE independently, there is still limited research published in the nexus between the two (Tseng et al., 2018), and there is a need for more research to systemically map CE approaches to emerging digital technologies (Okorie et al., 2018). Below, we summarize previous work that discusses how IoT could be used throughout the lifecycle of a product to reduce environmental impact, prolong product lifetimes, and close material loops.

In a review paper on digital technologies in the circular economy, Pagoropoulos et al. (2017) noted that IoT can enable monitoring of the health and actions of connected products. Salminen et al. (2017) discussed that increasing intelligence and automation can create new business opportunities and help optimize existing operations that are favorable in a circular economy, while Spring and Araujo (2017) argued that 'smart products' allow for *"connected, rich biographies of products"* which can support activities such as maintenance and reverse logistics, especially when products *"circulate beyond the direct governance of one coordinating firm"*. Jensen and Remmen (2017) similarly found that digitalization could potentially support product lifecycle management and the integration of information about, for example, material composition of products, which could stimulate high-quality recycling and reuse. Roy et al. (2016) emphasized the role of *"life cycle 'big data' analytics for continuous maintenance of products"*. Lopes de Sousa Jabbour et al. (2018) discussed the relationship between Circular Economy, Industry 4.0, and sustainable operations management. They suggested, for example, that 'product passports' can improve recovery, and that tracking of products can enable reverse logistics. Gligoric et al. (2019) highlighted the lack of a unified ontology for data exchange to support circular strategies, and presented a technology for printing sensors which could serve as product passports. These passports would carry data about, for example, material composition, recyclability, and potential for reuse.

Only a small number of peer-reviewed case studies have been published that describe the use of IoT for improved circularity of products and services in practice. Lightfoot et al. (2011) interviewed representatives from four companies about how ICT can support the implementation of advanced services. They provide examples of how data from connected trucks can support optimal fuel efficiency, and how data about the location and condition of trains can enable effective and efficient maintenance services. In the context of building equipment, Fargnoli et al. (2019) highlighted how building information management systems can support more effective management of maintenance activities and enhance information exchange between stakeholders in the equipment lifecycle. Grubic and Jennions (2018) performed a multiple case study in which they extracted factors that *"characterise the application of remote monitoring technologies in the context of servitized strategies"*. They found that remote monitoring technology supports *"a broad spectrum of product and service combinations, from warranty to availability contracts"*, and that a complex relationship exists between the technology and the servitized strategies. Ardolino et al. (2016, 2018) built on a literature review and a multiple case study to identify key digital capabilities for service transformation. In the context of performance-based contracts they found that the digital capabilities of 'usage monitoring' and 'prediction' could support the delivery of equipment up-time, and that the capability of 'adaptive control' could support services that promise specific levels of efficiency in product use. Lindström et al. (2017) conducted a case study about recycling management optimization supported by IoT technology. They studied how a company transformed to a PSS provider, how they used IoT, and how the new set-up affected their customers. Kiritsis (2011) studied the implementation of IoT for 'closed-loop product lifecycle management' in 10 demonstrator projects, for example describing how IoT was used to identify and assess the condition of vehicle components available for reuse. Moreno et al. (2017) described a case in which a 3D-printed shoe with integrated sensors could alert the user when repair was needed.

Two frameworks have previously been published that give an overview of the enabling effects of digitalization on circular strategies in business (Alcayaga et al. 2019; Bressanelli et al. 2018). Alcayaga et al. (2019) reviewed literature in the intersections between IoT, PSS and CE and proposed a concept of 'smart-circular PSS' including 'smart' use, maintenance, reuse, remanufacturing, and recycling. The authors give some indication about how different strategies are currently implemented in practice, stating that 'smart use' and 'smart maintenance' have high usage, while 'smart reuse' has medium usage, 'smart remanufacturing' low usage, and 'smart recycling' very low usage. However, this assessment is not clearly based on a review of cases from practice.

Bressanelli et al. (2018) conducted a literature review and a single case study to identify 'usage-focused business model functionalities' that could be supported by IoT and big data analytics, and which had impact on circular strategies. The eight functionalities extracted were the following: improving product design, attracting target customers, monitoring and tracking products activity, providing technical support, providing preventive and predictive maintenance, optimizing the product usage, upgrading the product, and enhancing renovation and end-of-life activities.

The framework by Bressanelli et al. (2018) was designed to analyze a single company case according to IoT-enabled circular strategies applied, while the framework in Alcayaga et al. (2019) was designed as a way to structure findings from literature. The frameworks do not explicitly distinguish between types of IoT solutions, which limits the potential for using the frameworks to identify additional opportunities in that dimension. Moreover, the frameworks were not designed to facilitate mapping and comparison between different cases.

To fulfill the aim of this paper, to better understand how IoT is currently implemented for CE in practice, and how that compares to the literature about how IoT might support the CE, we develop a framework which complements previous work by presenting a structured way of categorizing IoT-enabled circular strategies, and which facilitates mapping of diverse cases according to the IoT capabilities used, as well as the circular strategies enabled. We subsequently use this framework to map a larger set of cases from practice, in order to provide insights into how current implementation in practice is distributed between the different IoT-enabled circular strategies.

2.3. METHOD

To achieve the aim of this paper, we first developed a framework to categorize IoT-enabled circular strategies, and then used the framework to map a set of cases from practice. The research was carried out in four main steps: (1) rapid literature review and framework development; (2) identification of cases; (3) selection of relevant cases; and (4) analysis and mapping of cases to the framework (see Figure 2.1).

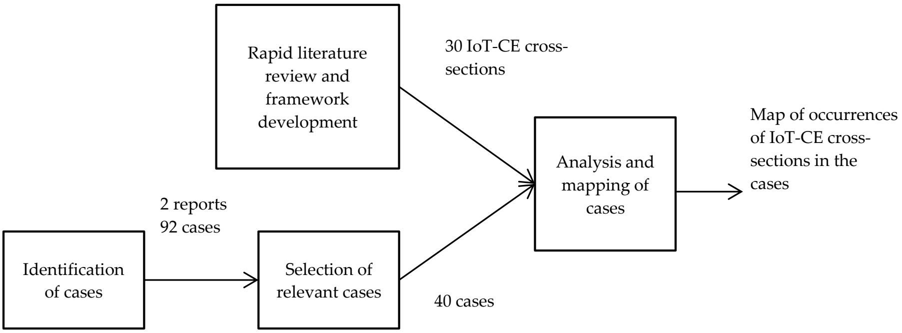


Figure 2.1: Steps in method to develop the framework, identify and select the cases, and map the cases to the framework.

2.3.1. RAPID LITERATURE REVIEW AND FRAMEWORK DEVELOPMENT

In order to categorize the company cases, a framework was developed which distinguishes between different categories of IoT capabilities on the one hand, and different categories of circular strategies on the other hand. To identify the key capabilities underpinning IoT and the key strategies applied in CE, a rapid literature review was conducted (Mays et al., 2001). This methodology was considered appropriate given the focused search target, the small number of academic sources specific to IoT-enabled CE, and the broad scope of the fields of IoT and CE as such. The goal of the review was to identify an established view among scholars about IoT capabilities and circular strategies, respectively. To this end, review papers were prioritized. Moreover, papers with few citations were excluded based on their low or, in the case of recent publications, still unclear scientific impact. In the field of IoT, papers were collected from academic journals based on the following criteria: the papers should (1) provide an overview of the technology and its enabling capabilities; (2) be general in the sense that the results could be applied across industries; and (3) be well cited (>15 citations) to demonstrate that the findings are recognized by other researchers. The search was performed using the scientific databases Scopus and Web of Science, and the selection resulted in eight articles published in academic outlets between 2010 and 2016.

In the field of CE, academic literature was consulted to identify existing frameworks describing product and business model design strategies. Similar selection criteria were applied. The papers should (1) explicitly focus on deriving design strategies for CE, and (2) present results which could be applied generally (not case or industry specific), and (3) have more than 15 citations. The search was performed using the scientific databases Scopus and Web of Science, and the selection resulted in five articles published in academic outlets between 2014 and 2017.

The IoT capabilities and circular strategies described in literature were interpreted and grouped together into categories, using frameworks from ‘grey’ literature as starting points. In the IoT dimension, we started from the four categories —monitoring, control, optimization and autonomy—as presented in the framework of capabilities of smart connected products in Porter and Heppelmann (2014). We then used the academic literature sources to extract additional IoT capabilities.

Similarly, to define categories of circular strategies, we built on the often cited framework presented by the Ellen MacArthur Foundation (2013), which identifies five main circular strategies: share, maintain or prolong, reuse or redistribute, refurbish or remanufacture, and recycle. Based on academic literature that presents design strategies for CE, we identified additional strategies to be added to the framework.

Finally, we excluded categories in both dimensions that did not prove to be relevant for the purpose of the framework. The framework development process is explained in more detail in Section 2.4.

2.3.2. IDENTIFICATION OF CASES FROM PRACTICE

Since there are few case studies published in academic literature about how IoT can be used for CE, 'grey' literature was used to extract cases from practice. Reports were scanned based on the following criteria: (1) it should discuss the application of IoT technology, while also taking into account environmental aspects; (2) it should review a large set of cases (>20), to allow for comparable case descriptions; and (3) it should not be directly authored by the ICT industry, to avoid bias. Based on these criteria, two reports were identified as suitable sources for a comprehensive overview of relevant company cases. One of the reports originates from the field of CE and is compiled by the Ellen MacArthur Foundation (2016), while the other report comes from the field of IoT and is compiled by the Harvard Business Review (Porter and Heppelmann, 2014). Both organizations are well known knowledge sources in their respective fields, and were judged to be reliable sources for the case review. The two reports present a combined total of 92 cases, describing a wide range of IoT and CE implementations in business. Considering the high number of cases reviewed in the two reports and the broad scope taken by both organizations in assembling the collections of cases, we treated the combined set of cases, although certainly not complete, as a representative sample of current practice of using IoT for CE in business.

2.3.3. SELECTION OF RELEVANT CASES

From the 92 cases presented in in the two reports (Ellen MacArthur Foundation, 2016; Porter and Heppelmann, 2014) we selected 40 cases to analyze in this study. The selection process of going from 92 cases to 40 cases is depicted in Figure 2.2. The following selection criteria were applied: (1) the case should be described in enough detail to allow for further analysis; (2) the case should depict the use of a circular strategy; (3) the case should be centered around the use of a IoT-enabled product; and (4) the case should describe an actual implementation to date. 22 cases were excluded because we lacked information to do the subsequent analysis and mapping. For example, if a large manufacturer was mentioned without any description regarding the product or service considered, the case could not be further analyzed. The remaining 70 cases were briefly analyzed in terms of relevance to IoT and CE. 12 cases were excluded because they did not describe any impact in terms of CE or environmental sustainability. Examples of cases that were excluded based on this criterion are FitBit (captures data about daily activities to support a healthy lifestyle) and iRobot Roomba (autonomous vacuum cleaner that uses sensors to navigate). Nine cases were excluded because they did not show a strong enough IoT component, i.e., they did not include any interactions with a physical smart product. Examples here are AirBnB (online platform to match supply and demand for short stay rental apartments) and PayByPhone (app that makes it easier to pay for parking). Finally, since the focus of the paper was to understand current implementation, we excluded prototypes and start-ups. Nine cases were excluded based on this criterion, for example Aganza (platform for offering products in a 'pay-as-you-go' model) and Burba (smart bin prototype).

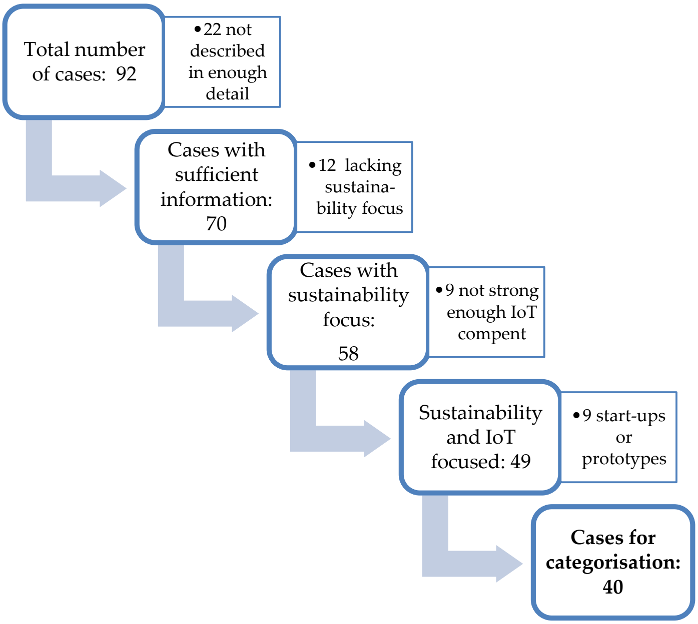


Figure 2.2: Process of selecting 40 cases for analysis.

2.3.4. ANALYSIS AND MAPPING OF CASES

For each of the selected cases, we read the description of the case in the publication where it was presented and highlighted information about the use of IoT, and about the implementation of circular strategies. When needed, additional data was retrieved from other sources, such as the company's website. Based on the data retrieved, we could map the case to the framework according to the definitions of IoT capabilities and circular strategies presented in Section 2.4. It should be noted that each case can display the use of several IoT capabilities and circular strategies. The mapping of all the cases, together with brief case descriptions, is provided in Appendix A.

2.4. FRAMEWORK

This section describes how the framework was developed based on literature. We explain, separately, how we derive five categories in the IoT dimension and six categories in the CE dimension.

2.4.1. IoT CAPABILITIES

CATEGORIES IN LITERATURE

While the exact terminology to describe IoT-related business opportunities varies between authors, we here synthesize core capabilities of the technology as found in literature. Porter and Heppelmann (2014) categorize the capabilities of 'smart, connected products' into four levels: monitoring, control, optimization, and autonomy. Monitoring relates to the ability of a product to provide information about its own use, and to sense its environment (Whitmore et al. 2015; Kortuem et al., 2010). For example, monitoring can be applied for diagnostics and prognostics of products-in-use, in order to enhance maintenance services in PSS (Grubic, 2014). On the level of the business model, monitoring can support business models that are based on product access and/or performance, as pricing can be based on actual product usage (Porter, 2015). Control refers to the ability to change product and system parameters. When a product is connected to the IoT, this control can happen remotely (Gubbi et al., 2013). Moreover, if the product is equipped with the capabilities of monitoring and processing, it can control itself based on insights from monitoring conditional parameters (Atzori et al., 2010). Optimization can be described as the application of algorithms and analytics to in-use or historical data, to optimize output parameters, utilization, or efficiency (Porter and Heppelmann, 2014). Autonomy brings about an additional layer of self-coordination to the functionality of smart products, giving enhanced ability to control system complexity, still using the capabilities of monitoring, control, and optimization (Atzori et al., 2016).

Additional capabilities, which are not explicitly considered in the framework by Porter and Heppelmann, (2014) can be extracted from literature. Firstly, an early development in the direction towards an IoT was the increased use of RFID technology to track products and parts (Kortuem et al., 2010; Atzori et al., 2016). RFID tags have, among other applications such as bank cards and road toll tags, been of large importance for supply chain management (Gubbi et al., 2013). Secondly, some authors explicitly highlight communication, networking (Gubbi et al., 2013), and processing (Kortuem et al., 2010) as important IoT capabilities. Thirdly, an important business opportunity brought about by the IoT is that products and systems can provide feedback from the use phase back to design (Lightfoot et al., 2011). This data feedback can give insights into actual product use and performance, and thereby inform design improvements (Porter, 2015). For example, this strategy can be used to identify weaknesses in current designs (Xia et al., 2016) or to evaluate how users react in real life to design interventions (Bogers et al., 2016). The idea of taking advantage of product-in-use data for design improvements is well established in the design of websites and software (e.g., Atterer et al., 2006). In the design of physical products, the phenomenon is emerging in academic literature using terms like closed-loop design evolution (Xia et al., 2016) and data-enabled design (Bogers et al., 2016). Table 2.1 shows IoT capabilities described in previous literature, and how we map them to seven main categories: *tracking*, *monitoring*, *control*, *optimization*, *design evolution*, *autonomy*, and *processing/networking/communication.*

Table 2.1: IoT capabilities described in literature.

Source	IoT Capability Described	Categories of IoT Capabilities: Tracking	Monitoring	Control	Optimization	Design Evolution	Autonomy	Processing/ Networking/ Communic.
Porter and Heppelmann, (2014)	Monitoring		x					
	Control			x				
	Optimization				x			
	Autonomy						x	
Grubic, (2014)	Diagnostics		x					
	Prognostics		x					
	Feedback to R&D					x		
Lightfoot et al., (2011)	Visibility of condition, operating characteristics, time in use		x					
	Visibility of location	x						
	Feedback from the use phase to product and service design					x		
Kortuem et al., (2010)	Sensing		x					
	Processing							x
	Networking							x
Whitmore et al., (2015)	Identifying, Tracking, Tracing	x						
	Sensing, Monitoring		x					
	Networking							x
	Processing							x
	Control			x				

Continuation of Table 2.1

Source	IoT Capability Described	Tracking	Monitoring	Control	Optimization	Design Evolution	Autonomy	Processing/ Networking/ Communic.
	Data-supported decision making				x			
	Development of new business models					x		
Gubbi et al., (2013)	Automatic Identification	x						
	Monitoring		x					
	Actuation			x				
	Automated decision making				x		x	
	User interaction and communication							x
Atzori et al., (2010)	Identification	x						
	Sensing		x					
	Communication							x
Atzori et al., (2016)	Readable, recognizable, locatable, addressable	x						
	Controllable			x				
	Embedded sensors and actuators		x	x				
	Self governance and self management						x	
Xia et al., (2016)	Closed-loop design evolution					x		
	Conditions monitoring		x					

CATEGORIES SELECTED

Based on the reviewed IoT capabilities, we select five categories as relevant for our framework: *tracking*, *monitoring*, *control*, *optimization* and *design evolution* (Table 2.2). Compared to the seven IoT capabilities presented in Table 2.1, we do not include *autonomy* or *processing/networking/communication*. The category of processing/networking/communication is excluded because it describes basic technical requirements needed to enable the other capabilities. The category of autonomy is excluded because it describes a feature that can be present to some level within all the other categories. For example, decisions about control and optimization can be taken by either a human or a machine, and many solutions show a combination of the two.

Table 2.2: IoT capabilities used in the framework.

IoT Capability	**Definition used in this paper**
Tracking	Information is available about a product's identity, location, or unique composition.
Monitoring	Information is available about a product's use, condition, or environment. This includes alerts and notifications.
Control	Product functionality can be controlled through software, based on predefined options. This includes pushing regular updates.
Optimization	Goal-based improvements of operations are supported by using 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.

2.4.2. CIRCULAR STRATEGIES

CATEGORIES IN LITERATURE

The CE is still a relatively new term in the academic literature, and a large number of different definitions have been published (Kirchherr et al., 2017). Previous research has shown that academics do not fully agree about which aspects should be included in the CE concept, and which not (Geissdoerfer et al., 2017). For the purpose of this paper, however, we choose to focus on design and business model strategies that can support environmental benefits in the CE. As we focus on IoT enabled products, we limit our search to strategies in the so-called technical metabolism (Braungart et al., 2007) i.e., products that have the potential to be recovered and reused, partly or as an entity, through several life cycles. Within this scope, we find that previous literature can be condensed to a set of eight key circular strategies, as seen in Table 2.3, and as summarized below.

The Ellen MacArthur Foundation (2013) defines five main circular strategies: share, maintain/prolong, reuse/redistribute, refurbish/remanufacture, and recycle. Sharing of products has the potential to increase their utilization, which could reduce the total number of products since one product could satisfy many peoples' need for a certain function (Tukker, 2004). Maintaining products and prolonging their lifetimes are mentioned as a circular strategy by, e.g., den Hollander et al. (2017) and Bocken et al. (2016). A core aspect of the CE is the looping of resources from a post-use stage back to production (Balkenende et al., 2017; Bocken et al., 2016). Remanufacturing and recycling have been researched extensively in the design for CE literature (e.g., Bakker et al., 2014; Moreno et al., 2016). Strategies for reuse of products are also often described in the CE literature, sometimes framed as part of product-lifetime extension strategies (Moreno et al., 2016) and sometimes as part of looping strategies (Ellen MacArthur Foundation, 2013).

Some additional strategies, not mentioned in the EMF framework (Ellen MacArthur Foundation, 2013), can be extracted from literature. Material efficiency in product design is a commonly used strategy to reduce unnecessary resource use (Bakker et al., 2014, Moreno et al., 2016). Similarly, sustainable design strategies to improve the efficiency of inputs during use are well established, particularly with regards to energy efficiency.

From a broader perspective, a core aspect of circular strategies is to support systemic change towards a more sustainable economy. In the design literature, previous research has produced specific design tools that aim to facilitate systems change. Such tools support designers in applying 'whole systems design', considering the complex system around the product or service in order to ensure environmental and societal benefits (Moreno et al., 2016). Table 2.3 shows circular strategies described in previous literature, and how we map them to eight main categories: *efficiency in use*, *increased utilization*, *product lifetime extension*, *reuse*, *remanufacturing*, *recycling*, *material efficiency*, and *systems change*.

Table 2.3: Design and business model strategies for CE.

		Categories of CE Strategies							
Source	**CE Strategy Described**	**Efficiency in Use**	**Increased Utilization**	**Product Lifetime Extension**	**Reuse**	**Remanufact.**	**Recycling**	**Material Efficiency**	**Systems Change**
Ellen MacArthur Foundation, (2013)	Share		x						
	Maintain/Prolong			x					
	Reuse/Redistribute				x				
	Refurbish/Remanufact.					x			
	Recycle						x		
Bocken et al., (2016)	Long-life products			x					
	Product life extension			x		x			
	Closing resource flows						x		
Bakker et al., (2014)	Material efficiency							x	
	Longer product life			x					
	Product repair			x					
	Product refurbishment				x	x			
	Product remanufacturing					x			
	Product/material recycling						x		

Continuation of Table 2.3

Source	**CE Strategy Described**	**Efficiency in Use**	**Increased Utilization**	**Product Lifetime Extension**	**Reuse**	**Remanufact.**	**Recycling**	**Material Efficiency**	**Systems Change**
Balkenende et al., (2017)	Durability			x					
	Upgrading			x					
	Adapting			x					
	Repair			x					
	Refurbishment			x		x			
	Parts harvesting				x	x			
	Remanufacturing					x			
	Recycling						x		
Moreno et al., (2016)	Design for resource conservation	x						x	
	Design for multiple cycles					x	x		
	Design for long life use of products			x	x				
	Design for systems change								x
den Hollander et al., (2017)	Design for long use			x					
	Design for extended use			x					
	Design for recovery					x			
	Design for recycling						x		

CATEGORIES SELECTED

We select six categories of circular strategies to be used in our framework: *efficiency in use, increased utilization, product lifetime extension, reuse, remanufacturing,* and *recycling* (Table 2.4).

Table 2.4: Circular strategies used in the framework.

Circular Strategy	**Definition used in this paper**
Efficiency in Use	Energy, water, and other inputs are used more efficiently during a product's use phase.
Increased Utilization	Time periods during which a product is not used by anyone are identified and reduced.
Product Lifetime Extension	A product's lifetime is extended by minimizing wear, through predictive, preventive or reactive maintenance and repair, or through updates.
Reuse	A product or component is identified, assessed and transferred from one user to another. The process can involve maintenance steps, such as cleaning.
Remanufacturing	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	The constituent materials of a product or component are assessed, sorted, and treated so that they can be used again.

Compared to Table 2.3, we exclude *material efficiency* and *systems change*. The reason to exclude material efficiency, is that this strategy can only be applied in the design phase, making it less relevant from an IoT point of view. Once the product design is defined, the material efficiency in set. This differs from, for example, efficiency in use, which depends on the product design as well as use patterns and conditions in the product's environment. In this case, IoT derived product-in-use data could thus be used to optimize the efficiency in use during the product's lifetime.

Furthermore, we exclude strategies related to systems change. The reason for this is that systems change is an overarching strategy with a primary focus on impact. We argue that circular systems change related to physical products is always the result of the application of one or more of the other circular strategies. Thus, while we note the importance of understanding system-level effects when designing for the circular economy, a categorization of the cases according to their systemic impact is outside the scope of this paper.

2.4.3. FINAL FRAMEWORK

Building on the IoT capabilities and the circular strategies derived from literature, we propose a framework composed as a matrix in which the categories of IoT capabilities and circular strategies form the columns and rows respectively. Each combination of

IoT capability and circular strategy forms a IoT-CE cross-section (Figure 2.3). The IoT capabilities in the framework are defined in Table 2.2. Tracking relates to the ability to uniquely identify and localize assets. Monitoring describes the use of sensors and metering devices to give information about a product's use, condition, and environment. Control makes it possible to steer product operations through some type of digital interface. Optimization relates to goal-based improvement using advanced algorithms as well as monitoring and/or control capabilities. Optimization can be applied to multiple levels. It can refer to adapting product-internal operations, system operations, or service operations such as maintenance. Finally, design evolution is the ability to learn from product-in-use data in order to improve the design of a product or a service. We note that this capability is different from the others in the way that it does not necessarily change the functionality of the product itself. Instead, it allows for learning about in-the-field product parameters, such as performance and use patterns. These insights can then be used in the design of a next generation of the product or PSS, rather than during use.

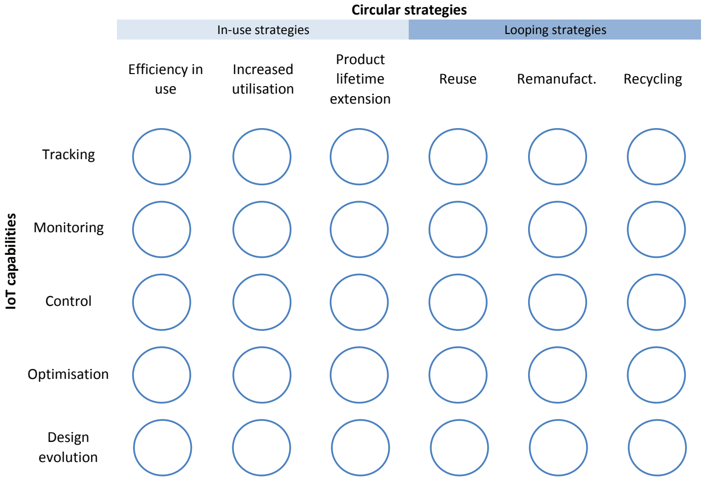


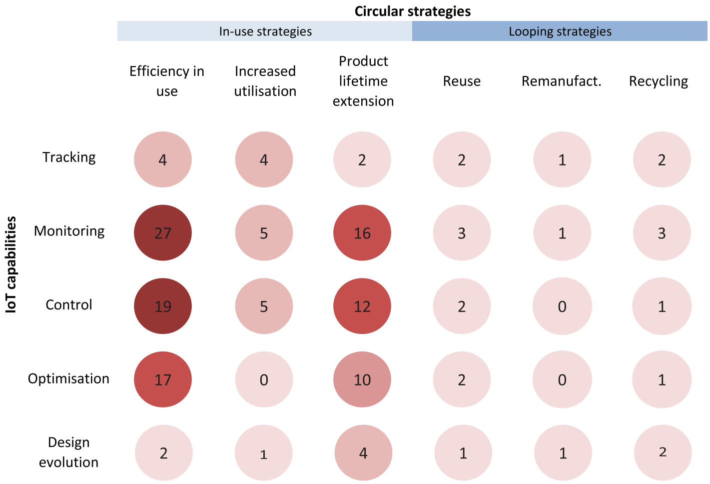
Figure 2.3: Framework categorizing IoT capabilities on the one hand, and circular strategies on the other.

The circular strategies in the framework are defined in Table 2.4. The first three strategies relate to the use phase of a product while the last three consider strategies in which products, parts and materials are looped from one use phase to the next. We use the term 'product lifetime extension' to describe activities or design consideration that minimize product wear, or that support maintenance, repair and/or updates. Compared to some other authors, we view reuse strategies as separate from product lifetime extension.

2.5. Mapping of the Cases to the Framework

The 40 analyzed cases cover a wide range of products and industries, targeting different customer groups. High-investment products such as mining equipment, wind turbines, and jet engines are examples of products represented in the cases. Moreover, assets in the built environment, infrastructure and the power grid are represented, as are smart connected cars used in different types of car sharing services. Several cases describe solutions for energy management in buildings through smart products such as thermostats, fans, HVAC systems, elevators, washing machines, and lighting systems. Printers and ATMs are also represented. Most of the identified cases show products and services offered in a business-to-business context, but business-to-customer and business-to-government examples are also present in the set. All cases concern products that can be looped through the technical cycle (Braungart et al., 2007) i.e., that have the potential to be recovered and reused through several life cycles.

Figure 2.4 shows the mapping of the 40 company cases to the framework. Each case was analyzed and mapped according to the categories of IoT capabilities and circular strategies defined in Section 2.4, resulting in a ‘heat map’ of the occurrences of IoT-CE cross-sections. Many of the cases describe more than one IoT-CE cross-section, leading to 150 categorized occurrences of IoT-CE cross-sections from the 40 cases. It should further be noted that while the categories are uniquely defined, they are not mutually exclusive. For example, cases displaying optimization often also rely on the use of monitoring or control capabilities. The results show that examples of IoT-enabled ‘efficiency in use’ and ‘product lifetime extension’ dominate in the analyzed set of cases, while IoT-enabled looping and design evolution are relatively unexplored.



	Circular strategies					
	In-use strategies			Looping strategies		
IoT capabilities	Efficiency in use	Increased utilisation	Product lifetime extension	Reuse	Remanufact.	Recycling
Tracking	4	4	2	2	1	2
Monitoring	27	5	16	3	1	3
Control	19	5	12	2	0	1
Optimisation	17	0	10	2	0	1
Design evolution	2	1	4	1	1	2

Figure 2.4: Heat map of IoT-CE cross-section occurrences found in the 40 analyzed cases.

Below, we present examples of cases which were mapped to different parts of the framework. To facilitate reading, the framework is divided into five sections: (A) IoT-enabled efficiency in use, (B) IoT-enabled increased utilization, (C) IoT-enabled product lifetime extension, (D) IoT-enabled looping, and (E) design evolution for circular strategies (Figure 2.5). A complete overview of all analyzed cases is provided in Appendix A.

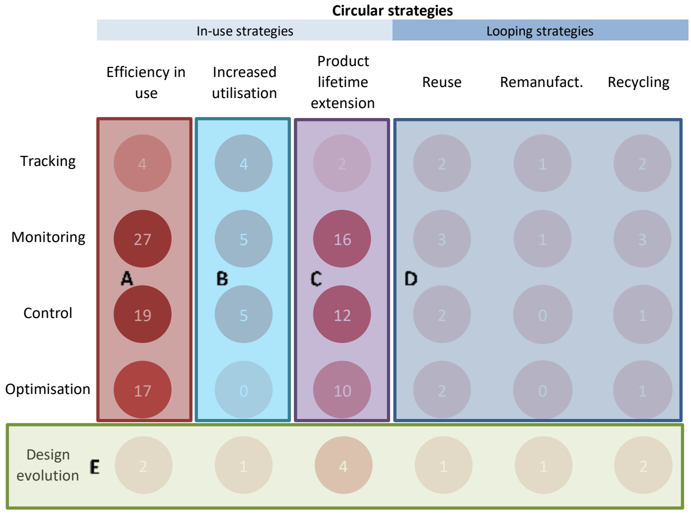


Figure 2.5: The five sections of the framework: (A) IoT-enabled efficiency in use, (B) IoT-enabled increased utilization, (C) IoT-enabled product lifetime extension, (D) IoT-enabled looping, and (E) design evolution for circular strategies.

IoT-Enabled Efficiency in Use

The cases in this group display the use of IoT for different types of efficiency measures in the use phase. Many examples describe strategies for saving energy, for example through tracking of vehicles, or by monitoring energy use and performance. Moreover, remote control of energy consuming products allows users to save energy, while advanced energy management systems can learn from the user's routines to optimize the system for efficiency and comfort. Another example is that smart farming systems can reduce water use for irrigation. Typical examples are presented in Table 2.5.

Table 2.5: Typical examples of cases that describe IoT-enabled efficiency in use.

IoT Capability	**Examples of use of IoT Capability for 'Efficiency in Use'**
Tracking	- Spire tracks vehicles using satellite technology. Among other things, the information can be used by the customer to optimize routing.
Monitoring	- Cisco Energy Management uses IoT to measure energy use and displays it to the user, so that actions can be taken to improve operational efficiency. - Libelium allows farmers to monitor their crops' condition, to better know how much pesticides, fertilizers, and water is needed.
Control	- Carrier systems' system for heating, ventilation, and air conditioning allows users to control the indoor climate in a building remotely, so that energy can be saved when nobody is present. - Auscott limited control irrigation systems based on soil moisture data, reducing excess water use.
Optimization	- Nest Labs' smart thermostats can adapt the system operations to the users' routines. In this way, an optimal balance between comfort and energy savings can be found. - AGCO Agcommand monitors use, condition of farm equipment, as well as environmental parameters, to optimize overall farm performance.

IOT-ENABLED INCREASED UTILIZATION

Several cases in this group describe services that allow users to access and use products that they do not own. For example, in a car-sharing service, IoT allows users to find a car that are close and available for use. The service provider can store information about who has used the car, for how long, and at what time. Another example is increased utilization of space in office buildings, allowing fewer rooms to serve more people. Some typical examples are listed in Table 2.6.

Table 2.6: Typical examples of cases that describe IoT-enabled increased utilization.

IoT Capability	**Examples of use of IoT Capability for 'Increased Utilization'**
Tracking	- DriveNow and Car2Go offer car sharing through mobile applications that let users find available cars based on location. - ZipCar recover lost or stolen cars (from their car sharing fleet), and provide facts for insurance claims if an accident happens.
Monitoring	- Cisco's "Smart+Connected Personalised Spaces" office management system aims at increasing the utilization of office spaces based on occupancy data.
Control	- Some level of control is needed in car/bike sharing systems (e.g., Car2Go, Zipcar, DriveNow, Hubway) in order to unlock the product without a physical key.

IOT-ENABLED PRODUCT LIFETIME EXTENSION

Cases in this group describe maintenance and repair activities, as well as upgrades (see Table 2.7). For example, tracking allows maintenance actors to identify and locate products that need to be serviced. Moreover, products can monitor their own use and status, and send alerts about when they need maintenance, and which spare parts to order. The capability of control can also enable remote maintenance, repair, and upgrades. In advanced cases, companies continuously monitor the condition of products and apply prediction models that allow them to optimally plan and execute maintenance before a product fails.

Table 2.7: Typical examples of cases that describe IoT-enabled product lifetime extension.

IoT Capability	**Examples of use of IoT Capability for 'Product Lifetime Extension'**
Tracking	- Philips' 'CityTouch' tracks products and parts installed at customer sites, facilitating maintenance activities.
Monitoring	- Whirlpool's washing machines give the user notifications about upcoming maintenance needs. - Philips' 'light-as-a-service' offering includes monitoring of faults, which is used to manage maintenance and repairs.
Control	- Diebold monitors its ATM machines and applies remote repairs and updates. - Tesla's cars can schedule their own repairs based on fault monitoring. Tesla also performs remote service and upgrades on their cars.
Optimization	- GE aviation uses hundreds of sensors to identify discrepancies between expected and actual performance of jet engines in use, in order to optimize repair and maintenance services.. - Joy Global monitors the performance and faults of mining machines and uses this data for predictive maintenance.

IOT-ENABLED LOOPING

Only a few cases describe IoT-enabled looping strategies. As summarized in Table 2.8, tracking of products in the field can give companies a better overview of the installed base of products that will eventually become available for reuse. By monitoring the use and condition of a product, reuse of products can be enabled. The capability of control can also make take-back systems more effective. Finally, the Philips' 'CityTouch' case suggests that the manufacturer, by monitoring the condition of products and parts, can optimize the use times in multiple use cycles on the individual part level.

Table 2.8: Typical examples of cases that describe IoT-enabled looping.

IoT Capability	**Examples of use of IoT Capability for 'Looping'**
Tracking	- Delta Development leases and tracks elevators in two recent development projects, and can identify elevators that could be reused in a different setting.
Monitoring	- Delta Development monitors the condition of elevators in use, to assess if they can be used again.

Continuation of Table 2.8

IoT Capability	**Examples of use of IoT Capability for 'Looping'**
Control	- HP's printers monitor ink levels and automatically order a new cartridge and, at the same time, an envelope to send the old cartridge back.
Optimization	- Philips' 'CityTouch' can monitor the use cycles of individual luminaires and their constituent parts which enables looping of components through additional use cycles.

CIRCULAR STRATEGIES ENABLED BY DESIGN EVOLUTION

As for IoT-enabled looping strategies, only a few cases described examples of how design evolution could enable circular strategies. However, some examples (shown in Table 2.9) describe how designers could improve product design based on information about the performance of products in the field. For example, in order to improve design both by avoiding technical failures, and by designing products and services that users value over time, designers could use detailed information about how products are used and discarded.

Table 2.9: Examples of cases that describe design evolution for circular strategies.

CE Strategy	**Examples of use of 'Design Evolution' for CE Strategy**
Efficiency in Use	- GE uses data from jet engines in use to support design improvement of the engine for optimal performance, including energy efficiency.
Increased Utilization	- ZipCar uses data about how vehicles are being used in order to improve their service design to achieve better availability as well as reduce operational costs.
Product Lifetime Extension	- In HP's 'instant ink service', data from products-in-use supports design for durability.
Looping	- The IBM 'reuse optimization tool' uses IoT data to support the design of services related to recovery strategies. The tool enables individual businesses to build a business case for looping.

2.6. DISCUSSION

The aim of this study was to answer the following research question: How have companies to date implemented IoT for circular strategies and how are these implementations distributed between the opportunities described in literature? As a first step to answer this question, a framework was developed which enabled the mapping of a large set of company cases according to the IoT capabilities used as part of particular circular strategies. The framework distinguishes between five types of IoT capabilities (tracking, monitoring, control, optimization, and design evolution) and six types of circular strategies (efficiency in use, increase utilization, product lifetime extension, reuse, remanufacturing, and recycling). The types of IoT-enabled circular approaches depicted in our framework are largely similar to approaches in previously published work (Bressanelli et al., 2018; Alcayaga et al., 2019). However, some differences can be noted. The framework by Alcayaga et al. (2019) defines five distinct IoT-enabled circular strategies: smart use, smart maintenance, smart reuse, smart remanufacturing, and smart recycling. The framework in (Bressanelli et al., 2018) presents eight IoT-enabled circular strategies related to products activity, technical support, preventive and predictive maintenance, product usage, upgrading, and end-of-life activities. However, neither of the two frameworks clearly distinguishes between different types of IoT capabilities used. In comparison, our categorization into six circular strategies and five IoT capabilities provides additional detail into how IoT could support circularity. The categorization of IoT capabilities into tracking, monitoring, control, optimization, and design evolution is useful in that it clarifies different ways in which IoT can be used, and in this study we further noted that the IoT capabilities are linked to each other. Tracking and monitoring can be used as stand-alone strategies, but also as a foundation for control, optimization, and/or design evolution strategies.

Our framework is also different from Bressanelli et al. (2018) and Alcayaga et al. (2019), in that it was designed to allow for easy mapping of a wide range of cases according to the IoT-enabled strategies implemented. Through further evaluation with practitioners, the framework could be developed into a tool for companies to map their current state of IoT-enabled CE implementation, and to consider additional opportunities that might be interesting for further exploration.

The second result of the paper is the mapping of 40 cases onto the framework. By analyzing and mapping the cases, we presented concrete examples of cases displaying the different IoT-enabled circular strategies. In response to the main research question posed, we observe that current implementations of IoT-enabled circular strategies are mainly applied in the use phase of products (Sections A, B, and C in Figure 2.5) and that only a few cases have implemented IoT-enabled reuse, remanufacturing, and recycling (Section D in Figure 2.5). This is an important finding, since reuse, remanufacturing and recycling are often seen as core strategies of the circular economy. Whilst literature has mentioned that IoT can support reuse, remanufacturing, and recycling (e.g., Spring and Araujo, 2017; Lopes de Sousa Jabbour et al., 2018), the results presented here show that real-world applications in these areas are still limited. This result is in line with Alcayaga et al. (2019), who stated that smart use and smart maintenance are more common than smart reuse, smart remanufacturing, and smart recycling. However, the analysis used to derive that conclusion is not clear by Alcayaga et al. (2019). In this paper, we systematically derived the implementation distribution between the different strategies, based on the analysis of a large set of cases from practice.

Based on our results, we further note that the capability of design evolution —the feedback of product-in-use data to design in order to improve products and services (E in Figure 2.5) —is not commonly used in practice to support circular strategies. To the best of our knowledge, this result has not been reported previously.

By pointing out under-explored areas, the findings in this paper provide a starting point for future research into why IoT-enabled looping and design evolution for circular strategies are not implemented to scale. We suggest future research into the real-world challenges of implementing circular looping strategies, and the opportunities and challenges of using IoT technology to support such strategies and associated business models.

Finally, some limitations of the paper in terms of scope and methodology should be mentioned. In this study, we intentionally focused on reviewing implemented solutions, i.e., solutions that are currently offered to customers. Therefore, we excluded prototypes and start-up companies from the analysis. Analyzing such early stage initiatives would enrich the picture with possible future developments in the implementation of IoT-enabled circular strategies.

Moreover, actual assessment of impact on environmental sustainability was outside the scope of this paper. In order for practitioners to be able to effectively use our framework as a tool when innovating on IoT-enabled circular strategies, it should be complemented with other tools that provide information on the sustainability impact of IoT-enabled circular solution.

From a methodology point of view, our study is limited in that it is based on two reports to source the company cases. Although the 40 selected cases include a diverse range of companies and products, it is possible that some relevant examples were not covered in the set. Thus, while the results presented in this paper answer the research question posed in Section 2.1 by presenting the distribution of implementations in the 40 cases, future studies could include additional cases in order increase the robustness of the results.

Also, the mapping of the cases to the framework unavoidably involved a degree of interpretation. However, we argue that although some cases could have been interpreted differently, it would not notably change the main resulti.e., the relative distribution in the implementation of the different IoT-enabled circular strategies. Also, as we show how we categorize each case in Appendix A, it is possible for other researchers to analyze the same set of cases and potentially come up with an alternative categorization.

Lastly, the rapid literature review approach followed when developing the framework is limited in that it is less comprehensive than a full ‘systematic literature review’. However, the goal of this review was not to compile a comprehensive list of publications in the fields of IoT and CE, but to identify commonly agreed views among scholars on IoT capabilities and circular strategies, respectively. Among the criteria used for selecting papers to include in the rapid literature review, one was to omit papers with few citations. This criterion was chosen since a high number of citations was considered a suitable indication that the results were accepted and acknowledged by the scientific community. It is possible, however, that this led to the exclusion of relevant articles that have only recently been published, and therefore lack citations at this point in time.

2.7. CONCLUSIONS

This study aimed to understand how companies have implemented IoT for circular strategies, and how those implementations compare to anticipated opportunities described in literature. To that end, a two-step approach was followed. First, a framework was develop based on previous literature. The framework gives a categorization of IoT-enabled circular strategies according to the IoT capabilities used, and the circular strategies enabled. The framework complements previously published frameworks, as it adds additional detail and allows for easy mapping of diverse cases. In its current form, the framework could be useful for companies since it provides an overview of IoT-enabled circular strategies. However, the usefulness of the framework for practitioners has not been evaluated in this paper.

Secondly, we collected 40 cases from practice depicting current implementation of IoT for CE, and mapped them to the framework. This way, we could provide concrete examples of cases mapped to different parts of the framework, and derive practice-based insights about the current distribution of implementation of IoT-enabled circular strategies.

Our results show that current implementation of IoT-enabled circular strategies mainly supports ‘efficiency in use’ and ‘product lifetime extension’. Only a small number of the reviewed cases displayed IoT-enabled ‘looping’ (reuse, remanufacturing, and recycling). This is a notable result, as ‘closing the loop’ is one of the main goals expressed in the CE literature. Moreover, few cases described ‘design evolution’ for CE, i.e., using the feedback of data from products-in-use to improve circular design.

Future research could build on the results presented in this paper to develop a tool for companies to map their current state of IoT-enabled CE implementation, and to improve their strategy further. To be able to provide such guidance for practitioners, more studies are needed. Specifically, future research should investigate why IoT-enabled looping strategies or design evolution for circular strategies have not been implemented to scale. To do so, in-depth case studies with companies would be relevant, as such studies could extract context-specific opportunities as well as implementation barriers perceived by the companies. Moreover, insights from studies focusing on the actual sustainability impact of different IoT-enabled circular strategies would be important as input to recommendations for practitioners about how to reap the benefits of IoT for CE.

Author Contributions:
E.I. is the corresponding author of this manuscript. She is the primary author of this manuscript. She was in charge of collecting and analyzing the data, and was the leading author of the paper. E.J. and R.B. supervised her in this process and contributed to the writing process and to reviewing the paper internally. G.K. provided expert knowledge and reviewed the manuscript at different stages of the process. All authors read and approved the final manuscript.

Funding:
This work was funded by the Circular European Economy Innovative Training Network, Circeuit, an action funded by the European Commission under the Horizon 2020 Marie Sklodowska Curie Action 2016 (grant agreement number 721909).

Acknowledgments:
The authors would like to express their gratitude towards the anonymous reviewers whose feedback helped improve this manuscript.

Conflicts of Interest:
The authors declare no conflict of interest.

REFERENCES

A. Alcayaga, M. Wiener, and E. G. Hansen (2019). Towards a framework of smart-circular systems: An integrative literature review. *Journal of Cleaner Production* **221**, 622.

M. Ardolino, M. Rapaccini, N. Saccani, P. Gaiardelli, G. Crespi, and C. Ruggeri (2018). The role of digital technologies for the service transformation of industrial companies. *International Journal of Production Research* **56**, 2116.

M. Ardolino, N. Saccani, P. Gaiardelli, and M. Rapaccini (2016). Exploring the Key Enabling Role of Digital Technologies for PSS Offerings. *Procedia CIRP* **47**, 561.

R. Atterer, M. Wnuk, and A. Schmidt (2006), Knowing the user's every move: user activity tracking for website usability evaluation and implicit interaction, in *Proceedings of the 15th Int. Conf. on World Wide Web*, Edinburgh, UK.

L. Atzori, A. Iera, and G. Morabito (2010). The Internet of Things: A survey. *Computer Networks* **54**, 2787.

L. Atzori, A. Iera, and G. Morabito (2016). Understanding the Internet of Things: definition, potentials, and societal role of a fast evolving paradigm. *Ad Hoc Networks* **56**, 122.

T. Baines and H. Lightfoot (2013). Information and Communication Technologies. in *Made to Serve: How manufacturers can compete through servitization and product-service systems*, edited by T. Baines and H. Lightfoot, Chap. 9, pp. 169–180. John Wiley & Sons, Incorporated.

C. Bakker, F. Wang, J. Huisman, and M. Den Hollander (2014). Products that go round: exploring product life extension through design. *Journal of Cleaner Production* **69**, 10.

R. Balkenende, N. Bocken, and C. Bakker (2017). Design for the Circular Economy. in *The Routledge Handbook of Sustainable Design*, edited by R. Egenhoefer. Routledge, London, UK.

N. M. P. Bocken, I. De Pauw, C. Bakker, and B. Van Der Grinten (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering* **33**, 308.

S. Bogers, J. Frens, J. V. Kollenburg, E. Deckers, and C. Hummels (2016), Connected Baby Bottle: A Design Case Study Towards A Framework for Data-Enabled Design, in *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*, Brisbane, Australia.

M. Braungart, W. McDonough, and A. Bollinger (2007). Cradle-to-cradle design: creating healthy emissions - a strategy for eco-effective product and system design. *Journal of Cleaner Production* **15**, 1337.

G. Bressanelli, F. Adrodegari, M. Perona, and N. Saccani (2018). Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies. *Sustainability* **10**, 639.

G. Cattelan Nobre and E. Tavares (2017). Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study. *Scientometrics* **111**, 463.

Ellen MacArthur Foundation (2013), *Towards the Circular Economy: Economic and business rationale for an accelerated transition*, Cowes, UK.
Available from: https://www.ellenmacarthurfoundation.org/publications.

Ellen MacArthur Foundation (2016), *Intelligent assets: Unlocking the Circular Economy Potential*, Cowes, UK.
Available from: https://www.ellenmacarthurfoundation.org/publications.

M. Fargnoli, A. Lleshaj, M. Lombardi, N. Sciarretta, and G. Di Gravio (2019). A BIM-based PSS approach for the management of maintenance operations of building equipment. *Buildings* **9**, 139.

M. Geissdoerfer, P. Savaget, N. M. P. Bocken, and E. J. Hultink (2017). Review: The Circular Economy A new sustainability paradigm? *Journal of Cleaner Production* **143**, 757.

GESI and Accenture (2016), *#SystemTransformation: How digital solutions will drive progress towards the sustainable development goals*, Global E-Sustainability Initiative & Accenture Strategy. Available from: http://systemtransformation-sdg.gesi.org.

N. Gligoric, S. Krco, L. Hakola, K. Vehmas, S. De, K. Moessner, K. Jansson, I. Polenz, and R. van Kranenburg (2019). SmartTags: IoT Product Passport for Circular Economy Based on Printed Sensors and Unique Item-Level Identifiers. *Sensors* **19**, 586.

T. Grubic (2014). Servitization and remote monitoring technology: A literature review and research agenda. *Journal of Manufacturing Technology Management* **25**, 100.

T. Grubic and I. Jennions (2018). Remote monitoring technology and servitised strategiesfactors characterising the organisational application. *International Journal of Production Research* **56**, 2133.

J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems* **29**, 1645.

M. C. den Hollander, C. A. Bakker, and E. J. Hultink (2017). Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. *Journal of Industrial Ecology* **21**, 517.

J. P. Jensen and A. Remmen (2017). Enabling Circular Economy Through Product Stewardship. *Procedia Manufacturing* **8**, 377.

J. Kirchherr, D. Reike, and M. Hekkert (2017). Conceptualizing the Circular Economy: An analysis of 114 definitions. *Resources, Conservation and Recycling* **127**, 221.

D. Kiritsis (2011). Closed-loop PLM for intelligent products in the era of the Internet of Things. *CAD Computer Aided Design* **43**, 479.

G. Kortuem, F. Kawsar, D. Fitton, and V. Sundramoorthy (2010). Smart objects as building blocks for the internet of things. *IEEE Internet Computing* **14**, 44.

P. Lacy (2015), *Using digital tech to spin the circular economy*, Accenture Outlook. Available from: www.accenture.com/outlook.

S. Li, L. D. Xu, and S. Zhao (2015). The internet of things: a survey. *Information Systems Frontiers* **17**, 243.

M. Lieder and A. Rashid (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production* **115**, 36.

H. W. Lightfoot, T. Baines, and P. Smart (2011). Examining the information and communication technologies enabling servitized manufacture. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **225**, 1964.

J. Lindström, A. Hermanson, M. Hellis, and P. Kyösti (2017), Optimizing Recycling Management Using Industrial Internet Supporting Circular Economy: A Case Study of an Emerging IPS2, in *Procedia CIRP 9th CIRP IPSS Conference: Circular Perspectives on PSS*, Copenhagen, Denmark.

A. B. Lopes de Sousa Jabbour, C. J. C. Jabbour, M. Godinho Filho, and D. Roubaud (2018). Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. *Annals of Operations Research* **270**, 273.

E. Manzini and C. Vezzoli (2003). A strategic design approach to develop sustainable product service systems: examples taken from the 'environmentally friendly innovation' Italian prize. *Journal of Cleaner Production* **11**, 851.

N. Mays, E. Roberts, and J. Popay (2001). Synthesising research evidence. in *Studying the Organisation and Delivery of Health Services: Research Methods*, edited by P. Allen, N. Black, A. Clarke, N. Fulop, and S. Anderson, Chap. 12. Routledge, London, UK.

M. Moreno, C. De los Rios, Z. Rowe, and F. Charnley (2016). A conceptual framework for circular design. *Sustainability* **8**, 937.

M. Moreno, C. Turner, A. Tiwari, W. Hutabarat, F. Charnley, D. Widjaja, and L. Mondini (2017), Re-distributed Manufacturing to Achieve a Circular Economy: A Case Study Utilizing IDEF0 Modeling, in *Manufacturing Systems 4.0 Proceedings of the 50th CIRP Conference on Manufacturing Systems*, Taichung City, Taiwan.

I. C. Ng and S. Y. Wakenshaw (2017). The Internet-of-Things: Review and research directions. *International Journal of Research in Marketing* **34**, 3.

O. Okorie, K. Salonitis, F. Charnley, M. Moreno, C. Turner, and A. Tiwari (2018). Digitisation and the Circular Economy: A Review of Current Research and Future Trends. *Energies* **11**, 3009.

A. Pagoropoulos, D. C. Pigosso, and T. C. McAloone (2017), The Emergent Role of Digital Technologies in the Circular Economy: A Review, in *Procedia CIRP 9th CIRP IPSS Conference: Circular Perspectives on PSS*, Copenhagen, Denmark.

M. E. Porter (2015). How smart, connected products are transforming companies. *Harvard Business Review* Available from: https://hbr.org/archive-toc/BR1510.

M. E. Porter and J. E. Heppelmann (2014). How smart, connected products are transforming competition. *Harvard Business Review*
Available from: https://hbr.org/archive-toc/BR1411.

M. Qu, S. Yu, D. Chen, J. Chu, and B. Tian (2016). State-of-the-art of design, evaluation, and operation methodologies in product service systems. *Computers in Industry* **77**, 1.

R. Roy, R. Stark, K. Tracht, S. Takata, and M. Mori (2016). Continuous maintenance and the future Foundations and technological challenges. *CIRP Annals - Manufacturing Technology* **65**, 667.

V. Salminen, H. Ruohomaa, and J. Kantola (2017). Digitalization and Big Data Supporting Responsible Business Co-evolution. in *Advances in Human Factors, Business Management, Training and Education - Proceedings of the AHFE 2016 International Conference on Human Factors, Business Management and Society.* Walt Disney World, Florida, USA.

M. Spring and L. Araujo (2017). Product biographies in servitization and the circular economy. *Industrial Marketing Management* **60**, 126.

J. A. Stankovic (2014). Research directions for the Internet of Things. *IEEE Internet of Things Journal* **1**, 3.

M. L. Tseng, R. R. Tan, A. S. Chiu, C. F. Chien, and T. C. Kuo (2018). Circular economy meets industry 4.0: Can big data drive industrial symbiosis? *Resources, Conservation and Recycling* **131**, 146.

A. Tukker (2004). Eight types of product-service system: Eight ways to sustainability? Experiences from SusProNet. *Business Strategy and the Environment* **13**, 246.

A. Tukker (2015). Product services for a resource-efficient and circular economy - A review. *Journal of Cleaner Production* **97**, 76.

A. Whitmore, A. Agarwal, and L. Da Xu (2015). The Internet of Things - A survey of topics and trends. *Information Systems Frontiers* **17**, 261.

M. Xia, T. Li, Y. Zhang, and C. De Silva (2016). Closed-loop design evolution of engineering system using condition monitoring through Internet of Things and cloud computing. *Computer Networks* **101**, 5

3

OPPORTUNITIES AND CHALLENGES IN IOT-ENABLED CIRCULAR BUSINESS MODEL IMPLEMENTATION —A CASE STUDY

This chapter has been published as:
E. Ingemarsdotter, E. Jamsin, and R. Balkenende (2020) Opportunities and Challenges in IoT-enabled Circular Business Model Implementation —A Case Study. *Resources, Conservation and Recycling* **162**, 105047.

Abstract: While the enabling capabilities of the Internet of Things (IoT) in the Circular Economy (CE) have been highlighted in a number of publications, knowledge about how to leverage IoT in actual implementation of circular strategies is still lacking. This paper aims to elucidate reasons for the apparent mismatch between the 'theoretical opportunities' of IoT for CE as described in literature, and current implementation in practice. To this end, we present a case study in the field of LED lighting, within a company with previous experience and knowledge in both IoT and CE. The primary data source is twelve semi-structured interviews with stakeholders from the company. We identify opportunities for using IoT to support circular strategies in this specific case: IoT can support servitized business models; improve tracking and record keeping of in-use and post-use products; enable conditions monitoring and predictive maintenance; improve estimations of remaining lifetime of used products; and inform design decisions to improve durability of products. Related to these opportunities, we identify implementation challenges faced by the company. The main IoT-specific implementation challenges in the case are (1) a lack of structured data management processes to ensure high quality data collection and analysis, and (2) the difficulty of designing IoT-enabled products for interoperability, adaptability, and upgradability, especially considering that IoT technologies develop at a high pace. By elucidating these challenges, this paper contributes with IoT-specific insights to the available literature about challenges in circular business model implementation. Moreover, this paper adds an important emphasis on real-world implementation challenges to the literature about digitally-enabled circular strategies.

Keywords: Digitalization, Circular economy, Product service systems, Predictive maintenance, Smart lighting

3.1. INTRODUCTION

The term Circular Economy (CE) envisions an economy that simultaneously considers environmental impact, resource scarcity and economic benefits (Lieder and Rashid, 2016). A commonly cited view describes the CE as *"an industrial system that is restorative or regenerative by intention and design"* (Ellen MacArthur Foundation, 2013). Design and business model strategies in the CE include long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (Bakker et al., 2014, Geissdoerfer et al., 2018).

Effective implementation of circular strategies requires not only innovation in product design, but also a focus on business models that incentivise companies to keep products and materials at their highest value for as long as possible, while ensuring minimal environmental impact (Balkenende et al., 2017). Designers aiming at developing circular offerings need to have the ability to integrate the design of both products and business models (Sumter et al., 2018). Research into circular and sustainable business models has shown that service-oriented value propositions have the potential to decouple profit from production volumes, and thereby reduce resource use (Bocken et al., 2014). Such business models have been studied extensively within the research field of Product Service Systems (PSS) (Tukker, 2015). PSS are combined product and service offerings designed to fulfil specific customer needs (Tukker, 2004). Compared to a traditional product manufacturer, a PSS provider has a stronger incentive to deliver on aspects such as quality, efficiency, durability and reusability. Moreover, business models based on product access rather than ownership can lead to reduced resource use through increased utilization of products, since one product can satisfy many peoples' need for a certain function that they only use occasionally. Examples are car sharing services and tool rental services (Tukker, 2015).

In parallel to the increased focus on sustainability, many companies find themselves in a race against competitors to seize new opportunities in the digital era (Porter and Heppelmann, 2014). Resulting from the fast development in sensing and communication technology, more and more products are being equipped with digital capabilities. A simple example is that of RFID tags, which allows for identification and location tracking of unique items (Atzori et al., 2016). Now, an Internet of Things (IoT) is emerging in which 'smart objects' can sense their local situation, process information and interact with their users (Kortuem et al., 2010). The IoT has been defined as a *"system of uniquely identifiable and connected constituents capable of virtual representation and virtual accessibility leading to an Internet-like structure for remote locating, sensing, and/or operating the constituents with real-time data/information flows between them, thus resulting in the system as a whole being able to be augmented to achieve a greater variety of outcomes in a dynamic and agile manner"* (Ng and Wakenshaw, 2017) [p. 6]. The IoT is thus closely linked to other digital technologies, such as cloud computing and big data analytics. Recent studies have shown that, in order to reap the benefits of the IoT, organizations will need to develop digital maturity (Kane et al., 2016), and find ways to *"create value from data"*, ensuring that the collected data can effectively inform actions and decisions (Raynor and Cotteleer, 2015).

Recent literature has pointed out the enabling effects of digitalisation and IoT on the design and implementation of circular strategies (Alcayaga et al., 2019; Antikainen et al., 2018; Bressanelli et al., 2018; Ingemarsdotter et al., 2019; Okorie et al., 2018; Pagoropoulos et al., 2017; Bocken et al., 2019). The Ellen MacArthur Foundation, an organization that has popularised and spread the CE concept, has published two reports on the topic (Ellen MacArthur Foundation, 2016; Ellen MacArthur Foundation, McKinsey & Company, and Google, 2019).

However, the opportunities of IoT for CE as presented in literature (summarized in Section 3.2.1) have not been fully realised in practice (Alcayaga et al., 2019; Ingemarsdotter et al., 2019). As such, more research is needed to understand what is hindering the uptake of IoT-enabled circular strategies. This argument has been made by, e.g., Cattelan Nobre and Tavares (2017), who, in their bibliometric study of the application of IoT and big data for CE, highlighted the need for researchers to take the next step from *"imagining the possibilities"*, to studying real cases (Cattelan Nobre and Tavares, 2017). Similarly, both Antikainen et al. (2018) and Okorie et al. (2018)

noted the need for more research on challenges that companies face when trying to implement digitally-enabled circular strategies. While literature is available which covers implementation challenges for circular business models more in general (summarized in Section 3.2.2), it lacks a specific focus on challenges related to IoT-enabled circular strategies. A research gap can thus be identified: the lack of studies researching actual cases of IoT-enabled circular strategies in practice, and specifically focusing on understanding the implementation challenges faced by companies.

In this paper, we aim to elucidate reasons for the apparent mismatch between the opportunities of using IoT for CE as described in literature (hereafter referred to as 'theoretical opportunities'), and actual implementation in practice. Towards this aim, we perform a case study within a company that is currently exploring how they could use IoT to support circular strategies. We investigate the opportunities of using IoT for CE in the specific context, and the associated implementation challenges faced by the company. The studied company is a LED lighting manufacturer, and our study focuses on the customer segment of food retail, i.e., on LED lighting systems in supermarkets.

3.2. BACKGROUND

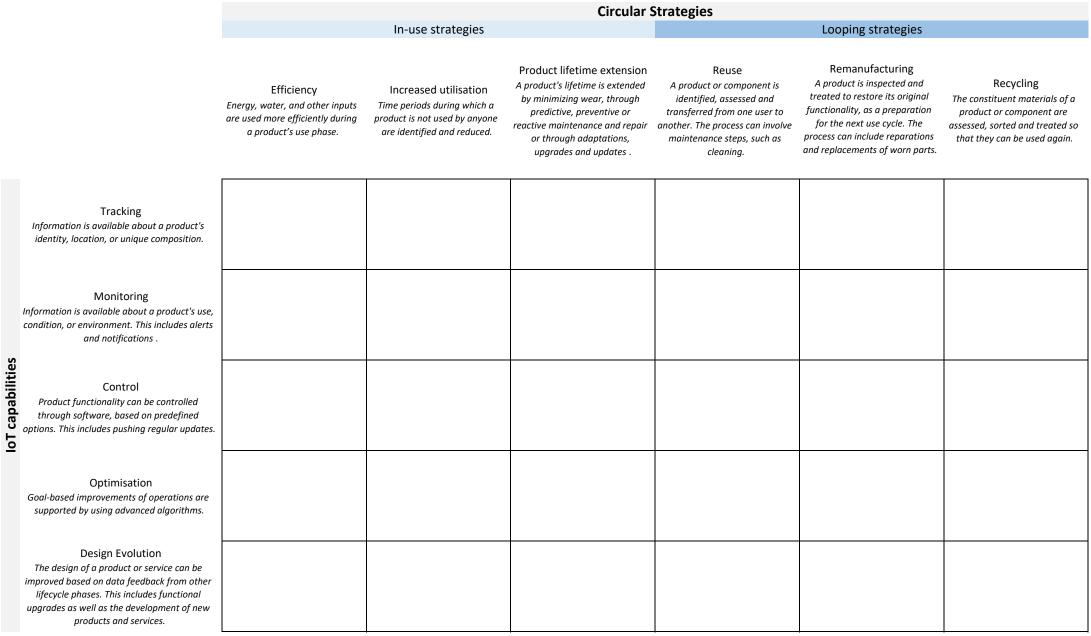
3.2.1. IOT AS AN ENABLER FOR CE

Previous literature has emphasized the role of IoT to support the implementation of circular strategies and business models in companies, often in the context of PSS. For example, case studies have shown that IoT can support companies in extending the scope of value creation beyond design and manufacturing to 'use solutions' and 'operations services' (Rymaszewska et al., 2017). IoT has also been pointed out as a supportive technology for improved maintenance and repair in PSS (Baines and Lightfoot, 2013). Specifically, sensor-enabled prognostics can improve operational reliability and allow for preventive and predictive maintenance, which can extend the service life of products and systems (Sun et al., 2012). Moreover, by collecting data from the use phase, companies can continuously improve the design of their products, for example to enhance durability (Bressanelli et al., 2018).

Another aspect mentioned in literature is that products with digital elements can more easily be upgraded with additional functionality, something that could increase their useful lifetime (Bressanelli et al., 2018; Pialot et al., 2017). In relation to the circular strategy of increased utilization, IoT can also support sharing of products between multiple users by allowing for monitoring of product condition, status, location, and usage (Bressanelli et al., 2018).

Product-in-use data can also be used to improve product recovery strategies such as reuse, remanufacturing and recycling (Alcayaga et al., 2019; Zeid et al., 2004). In remanufacturing literature, specifically, uncertainty about the type and condition of products available for remanufacturing at a certain time has been acknowledged as a persisting challenge (Zhang et al., 2018). Inspection and testing of products entering a remanufacturing process could benefit from more information about, for example, original design specifications and repair history (Yang et al., 2018). However, such information flows are not yet well established (Kurilova-Palisaitiene et al., 2015). Moreover, accurate estimations of remaining useful lifetime could support decisions about when to optimally remanufacture a product (Zhang et al., 2015), and thereby improve the profitability of remanufacturing activities (Dulman and Gupta, 2018). In relation to recycling, previous literature has mentioned opportunities for RFID tags in products to increase recycling efficiency (Luttropp and Johansson, 2010) and for improved information about material composition of used material to make recovery processes more profitable (Wilts and Berg, 2017).

In a recent paper, we reviewed literature about IoT and CE, and proposed a framework of 'IoT-enabled circular strategies' (Ingemarsdotter et al., 2019). The framework is a matrix made up of circular strategies in one dimension, and IoT capabilities in the other, see Figure 3.1. In this paper, we use this framework to represent the 'theoretical opportunities' of using IoT for CE.



		Circular Strategies					
		In-use strategies			Looping strategies		
		Efficiency *Energy, water, and other inputs are used more efficiently during a product's use phase.*	Increased utilisation *Time periods during which a product is not used by anyone are identified and reduced.*	Product lifetime extension *A product's lifetime is extended by minimizing wear, through predictive, preventive or reactive maintenance and repair or through adaptations, upgrades and updates .*	Reuse *A product or component is identified, assessed and transferred from one user to another. The process can involve maintenance steps, such as cleaning.*	Remanufacturing *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 *The constituent materials of a product or component are assessed, sorted and treated so that they can be used again.*
IoT capabilities	Tracking *Information is available about a product's identity, location, or unique composition.*						
	Monitoring *Information is available about a product's use, condition, or environment. This includes alerts and notifications .*						
	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 using 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.*						

Figure 3.1: Framework categorizing 'IoT-enabled circular strategies', from Ingemarsdotter et al. (2019).

3.2.2. BARRIERS TO CIRCULAR BUSINESS MODEL IMPLEMENTATION

This section presents barriers to circular business model implementation in general, as no literature could be found about the specific challenges associated with implementing IoT-enabled circular strategies. This background is used later, in Section 3.6, to discuss how the challenges found when specifically focusing on IoT-enabled circular strategies compare to barriers to circular business model implementation in general.

Barriers to circular business model implementation have been studied and categorized in several investigations (Bressanelli et al., 2019; Linder and Williander, 2017; Ritzén and Sandström, 2017; Sousa-Zomer et al., 2018; Vermunt et al., 2019). Ritzén and Sandström (2017) summarized the barriers to circular business model implementation into five main categories: structural, operational, financial, attitudinal and technological barriers. They relate structural barriers to unclear distribution of roles and responsibilities for CE issues in the company, as well as limited information exchange between actors.

Operational barriers concern infrastructure and supply chain management (Ritzén and Sandström, 2017). Related to this, Linder and Williander (2017) discuss 'return flow challenges', i.e. challenges related to effectively managing product-take-back systems in circular business models. In particular, many remanufacturers are struggling with low predictability in quantity and quality of incoming products to be remanufactured, which often leads to inefficiencies in the remanufacturing system (Linder and Williander, 2017).

Financial barriers are mainly related to uncertainty in financial benefits and potential profitability of circular concepts (Ritzén and Sandström, 2017). Linder and Williander (2017) found that financial barriers, especially related to financial risk and uncertainty, can partly explain the current reluctance amongst companies to adopt circular business models. Circular business models often imply larger operational risk for the provider than a pure sales model, as use-phase services such as maintenance are taken on by the provider. In business models where the provider keeps the ownership of the product, the 'capital tied up' also adds financial risk for the provider (Linder and Williander, 2017). Furthermore, in the case of remanufacturing, an important financial uncertainty is the *"product attractiveness at a certain remanufacturing cost compared with competitors and substitutes"* at the point in the future when a product leaves one use cycle to enter the next (Linder and Williander, 2017). In order to calculate the total business case of several use cycles of a product in a remanufacturing model, both the remanufacturing cost and the customers' future willingness to pay for the remanufactured product need to be estimated.

The value of a remanufactured product depends on how the market for a certain product category develops over time. Linder and Williander (2017) emphasise the barrier of 'fashion vulnerability' (also mentioned by Bressanelli et al. (2019)), meaning that if the market demands change quickly, it can be challenging to propose business models that favour long and multiple use cycles. Such changes in market demand can be fashion driven, or due to fast technological developments. Products which are sensitive to changing fashion, or that are undergoing fast technological changes, are thus extra challenging.

Attitudinal barriers relate to actors' perception of sustainability and level of risk aversion (Ritzén and Sandström, 2017). Attitudinal barriers can relate to different actors in the supply chain. Sousa-Zomer et al. (2018) bring up leadership behaviour and attitudes of employees, and Vermunt et al. (2019) highlight barriers in low customer acceptance caused by factors such as long standing procurement habits, or the perception that reused products are inferior to new ones. Linder and Williander (2017) also mention 'customer type restrictions' meaning that not all types of customers are receptive to all types of circular business models.

Technological barriers concern product design and production processes (Ritzén and Sandström, 2017). Linder and Williander (2017) discuss 'product category restrictions', stating that some types of products are more suitable for circular business models than others. Examples of product features that the authors mention as beneficial for a circular business model are that it fails functionally rather than by dissipation, that the value added of the returned components is high relative to market value and original cost, and that the product technology is stable (Linder and Williander, 2017).

Finally, institutional barriers to circular business model implementation include the lack of supporting regulations and the lack of social awareness (Bressanelli et al., 2019; Linder and Williander, 2017; Vermunt et al., 2019).

3.3. METHODOLOGY

The aim of this study is to elucidate reasons for the apparent mismatch between the 'theoretical opportunities' of using IoT for CE, and actual implementation in practice. Towards this aim, we perform an in-depth single case study, following Yin's definition: *"A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between object of study and context are not clearly evident."* (Yin, 2014). In this paper, the case context is a LED lighting manufacturing company, and the case is the early phase development of a circular PSS concept for LED lighting in the food retail segment. Within this particular case context, our inquiry focuses on the current level of IoT and CE implementation, the perceived opportunities for IoT to further support circular strategies, and the challenges associated with implementing IoT-enabled circular strategies. Case study methodology fits the aim of this study since we need to understand contextual factors in practice, which can help explain the limited uptake of IoT-enabled circular strategies. By focusing on one single case, we can dive deep into the context and ensure sufficient understanding of such contextual factors.

3.3.1. CASE SELECTION

The company was selected as relevant for this study because it has positioned itself as a front runner in circular and service-oriented business models. The company is also actively pursuing IoT solutions, and expressed interest in using IoT to further support circular strategies. The food retail segment was chosen because the company saw innovation potential for IoT and CE in this segment, and because the company was (at the time of data collection) going through a process to design and develop a new service-oriented value proposition for this segment, considering both IoT and CE. The case provided a real-world example in which IoT-enabled circular strategies were being tried out in practice. The case actors had prior knowledge about both IoT and CE, and could use this knowledge to discuss opportunities and challenges in the particular case. In accordance with Yin (2014), an additional criterion used for selecting the particular case was that it provided sufficient access to data. In Section 3.6, we will discuss how the opportunities and challenges of using IoT for circular strategies, as found in the particular context of the studied case, might be transferable to other cases.

3.3.2. DATA COLLECTION

The study was conducted over the course of one year. Twelve semi-structured interviews were conducted with stakeholders from the company, with different perspectives on the case. We first identified a list of experts in CE, IoT, and/or in the current product and service offerings in the food retail segment. These interviewees referred to additional stakeholders, who were also added to the list. Table B.1 in Appendix B provides an overview of the interviewees' professional roles, and their main area of expertise: food retail, Circular economy or Internet of Things.

Apart from conducting the interviews, the main researcher visited the company multiple times throughout the year in order to discuss collected insights and possible next steps with company representatives. This allowed her to ask clarifying questions when needed. Moreover, marketing material, product and service brochures, website content, as well as internal documents such as white papers and results from previous R&D projects, were accessed. These activities allowed us to obtain a profound understanding of the company-specific context.

The interviews were based on an interview guide, designed with the aim to learn about the current state of CE implementation, as well as perceived opportunities and challenges to use IoT for CE in the food retail segment. The main themes discussed in the interviews, as well as example questions, are shown in Table B.2 in Appendix B. All interviews followed a similar structure. First, the researchers introduced the topic and the goal of the research project. Then, the interviewees were asked to describe their role in the company. If the interviewee had been involved in a particular project related to circular economy or IoT, he or she was asked to explain more about the project and what learnings could be applied to the food retail case. The interviewees were also asked to reflect on strengths and weaknesses of the current offering in the food retail segment. Thereafter, the researcher asked specifically to what extent circular strategies were considered in the current offering, and what could be relevant improvements to strengthen the CE aspect of the offering. For opportunities that were mentioned but not yet implemented, the researcher asked follow-up questions about why this was the case. The researcher then moved into asking questions specific to IoT. The interviewees were asked to discuss if they thought that IoT could support circular strategy implementation in the food retail segment, and if so, how. If interviewees mentioned opportunities for IoT to support circular strategies in the specific case, they were also asked to reflect on challenges that they saw related to realising those opportunities.

When discussing circular strategies, the interviewees were first able to give answers based on their own interpretation of the term ‘circular strategy’. Thereafter, the researcher showed a visualization of circular strategies. In this way, we could combine insights based on each individual’s own interpretation of CE with insights based on circular strategies from literature. The visualization that we used shows the loops (with slightly adapted wording) in the technical cycle from the so called ‘butterfly diagram’ or ‘Circular Economy System Diagram’ (Ellen MacArthur Foundation, 2013) [p. 24]. This visualization had already been used for some time within the company in communications around the CE, which meant that many of the interviewees were familiar with it. Similarly, during the discussion about opportunities and challenges of using IoT for circular strategies, the interviewees first reasoned freely, and were then shown the framework presented in Figure 3.1.

3.3.3. DATA ANALYSIS

The interviews were recorded and transcribed. By combining information from the interviews with other collected contextual data from the company, we could summarize the current state of development of the IoT-enabled circular PSS in the food retail segment. Already implemented IoT-enabled circular strategies were mapped in relation to the ‘theoretical opportunities’. We also collected information about how IoT was being implemented, and which circular strategies were carried out, in other customer segments.

Thereafter, we analyzed the interview transcripts in order to categorise the different views with regards to how IoT could further support circular strategies in the case of food retail. We mapped the quotes into the following three categories: (1) “Opportunities for IoT to support the circular strategy”, (2) “IoT-specific challenges faced or expected when trying to realise the opportunities of using IoT to support the circular strategy.”, and (3) “General (i.e., not IoT-specific) challenges faced or expected when trying to implement the circular strategy”. Within these three categories, sub categories were identified describing types of opportunities and challenges. Example quotes for each sub category are given in Tables B.3 and B.4 in Appendix B. We also mapped the opportunities mentioned by the interviewees in relation to the ‘theoretical opportunities'. To assess the validity of the conclusions drawn from analyzing the interviews, representatives from the company read and commented on a draft of this paper.

3.4. THE CASE AND ITS CONTEXT

3.4.1. THE CASE CONTEXT: THE COMPANY AND ITS EXPERIENCES WITH IOT AND CE FROM OTHER CUSTOMER SEGMENTS

The case in focus for this study is embedded within a large LED lighting manufacturer, based in Europe, that offers lighting solutions for a range of applications. The company is going through a transition from mainly a product manufacturer to a PSS provider and the company strategy is pointing towards increased use of digital technologies and a larger focus on digital services beyond the lighting function.

At the time of data collection, circular propositions were already in place for other customers segment than food retail. The circular propositions were based on customised service contracts which could include energy management and maintenance services, as well as an agreement that the lighting provider would responsibly take care of the lighting system after the end of its use. However, as these lighting systems were still relatively recently installed, the company did not yet have experience with large scale take-back of used products.

Some service contracts were set up to guarantee a certain level of energy savings, which required that the system should be connected to the Internet and send updates about its energy use back to the lighting provider. Specifically, in the street lighting segment, the lighting systems were connected to a digital platform through which the lights could be remotely monitored and controlled. In the street lighting segment, products were also tagged with a quick response (QR) code, which could be scanned to retrieve information about the components inside the product, as well as the maintenance activities that have been performed on this particular product. This supported more effective maintenance activities, since technicians knew which spare parts they would need before starting to repair a luminaire. Building on this, there was an ongoing research project in place to develop predictive maintenance services in the street lighting segment. In the project, data collected from a customer's installed lighting system was being analyzed to develop a failure prediction model that could allow for condition monitoring and predictive maintenance.

Moreover, a score card system was used in product development to encourage circular design approaches, such as 'design for serviceability' and 'design for recyclability'. The design changes made had, for example, focused on enabling easier disassembly of luminaires by reducing the number of glued parts, and by using click-connectors for electronics rather than soldering.

3.4.2. THE CASE: THE EARLY PHASE DEVELOPMENT OF A CIRCULAR PSS IN THE FOOD RETAIL SEGMENT

This case study focused specifically on the customer segment of food retail, i.e., on lighting systems for supermarkets. In the established value proposition to food retailers, at the time of data collection, implementation of circular strategies was limited to ‘efficiency in use’. Efficiency in use was achieved through the use of efficient LED luminaires and, when applicable, through the use of presence and daylight detection sensors to adapt lighting levels on a needs basis. Also, a computer or tablet-based lighting control system was available to the food retailers. The system connected the luminaires installed in a supermarket, and could be used to, for example, control the lights, and set up so called ‘light recipes’.

At the time of data collection for this study, the company was going through a design process to develop new value propositions for their customers in the food retail segment. As part of this effort, the company had started to prototype concepts of a circular PSS in the food retail segment, and were actively searching for ways in which IoT could add value to their food retail customers.

An important aspect of the design process was to define what a circular proposition would mean in the case of food retail. In comparison to industry and street lighting customers, who tend to value long product lifetimes and low downtime, the interviewees mentioned that customers in the food retail segment would often discard of lighting products before the end of the products’ technical lifetime. A food retail store always needs to look new and attractive, and therefore complete store refurbishments are performed regularly. According to the interviewees, the time in between store refurbishments is decreasing, from approximately ten years down to around five years, and sometimes even less. The products offered by the lighting manufacturer have significantly longer technical lifetimes than the duration of these refurbishment cycles, and the company is thus facing competition from less CE-minded competitors who could offer low-price alternatives designed to last for the duration of one refurbishment cycle only. To offer a circular business model in this customer segment, the company therefore investigated how they could prolong the use time of their products to better match the technical lifetime that the products were designed for. To do this, the company was developing concepts in which they could prolong the relevance of their products over time through offering, for example, system adaptations and upgrades.

In line with this, the company had started to design products that could be adapted to changing customer needs. Some interviewees mentioned that they were working on using 3D printing technology to print new parts that could change the aesthetic appearance of the product without having to replace the whole luminaire. They were also starting to introduce QR tags (as had already been done in the street lighting segment) which provide information about all components within each unique luminaire, thereby enabling better record keeping of all parts installed in a supermarket. The interviewees mentioned that this tracking solution could be extended to also include monitoring of the condition of products and parts to anticipate future failures and to estimate the remaining useful lifetime for each individual part. These future opportunities are further explored in Section 3.5.

3.5. RESULTS

3.5.1. OPPORTUNITIES FOR IOT TO SUPPORT A CIRCULAR PSS FOR LED LIGHTING IN THE FOOD RETAIL SEGMENT

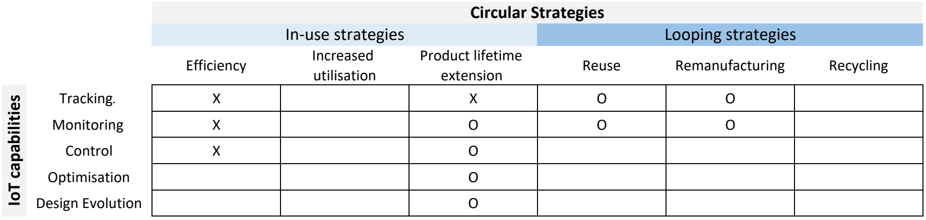
The opportunities for IoT to support a circular PSS in the food retail segment, as perceived by the interviewees, are summarized in Table 3.1 and explained below. Figure 3.2 displays the already implemented IoT-enabled circular strategies in the food retail segment (as presented in Section 3.4.2), as well as the opportunities expressed by the interviewees, compared to the range of theoretical opportunities. The interviewees imagined a circular PSS in which the company would retain ownership of the luminaires, continuously upgrade and adapt the lighting system to fulfil the customers' changing needs over time, and finally take the system back at the end of a contract period. Firstly, IoT could support servitized business models since it allows the lighting manufacturer to more accurately measure the actual performance of the lighting systems, supporting a performance-based service contract. As mentioned in Section 3.4, these kinds of performance-based models had already been implemented in other customer segments.

Secondly, IoT would allow the company to develop and offer new data-enabled services on top of the lighting function. The interviewees saw opportunities in the fact that their lighting infrastructure is "everywhere" in the supermarket, making up suitable nodes in a network of sensors and connected devices on which data-enabled services could be built. According to the interviewees, such services could imply a closer relationship between the lighting provider and the food retailer, and make the PSS a more attractive proposition. In the food retail segment, data-enabled services mentioned were, for example, advice on how to redesign the store in order to optimise sales, and evaluation of the effect of events in the store on sales numbers.

Thirdly, the interviewees mentioned the opportunity to collect and store data about the composition and condition of products over time. This could improve the maintenance and adaptations of the system since the lighting provider, as well as contracted installers, would have an overview of all the installed products and parts and their performance. Some interviewees also saw an opportunity in using IoT for predictive maintenance in food retail. If failures could be predicted and actions taken before breakdown, the number of maintenance visits required could be reduced and it could be ensured that the service technicians were always well prepared for the job, including bringing the right spare parts.

Fourthly, some interviewees also mentioned that IoT could support reuse by allowing the company to track and trace used products and parts, and to more accurately estimate their remaining lifetimes after one use cycle, by monitoring the condition of products over time. Since the remaining lifetime affects the residual value of a product, this could reduce some of the risk related to reuse strategies.

Fifthly, some interviewees also mentioned that insights into the condition of products could be used to support redesign of products, making them more durable, and thereby avoiding failures in the first place.



IoT capabilities	Circular Strategies					
	In-use strategies			Looping strategies		
	Efficiency	Increased utilisation	Product lifetime extension	Reuse	Remanufacturing	Recycling
Tracking.	X		X	O	O	
Monitoring	X		O	O	O	
Control	X		O			
Optimisation			O			
Design Evolution			O			

Figure 3.2: Map of the IoT-enabled circular strategies which were implemented (X) or seen as opportunities (O) in the studied case , mapped to the range theoretical opportunities for IoT to support CE. Framework based on Ingemarsdotter et al. (2019).

3.5.2. CHALLENGES ASSOCIATED WITH IMPLEMENTING IOT-ENABLED CIRCULAR STRATEGIES

The challenges found are explained below, and summarized in Table 3.2. Although the focus of this study was primarily on challenges specific to using IoT to support circular strategies, more general challenges to circular business model implementation unavoidably also came up during the interviews.

As presented in Table 3.2, the interviewees mentioned challenges related to data management and quality. These insights were mainly derived from previous experiences in the street lighting segment where a project had been carried out to develop a failure prediction model for predictive maintenance.

Firstly, there was a lack of data from products that had actually failed, which made it difficult to develop a reliable model. The lack of data that describe actual failures in the field can be explained by the fact that smart lighting systems are relatively new (data gathering only started in the last few years), and that LED luminaires have long lifetimes (hence, they fail slowly). The interviewees also mentioned that the long time required to produce a reliable model was a challenge with respect to subsequent product generations. It is not certain that a model that works for one version of the product, also produces reliable results for a new version. Secondly, the collected datasets were missing parameters known to be important for describing the condition of a LED luminaire, and it was not always clear which data set originated from which product. The latter is important since the expected product lifetime depends on the product version and configuration. Thirdly, the analyst mentioned the need for information about which luminaires actually failed in the field, in order to appropriately label the sensor data. This information was not sufficiently structured, which hampered the model development.

Moreover, several interviewees highlighted the challenge of developing both hardware and software to be adaptable, interoperable and upgradable, as would be required to fit the envisioned circular PSS. Specifically, as mentioned above, the interviewees saw a challenge in translating failure prediction models between product versions. This challenge might be reduced if products were intentionally designed for interoperability. However, the interviewees also pointed out that there is a large uncertainty about what kind of IoT technology will be available and demanded by customers in a few years. It is possible that both hardware and software will be outdated quickly, which could reduce the lifetimes of smart lighting products rather than prolonging them. One interviewee with insights into product design saw a practical challenge in designing products that could continuously be upgraded with the latest hardware over time, since it would be difficult to combine an aesthetically appealing product design with a requirement to leave space in the product for a range of potential new sensor modules.

Apart from the IoT-specific challenges, the interviewees brought up more general challenges to the implementation of a circular PSS for supermarket lighting. Firstly, the interviewees mentioned that there is an uncertainty in how the buying preferences of the food retailers will develop, and if they would accept a service contract instead of the transactional sales model that they are used to. The challenge would be to really make the service model attractive for the food retailers. Moreover, the interviewees pointed out the challenge of designing a lighting system that could stay relevant to the food retailer over the full duration of its technical lifetime, accommodating for changes in the retailer's needs and wants over time.

Finally, the interviewees pointed out a barrier related to the financial uncertainty of reuse. Even if IoT could enable more accurate estimations of the remaining lifetime of used products, the profitability of reuse also depends on the market demand for the products in the future, which is difficult to predict.

Table 3.1: Opportunities for IoT to support circular strategies in the studied case as perceived by the interviewees.

Data category	Type of opportunity	Main points put forward by the interviewees
Opportunities	IoT supports servitized business models	- IoT allows for monitoring of system performance, enabling performance-based service contracts. - IoT makes service models more attractive through adding digital services beyond the lighting function.
	IoT supports maintenance	- IoT enables detailed record keeping of installed products and parts, facilitating maintenance and adaptations. - IoT enables condition-based and predictive maintenance.
	IoT supports reuse and/or remanufacturing	- IoT enables tracking of used products, parts and materials. - IoT enables better estimations of remaining lifetime.
	IoT supports design for durability	- Data about products' condition in the field can inform product.

Table 3.2: Challenges associated with the implementation of the identified IoT for CE opportunities, as found in the studied case. The challenges are categorised as IoT-specific or General (i.e. not IoT-specific).

Data category	Type of challenge	Main points put forward by the interviewees
IoT-specific challenges	Data quality management	- Lack of data from products that have actually failed. - Parameters known to influence the condition of the product not collected. - Not always clear which data set originated from which product. - Lack of data about which luminaires actually failed in the field (labelled data).
	Design for interoperability, adaptability and upgradability	- Design changes might lead to the need for new models for failure prediction and remaining lifetime estimation for every new product version. - The uncertainty of future technological developments makes it difficult to design for interoperability over time.
General challenges	Financial risk and uncertainty	- The value of used products depends on future market developments that are difficult to predict, especially since IoT might speed up the development.
	Customer preferences and behaviour	- The food retailers are used to a transactional way of buying lighting, and might not be willing to accept a service-based business model. - The PSS has to stay relevant over time even if the customers' needs keep changing.

3.6. DISCUSSION

In this section, we relate our findings to previous literature about IoT as an enabler for CE (Section 3.2.1) and barriers to circular business model implementation (Section 3.2.2). We also discuss possible reasons why some of the theoretical opportunities mentioned in literature were not seen as opportunities in the studied case. Finally, we discuss limitations of this study, and the generalizability of the findings.

3.6.1. THE CASE RESULTS IN RELATION TO PREVIOUS LITERATURE

In line with previously published work (Baines and Lightfoot, 2013; Rymaszewska et al., 2017), we found that IoT can make service-oriented business models more attractive for the customers. In the studied case, IoT implementation enabled the development of new digital services beyond the lighting function, which created a closer relationship between the lighting provider and the food retailers.

Moreover, also in line with previous research (Sun et al., 2012), our results suggest that IoT can be used for tracking of location and composition of products and parts, as well as condition monitoring. This can support product lifetime extension through efficient and predictive maintenance, and reuse through improved visibility of products available for reuse and through more accurate estimations of remaining product lifetime. In relation to these opportunities, a core challenge found in this study was to manage the data collection and analysis, and to ensure sufficient data quality in order to derive useful insights. Challenges in creating value from data have previously been brought up in IoT literature (Raynor and Cotteleer, 2015), and our results highlight the importance of having a systematic approach in IoT-enabled circular strategy implementation for defining data quality requirements, and for using the requirements to guide data collection. Using the categorization provided in Ritzén and Sandström (2017), we would describe these challenges as mainly structural, as they concern the need for a more structured and collaborative process. These challenges have not been detailed in previous literature about barriers to circular business model implementation.

Another important IoT-specific challenge found in this study was to design both software and hardware for interoperability, adaptability and upgradability. The need to plan product generations and to anticipate how a product will evolve over time has been brought up in previous literature in the design for circular economy field (Sumter et al., 2018), and we see a need for research specifically investigating this in the context of IoT-enabled products.

Moreover, challenges were brought up with regards to the financial risk of reuse and remanufacturing strategies in the food retail segment, considering the uncertainty of the future residual value of products. This finding is line with Linder and Williander (2017). Since IoT technology might accelerate technology development in the LED lighting industry, this could increase the uncertainty of the future value of reused products even more. As discussed in Linder and Williander (2017) and Bressanelli et al. (2019), if technology develops quickly, there is an increased risk that products become obsolete before they reach their technical lifetime, and that their market relevance might be too low after one use cycle to make reuse a valid option.

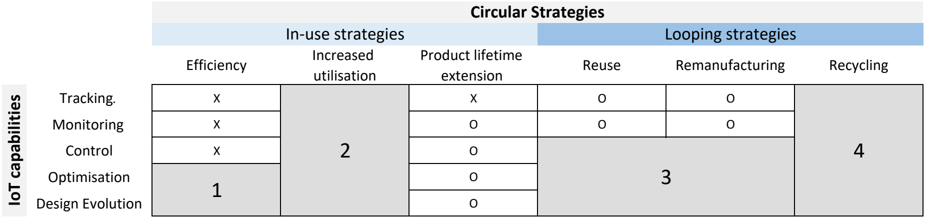
Moreover, some interviewees expressed doubts concerning the willingness of the food retailers to adopt a new service-oriented proposition. This can be seen as an attitudinal barrier on the customer side, according to the categorization of barriers to circular business model implementation as presented in Ritzén and Sandström (2017), or a customer type restriction as presented in Linder and Williander (2017).

In summary, this study confirmed CE implementation barriers already identified in literature (Ritzén and Sandström, 2017), while contributing with new IoT-specific challenges related to (1) data quality and management, and (2) design for interoperability, adaptability, upgradability, in the context of IoT-enabled circular business model implementation.

Apart from outlining the challenges found in relation to case-specific opportunities, our results also show that some the theoretical opportunities for IoT to support circular strategies were not considered as opportunities in the case studied. As highlighted by the grey areas in Figure 3.3, the following four categories of theoretical opportunities were not considered in the case: (1) optimization and design evolution for efficiency in use, (2) IoT-enabled increased utilization, (3) control, optimization, and design evolution for reuse and remanufacturing, and (4) IoT-enabled recycling. The fact that (4) was not considered an opportunity is surprising since the company had previous experience in design for recycling, and since literature has highlighted opportunities for IoT to support recycling (Luttropp and Johansson, 2010). On the other hand, the case results confirm previous research stating that the implementation levels in practice for IoT-enabled looping strategies are low (Alcayaga et al., 2019; Ingemarsdotter et al., 2019).

For categories (1) and (2), the interviewees expressed clear reasons why they did not see case-specific opportunities. More advanced improvements in energy efficiency was not considered an opportunity since the lighting systems were already so efficient that there was little incentive for the food retailers to reduce the energy consumption further. Increased utilization was not seen as relevant in the studied context, because no utilization gaps could be identified for the lighting system in supermarkets.

However, the interviewees did not provide clear explanations as to why (3) and (4) were not seen as opportunities. We note, however, that both strategies would require some level of data sharing with company-external actors. While literature has pointed out the importance of sharing data between stakeholders in the value chain (Kiritsis, 2011; Kurilova-Palisaitiene et al., 2015; Wilts and Berg, 2017), this has also proven difficult to achieve in practice (Derigent and Thomas, 2016). For example, previous research has highlighted important information gaps in remanufacturing, and a lack of incentives for information sharing between a product's design, use and recovery phases (Kurilova-Palisaitiene et al., 2015). To explore this topic further, future research could investigate under which conditions data sharing with supply chain actors, to support reuse, remanufacturing and recycling, would be seen as an opportunity for manufacturers.



		Circular Strategies					
		In-use strategies			Looping strategies		
		Efficiency	Increased utilisation	Product lifetime extension	Reuse	Remanufacturing	Recycling
IoT capabilities	Tracking.	x	2	x	o	o	4
	Monitoring	x		o	o	o	
	Control	x		o	3		
	Optimisation	1		o			
	Design Evolution			o			

Figure 3.3: The four types of theoretical opportunities not considered in the studied case are shown in grey: (1) optimization and design evolution for efficiency in use, (2) IoT-enabled increased utilization, (3) control, optimization, and design evolution for reuse and remanufacturing, and (4) IoT-enabled recycling. Framework based on Ingemarsdotter et al. (2019).

3.6.2. LIMITATIONS AND TRANSFERABILITY OF RESULTS

This study reveals context-specific aspects of implementing IoT-enabled circular strategies in practice, which could only be extracted by digging deep into a specific a case. However, results from a case study cannot be directly transferred to different contexts. A discussion about the generalizability of the results is thus in place. As mentioned in Flyvbjerg (2006), two suitable ways to generalise from single case studies are (1) through the analogy of a critical experiment, and (2) through falsification. (1) means that, for example, if the case context can be seen as a particularly unfavourable setting for an event to occur, and the event still occurs, then the event is likely to occur also in other, more favourable, settings. (2) means that if the study can show that a hypothesis is not true in one case, then it can be concluded that the hypothesis is not generally true. Following the logic of a critical experiment, we can identify certain aspects of the case which might make it more or less favourable for IoT-enabled circular business model implementation. As mentioned in Section 3.2, there are product-type restrictions that create barriers for circular business model implementation (Bressanelli et al., 2019; Linder and Williander, 2017). Typically, the barriers are lower for high value products with slow technological development, and low fashion vulnerability (Linder and Williander, 2017). The case studied in this paper concerned a product of relatively low value, and with a fast technological development. This suggests that the challenges associated with interoperability, financial uncertainty, and consumer acceptance are likely to be larger in the studied case compared to, for example, capital goods.

The challenges found related to data quality and management, on the other hand, are likely to depend more on the digital maturity of the company (Kane et al., 2016), than on the type of product. Since no assessment of digital maturity was performed as part of this study, we cannot compare the studied case to other cases based on this aspect. However, based on the logic of falsification, our study indicates that the lack of structured processes for handling data quality and management in the context of IoT-enabled circular strategies is also likely to be an issue for other companies. While the severity of this challenge might vary between different cases, our study exemplifies real-world difficulties that might follow in the absence of a structured process.

Finally, the fact that IoT-enabled recycling was not considered as an opportunity in the studied case, even if the company is relatively experienced in 'design for recycling' strategies, might suggest that companies with less experience in 'design for recycling' would also not consider IoT-enabled recycling as an opportunity.

3.7. CONCLUSIONS AND FUTURE RESEARCH

In this paper, we have presented one of the first in-depth case studies specifically focusing on the opportunities and challenges in IoT-enabled circular business model implementation. By highlighting opportunities and challenges from a concrete case, this paper provides a first step towards explaining the mismatch between the opportunities of IoT for CE as anticipated in literature and actual implementation in practice.

The identified opportunities for IoT to support circular strategies in the studied case demonstrate that IoT can support a servitized business model, support tracking and record keeping of in-use and post-use products, enable conditions monitoring and predictive maintenance, improve estimations of remaining lifetime of used products, and inform design decisions to improve durability of products.

In relation to these opportunities, we extracted two main IoT-specific challenges: (1) the lack of structured data management processes to ensure high quality data collection and analysis, and (2) the difficulty of designing both software and hardware of IoT-enabled products and components for interoperability, adaptability and upgradability, as technology keeps developing. These findings add IoT-specific insights to previous literature on challenges in circular business model implementation. We also extracted general (i.e., not IoT specific) challenges regarding the financial uncertainty and limited customer acceptance of circular business models, confirming previous literature.

Based on our findings, we suggest future research into processes for data management in the context of IoT for CE, and guidelines for how to design IoT-enabled products for interoperability, adaptability and upgradability. Lastly, future case studies on the topic of IoT for CE could investigate high value products with stable technologies, as these are the products for which implementation barriers are expected to be lowest.

Author Contributions:
E.I. is the primary author of this manuscript. E.I. was in charge of collecting and analyzing the data, and lead the writing process. E.J. and R.B. supervised the research and contributed to writing and reviewing the paper internally.

Funding:
This work was funded by the Circular European Economy Innovative Training Network, Circeuit, an action funded by the European Commission under the Horizon 2020 Marie Sklodowska Curie Action 2016 (Grant Agreement number 721909).

Declaration of Competing Interest:
The authors declare no conflict of interest.

Acknowledgements:
The authors would like to thank all the interviewees for their participation in the study, the contact persons at the case company for support in planning and coordinating data collection, and the anonymous reviewers for valuable feedback.

REFERENCES

A. Alcayaga, M. Wiener, and E. G. Hansen (2019). Towards a framework of smart-circular systems: An integrative literature review. *Journal of Cleaner Production* **221**, 622.

M. Antikainen, T. Uusitalo, and P. Kivikytö-Reponen (2018), Digitalisation as an Enabler of Circular Economy, in *10th CIRP Conference on Industrial Product-Service Systems*, Linköping, Sweden.

L. Atzori, A. Iera, and G. Morabito (2016). Understanding the Internet of Things: definition, potentials, and societal role of a fast evolving paradigm. *Ad Hoc Networks* **56**, 122.

T. Baines and H. Lightfoot (2013). Information and Communication Technologies. in *Made to Serve: How manufacturers can compete through servitization and product-service systems*, edited by T. Baines and H. Lightfoot, Chap. 9, pp. 169–180. John Wiley & Sons, Incorporated.

C. Bakker, F. Wang, J. Huisman, and M. Den Hollander (2014). Products that go round: exploring product life extension through design. *Journal of Cleaner Production* **69**, 10.

R. Balkenende, N. Bocken, and C. Bakker (2017). Design for the Circular Economy. in *The Routledge Handbook of Sustainable Design*, edited by R. Egenhoefer. Routledge, London, UK.

N. Bocken, E. Ingemarsdotter, and D. Gonzalez (2019). Designing Sustainable Business Models: Exploring IoT-Enabled Strategies to Drive Sustainable Consumption. in *Sustainable Business Models*, edited by A. Aagard, Chap. 3. Palgrave Macmillan, Cham, Switzerland.

N. M. P. Bocken, S. W. Short, P. Rana, and S. Evans (2014). A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production* **65**, 42.

G. Bressanelli, F. Adrodegari, M. Perona, and N. Saccani (2018). Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies. *Sustainability* **10**, 639.

G. Bressanelli, M. Perona, and N. Saccani (2019). Challenges in supply chain redesign for the Circular Economy : a literature review and a multiple case study. *International Journal of Production Research* **57**, 7395.

G. Cattelan Nobre and E. Tavares (2017). Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study. *Scientometrics* **111**, 463.

W. Derigent and A. Thomas (2016). End-of-Life Information Sharing for a Circular Economy: Existing Literature and Research Opportunities. in *Service Orientation in*

Holonic and Multi-Agent Manufacturing, Chap. 4. Springer International Publishing, Switzerland.

M. T. Dulman and S. M. Gupta (2018). Maintenance and remanufacturing strategy: using sensors to predict the status of wind turbines. *Journal of Remanufacturing* **8**, 131.

Ellen MacArthur Foundation (2013), *Towards the Circular Economy: Economic and business rationale for an accelerated transition,* Cowes, UK.
Available from: https://www.ellenmacarthurfoundation.org/publications.

Ellen MacArthur Foundation (2016), *Intelligent assets: Unlocking the Circular Economy Potential,* Cowes, UK.
Available from: https://www.ellenmacarthurfoundation.org/publications.

Ellen MacArthur Foundation, McKinsey & Company, and Google (2019), *Artificial Intelligence and The Circular Economy,* Ellen MacArthur Foundation McKinsey & Co Google. Available from: https://www.ellenmacarthurfoundation.org/publications.

B. Flyvbjerg (2006). Five misunderstandings about case-study research. *Qualitative Inquiry* **12**, 219.

M. Geissdoerfer, D. Vladimirova, and S. Evans (2018). Sustainable business model innovation: A review. *Journal of Cleaner Production* **198**, 401.

E. Ingemarsdotter, E. Jamsin, G. Kortuem, and R. Balkenende (2019). Circular strategies enabled by the Internet of Things—A framework and analysis of current practice. *Sustainability* **11**, 5689.

G. C. Kane, D. Palmer, A. N. Phillips, D. Kiron, and N. Buckley (2016), *Aligning the Future for Its Digital Organization,* MIT Sloan Management Review Deloitte University Press. Available from: http://sloanreview.mit.edu/digital2016.

D. Kiritsis (2011). Closed-loop PLM for intelligent products in the era of the Internet of Things. *CAD Computer Aided Design* **43**, 479.

G. Kortuem, F. Kawsar, D. Fitton, and V. Sundramoorthy (2010). Smart objects as building blocks for the internet of things. *IEEE Internet Computing* **14**, 44.

J. Kurilova-Palisaitiene, L. Lindkvist, and E. Sundin (2015), Towards facilitating circular product life-cycle information flow via remanufacturing, in *Procedia CIRP The 22nd CIRP Conference on Life Cycle Engineering,* Sydney, Australia.

M. Lieder and A. Rashid (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production* **115**, 36.

M. Linder and M. Williander (2017). Circular Business Model Innovation: Inherent Uncertainties. *Business Strategy and the Environment* **26**, 182.

C. Luttropp and J. Johansson (2010). Improved recycling with life cycle information tagged to the product. *Journal of Cleaner Production* **18**, 346.

I. C. Ng and S. Y. Wakenshaw (2017). The Internet-of-Things: Review and research directions. *International Journal of Research in Marketing* **34**, 3.

O. Okorie, K. Salonitis, F. Charnley, M. Moreno, C. Turner, and A. Tiwari (2018). Digitisation and the Circular Economy: A Review of Current Research and Future Trends. *Energies* **11**, 3009.

A. Pagoropoulos, D. C. Pigosso, and T. C. McAloone (2017), The Emergent Role of Digital Technologies in the Circular Economy: A Review, in *Procedia CIRP 9th CIRP IPSS Conference: Circular Perspectives on PSS*, Copenhagen, Denmark.

O. Pialot, D. Millet, and J. Bisiaux (2017). Upgradable PSS: Clarifying a new concept of sustainable consumption/production based on upgradability. *Journal of Cleaner Production* **141**, 538.

M. E. Porter and J. E. Heppelmann (2014). How smart, connected products are transforming competition. *Harvard Business Review*
Available from: https://hbr.org/archive-toc/BR1411.

M. E. Raynor and M. J. Cotteleer (2015), *The more things change. Value creation, value capture, and the Internet of Things*, Deloitte Review.
Available from: https://www.deloitte.com/insights.

S. Ritzén and G. Ö. Sandström (2017), Barriers to the Circular Economy - Integration of Perspectives and Domains, in *Procedia CIRP 9th CIRP IPSS Conference: Circular Perspectives on PSS*, Copenhagen, Denmark.

A. Rymaszewska, P. Helo, and A. Gunasekaran (2017). IoT powered servitization of manufacturing-an exploratory case study. *International Journal of Production Economics* **192**, 92.

T. T. Sousa-Zomer, L. Magalhães, E. Zancul, and P. A. Cauchick-Miguel (2018). Exploring the challenges for circular business implementation in manufacturing companies: An empirical investigation of a pay-per-use service provider. *Resources, Conservation and Recycling* **135**, 3.

D. Sumter, C. Bakker, and R. Balkenende (2018). The role of product design in creating circular business models: A case study on the lease and refurbishment of baby strollers. *Sustainability* **10**, 2415.

B. Sun, S. Zeng, R. Kang, and M. G. Pecht (2012). Benefits and challenges of system prognostics. *IEEE Transactions on Reliability* **61**, 323.

A. Tukker (2004). Eight types of product-service system: Eight ways to sustainability? Experiences from SusProNet. *Business Strategy and the Environment* **13**, 246.

A. Tukker (2015). Product services for a resource-efficient and circular economy - A review. *Journal of Cleaner Production* **97**, 76.

D. A. Vermunt, S. O. Negro, P. A. Verweij, D. V. Kuppens, and M. P. Hekkert (2019). Exploring barriers to implementing different circular business models. *Journal of Cleaner Production* **222**, 891.

H. Wilts and H. Berg (2017). The digital circular economy: can the digital transformation pave the way for resource-efficient materials cycles? *International Journal of Environmental Sciences & Natural Resources* **7**, 555725.

S. Yang, A. M. R., J. Kaminski, and H. Pepin (2018). Opportunities for Industry 4.0 to Support Remanufacturing. *Applied Sciences* **8**, 1177.

R. K. Yin (2014), *Case Study Research: Design and Methods,* 5th ed., SAGE Publications, Thousand Oaks, CA, USA.

I. Zeid, S. V. Kamarthi, and S. M. Gupta (2004), Product Take-Back: Sensors-Based Approach, in *Proceedings of SPIE - The International Society for Optical Engineering,* Vol. 5583, Philadelphia, Pennsylvania, United States.

H.-C. Zhang, S. Liu, H. Lu, Y. Zhang, and Y. Hu (2015). Remanufacturing and Remaining Useful Life Assessment. in *Handbook of Manufacturing Engineering and Technology,* Chap. 86. Springer-Verlag, London, UK.

Y. Zhang, S. Liu, Y. Liu, H. Yang, M. Li, D. Huisingh, and L. Wang (2018). The 'Internet of Things' enabled real-time scheduling for remanufacturing of automobile engines. *Journal of Cleaner Production* **185**, 562

4

CHALLENGES AND SOLUTIONS IN CONDITION-BASED MAINTENANCE IMPLEMENTATION —A MULTIPLE CASE STUDY

This chapter is submitted and under review as:
E. Ingemarsdotter, M. L. Kambanou, E. Jamsin, T. Sakao, and R. Balkenende (in review) Challenges and Solutions in Condition-Based Maintenance Implementation —A Multiple Case Study. *Journal of Cleaner Production* **xx**, xx.

Abstract: Previous literature has highlighted many opportunities for digital technologies, such as the Internet of Things (IoT) and data analytics, to enable circular strategies, i.e., strategies which support the transition to a circular economy (CE). As one of the key circular strategies for which the digital opportunities are apparent, maintenance is selected as the focus area for this study. In the field of maintenance, IoT and data analytics enable companies to implement condition-based maintenance (CBM), i.e., maintenance based on monitoring the actual condition of products in the field. CBM can lead to more timely and efficient maintenance, better performing products-in-use, reduced downtime in operations, and longer product lifetimes. Despite these benefits, CBM implementation in practice is still limited. The aim of this research is thus to understand the challenges related to CBM implementation in practice, and to extract solutions which companies have applied to address these challenges. Towards this aim, a multiple case study is conducted at three original equipment manufacturers (OEMs). A framework is derived which allows for a broad analysis of challenges and solutions in the cases. We identify 19 challenges and 16 solutions and translate these into a set of actionable recommendations. Our findings contribute to the field of CBM with a comprehensive view of challenges and solutions in practice, from the OEM's point of view. Moreover, we contribute to CE literature with a concrete case study about IoT-enabled circular strategy implementation.

Keywords: Circular Economy, Condition-Based Maintenance, Digitalization, Internet of Things, Case Study

4.1. INTRODUCTION

The circular economy has been defined as *"an economy that is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times"* (Webster, 2015) (p.16). Design and business model strategies for the CE include product lifetime extension strategies (maintenance and repair) and looping strategies (reuse, remanufacturing, and recycling). While looping strategies are core to the actual circulation of products and materials, product lifetime extension strategies have a higher potential to reduce environmental impact (European Commission, 2008), as they keep products close to their original function and value (Potting et al., 2017). Based on this logic, maintenance and repair strategies are given higher priority than looping strategies in the EU waste directive (European Commission, 2008). Moreover, previous research has shown that increased maintainability and reparability of products in turn also benefits reusability and remanufacturability (Takata et al., 2004). As such, maintenance and repair are key strategies to explore for companies aiming to provide circular products and services. In this paper, we focus specifically on maintenance and its implementation in practice.

One of the most important trends in maintenance management is digitalization (Akkermans et al., 2016). Based on the Internet of Things (IoT) and data analytics, the condition of products in the field can be monitored continuously and remotely, enabling optimized condition-based maintenance (CBM). Condition monitoring also enables better insight into remaining product lifetime, degradation status, and environmental factors (Ren et al., 2019), which can be used to improve looping strategies (Bressanelli et al., 2018; Ellen MacArthur Foundation, 2016; Ellen MacArthur Foundation et al., 2019; Spring and Araujo, 2017; Ondemir and Gupta, 2014). However, actual implementation of condition-based looping strategies in practice remains low (Alcayaga et al., 2019 Ingemarsdotter et al., 2019).

As for all circular strategies, design is a key enabler of successful maintenance (Mulder et al., 2012). Original Equipment Manufacturers (OEMs) can intentionally design their products to facilitate CBM, for example by ensuring the integration of sensors needed to derive reliable insights about a product's condition. Previous literature has shown successful examples of OEMs monitoring their customers' products remotely and offering CBM as part of a service-based value proposition (Lightfoot et al., 2011; Rymaszewska et al., 2017). However, this is far from common practice and many OEMs, while seeing the business opportunity of offering CBM, still struggle with its implementation (Bouskedis et al., 2020; March and Scudder, 2017).

Previous literature highlights a gap between the current focus of academic research and the real-world challenges that companies face when implementing CBM. As such, there is a need for more practice-oriented research in this field (Fraser et al., 2015). Similarly, recent papers in the field of CE highlight a need for more case studies of IoT-enabled circular strategies (e.g., CBM), to better understand implementation challenges in practice (see, for example, Antikainen et al., 2018; Cattelan Nobre and Tavares, 2017; Pagoropoulos et al., 2017; Ingemarsdotter et al., 2020). Specifically, authors from both fields call for a wider understanding of implementation challenges beyond purely technological aspects (e.g., Kirchherr et al., 2017; Coleman et al., 2017; Lee, 2020).

In this paper, we aim to understand the challenges that OEMs face when implementing CBM as part of the value proposition to their customers. More specifically, we study the challenges that they face when developing an IoT artefact for CBM and the solutions that they have applied to address these challenges. Towards this aim, we develop a framework, which takes a wide perspective on CBM implementation by integrating technological, organizational, and user-related aspects. The framework is then used to analyse the cases. This way, we aim to contribute to CBM literature with empirically grounded insights from the OEM's perspective, beyond a purely technological focus. Moreover, we see CBM as one of the most commonly implemented IoT-enabled circular strategies, for which we were able to gain access to real-world company cases. As CBM shares key characteristics with other IoT-enabled circular strategies, in particular condition-based reuse and remanufacturing, our aim is that the findings extracted from this paper will also be valuable for CE literature beyond maintenance.

The remainder of the paper is structured as follows. Section 4.2 first introduces the concept of CBM, including key steps and technologies (Section 4.2.1). Thereafter, we present previous literature on challenges and solutions in CBM implementation and argue for the need for an integrated perspective, considering technological, organizational, and user-related aspects (Section 4.2.2). Section 4.3 describes the research methods, while Section 4.4 explains how the integrated framework was developed based on previous literature. Section 4.5 presents the cases, and Section 4.6 presents the identified challenges and solutions. In Section 4.7, we discuss the results in relation to previous literature, and translate our findings into a set of recommendations for practitioners. Finally, Section 4.8 states the main conclusions of the paper and present suggestions for future research.

4.2. BACKGROUND

4.2.1. INTRODUCTION TO CONDITION-BASED MAINTENANCE

CBM has been defined as *"preventive maintenance which include assessment of physical conditions, analysis and the possible ensuing maintenance actions"* (British Standard Institution, 2017). If implemented successfully, CBM can reduce the number of unnecessary preventive maintenance activities as maintenance only takes place if the data shows signs of abnormalities (Jardine et al., 2006). Moreover, CBM has environmental advantages resulting from, for example, extended operational product lives, more intensive use of products, and reduced transportation of personnel and spare parts (Johansson et al., 2019).

Jardine et al. (2006) distinguish between three key steps in CBM: data acquisition, data processing, and maintenance decision making. Data acquisition includes collection and sorting of data about products in the field, both condition monitoring data (e.g., vibration data, acoustic data, oil analysis data, temperature, pressure, or moisture) and so called event data, i.e., what happened to the product in a particular situation, or which maintenance tasks were performed on the product. Event data often requires manual data entry. Condition monitoring data can be collected both automatically through sensors or other measurement techniques, or manually through for example daily oil quality checks (Ahmad and Kamaruddin, 2012). While the definition of CBM does not explicitly require automatic sensor-enabled data collection for condition monitoring, this is often implicitly assumed in the current technological context. The data processing step includes data cleaning, analysis and interpretation. In the decision-making step, maintenance policies are selected, and maintenance actions are carried out, based on the derived insights.

CBM can be categorised into four types, according to the level of data analytics performed: descriptive, diagnostic, predictive and prescriptive analytics (Baum et al., 2018). According to Baum et al. (2018), descriptive analytics aims to understand events based on historical data, whereas diagnostic analytics investigates why an event took place. In predictive and prescriptive analytics, mathematical models are used predict future outcomes and to prescribe optimal interventions, respectively. The term 'predictive maintenance' has been gaining traction in literature, with many studies highlighting its business opportunities (e.g., Bouskedis et al., 2020; March and

Scudder, 2017). In this paper, we use the term CBM to include maintenance activities based on data analytics at any of the four levels.

An extensive body of literature has been built up around mathematical models and data analytics methods for CBM. Two closely related research areas can be identified: research into the selection of optimal maintenance policies, and research into data analytics for failure diagnostics and prognostic. Maintenance policy optimization is usually based on cost, reliability, or availability and considers parameters such as the products' degradation patterns, the resources available for maintenance, and the consequences of a potential stand-still (Alaswad and Xiang, 2017). Recently, attention has also been paid to understanding dependencies between different components in complex systems, and how that might influence the optimal choice of maintenance policy for the system as a whole (Olde Keizer et al., 2017).

Component-level diagnostic and prognostic approaches have been reviewed in multiple papers, e.g., by Atamuradov et al. (2017), Jardine et al. (2006), and Lei et al. (2018). Although different categorisations have been suggested in literature, three types of approaches are often put forward: model-based (or physics-based), data-driven, and hybrid approaches (Atamuradov et al., 2017; Kwon et al., 2016). Below, we briefly describe model-based and data-driven approaches. Hybrid approaches are defined as combinations of these two, with the aim to use the advantages of both.

Model-based approaches use mathematical models to describe degradation processes. Condition monitoring data is fed to the model, which calculates a predicted state. These kinds of models can be relatively accurate, also for long-term predictions, but requires in-depth knowledge about the physics of degradation for the specific product (Jardine et al., 2006, Shimomura et al., 1995). Moreover, the applicability of these degradation models in practice is sometimes limited by the complexity of the real-world system in which individual components operate. Examples of use cases where model-based approaches are common and effective include condition monitoring of bearings and of the structural health of materials (e.g., in bridges) (Atamuradov et al., 2017).

Data-driven approaches are instead based on analysing condition monitoring data to detect anomalies and translate such anomalies into insights about potential faults. This way, degradation models are built up from the data, often using machine learning techniques (Heng et al., 2009). Data-driven approaches require less experts knowledge about how the product or component fails, but instead requires more computational power than model-based approaches, as well as access to large amount of high quality data. The accuracy of the model depends directly on the amount and quality of the data that is used to build it (Atamuradov et al., 2017). In practice, challenges arise as the collected data is often heterogeneous and disperse. Research into new algorithms for prognostics evolves at a fast speed, see e.g., Stetco et al. (2019) or Kumar et al. (2020).

There is still a need to improve the available diagnostic and prognostics approaches to achieve high levels of accuracy in real world settings, especially in long-term predictions. Alaswad and Xiang (2017) highlight that most research has focused on single-component systems, and that more work is needed to understand the condition of complex products and systems with multiple different components. For example, they mention the need to model dependencies between degradation processes in different components, as well as possible human errors related to CBM.

4.2.2. PREVIOUS RESEARCH ON CHALLENGES AND SOLUTIONS IN CBM IMPLEMENTATION

Despite the abundance of technical literature, companies still struggle to effectively implement CBM in practice (van de Kerkhof et al., 2016; Tiddens, 2018). Based on a survey of 98 Swedish companies, Ylipää et al. (2017) found that maintenance personnel still mainly carry out reactive repairs, rather than proactive maintenance. Similar findings have been reported by Jin et al. (2016) and Chinese and Ghirardo (2010), based on data from the United States and Italy, respectively. Further, Veldman et al. (2011) and Tiddens (2018) noted that, among the companies who have set up CBM implementation projects, many do not follow systematic processes. As such, we note that there is a gap between the challenges faced by companies wanting to implement CBM and the advanced solutions presented in literature.

Other researchers have also highlighted such a gap and called for more empirically-based research which can actually help solving “real problems in industry” (Fraser et al., 2015). Olde Keizer et al. (2017) note that the fact that CBM implementation in practice is lagging behind could, at least partly, be explained by the complexity of real-life systems compared to the simplified systems often studied in academia. Other technical challenges related to implementing CBM in real-life settings include the lack of failure data from products in the field, making it challenging to develop robust diagnostics and prognostics (Jin et al., 2016; Goyal and Pabla, 2015). Selcuk (2017) and Rastegari et al. (2013) both highlight technology selection as a critical factor for CBM implementation, including, for example, which components to monitor, which measurement techniques to use, and what types of data analytics models to apply. Stecki et al. (2014) concluded that challenges to widespread CBM implementation exist across all technical levels, from data collection, through data analysis to decision support. Related to this, Rastegari et al. (2013) highlight competence building around data collection and analysis as a critical challenge.

Some research is available which aims to support companies in overcoming these technical implementation challenges. For example, Lee et al. (2014) and Tiddens (2018) presented methods for selecting critical components to monitor and algorithms to use when processing the data. Stecki et al. (2014) formulated recommendations for how to set up an effective CBM program, highlighting the need to understand the risks to which a system is exposed, as well as to analyse and define failure dependencies. Mourtzis et al. (2020) presented a framework where Augmented Reality (AR) was used to support effective real-time communication and data exchange between service technicians in the field and expert engineers located remotely.

However, technical aspects only form one of several important dimensions in CBM implementation (Lee, 2020). A recent Deloitte report emphasises the importance of looking beyond technology and focus more on processes and organizational changes needed for successful CBM implementation (Coleman et al., 2017). Similarly, Lee (2020) argues that the biggest challenge of Industrial AI (including CBM) is not a lack of suitable technology, but rather how to create real value from a combination of technologies in a resource efficient and collaborative way. Selcuk (2017) highlights organizational challenges related to the fact that CBM implementation is a multi-disciplinary undertaking with implications for, for example, hardware, software, personnel and training requirements.

With this in mind, our research takes a wide perspective on CBM implementation, including technological, organizational and user-related aspects. A small set of previous papers take a similar direction. Veldman et al. (2011) identified challenges in CBM implementation related to a lack of strict procedures, and a lack of employee training to support correct execution. More recently, Jin et al. (2016) highlighted barriers related to costs, workforce and level of skills, organizational and technology readiness, and complexity of system design changes. They also saw a need for clear strategies to motivate and train personnel, create incentives, and ensure interdepartmental collaboration. Bokrantz et al. (2020) identified implementation challenges for CBM related to, for example, costs and cultural resistance. Rastegari et al. (2013) concluded that one of the main challenges when changing the company culture from reactive to proactive maintenance strategies is a lack of management support. Golightly et al. (2018) studied human and organizational factors in CBM implementation and derived high-level recommendations related to company culture, effective processes, resource deployment, and collaboration. In Section 4.7, we discuss how our findings relate to these previous papers.

4.3. METHOD

We conducted a multiple case study at three original equipment manufacturers (OEMs). Case study methodology is suitable when studying *"a contemporary phenomenon within its real-life context"* (Yin, 2014). This aligns with the aim of this research, i.e., to understand challenges and solutions related to CBM implementation in practice. In each of the studied cases, we were interested in challenges and solutions related to developing and implementing the technical artefact needed to realise CBM (the 'IoT artefact'). Below, we describe how the cases were selected, and how data was collected and analysed. Section 4.4 describes how we developed the integrated framework which was used to analyse the data.

4.3.1. CASE SELECTION

To be considered a relevant case for this study, three criteria had to be fulfilled. Firstly, the case should be embedded within the context of a manufacturer of high value, complex products. This ensured comparability between the cases, and is based on the notion that maintenance costs for such products are high in relation to production costs, compared to other types of products (Mulder et al., 2012). Secondly, the case should describe an, at least partly, implemented CBM solution. Thirdly, the CBM solution should be part of a maintenance service delivered to the end user of the product. The type of product that was studied for each of the selected cases is presented in Table 4.1. More detailed descriptions of the cases are given in Section 4.5.

Table 4.1: Products studied in the three cases.

Case A	Forklifts
Case B	Industrial robots
Case C	Heat pumps

4.3.2. DATA COLLECTION

Semi-structured interviews were conducted with company representatives (Table 4.2) using an interview guide. The interview guide is presented in Table C.1 in Appendix C. The interviews, which were audio-recorded, took place between April and July 2019, each lasting between 40 and 75 minutes. The aim was to interview at least one person from the R&D department who had experience in IoT and/or data analytics, and one from the maintenance or aftermarket department. This way, we could capture the views of actors involved in developing the IoT artefact as well as actors using it. For Case B, no one from the maintenance or aftermarket department could be accessed. However, a user experience (UX) designer could provide insights into how the maintenance and customer support staff used the CBM solution.

Table 4.2: Interviews conducted per case company.

Case	#	Role	Interviewee ID	Total amount of data collected
A	7	R&D manager	Int-A1	6 hours
		Service manager	Int-A2	
		Product specialist with aftermarket responsibilities	Int-A3	
		R&D manager	Int-A4	
		Manager ‘Software Systems Solutions’	Int-A5	
		Manager ‘Technology solutions’	Int-A6	
		Head of Group, Embedded software	Int-A7	
B	4	Program manager digital services	Int-B1	4 hours 20 min
		Senior principle scientist	Int-B2	
		Senior R&D engineer	Int-B3	

Continuation of Table 4.2

Case	#	Role	Interviewee ID	Total amount of data collected
		User experience designer	Int-B4	
C	4	Senior project manager R&D	Int-C1	3 hours 50 min
		Systems architect	Int-C2	
		Technical support	Int-C3	
		Senior data analyst	Int-C4	
	15			**14 hours 10 min**

4.3.3. DATA ANALYSIS

The data analysis process is shown in Figure 4.1. The audio recordings of the interviews were transcribed, and then coded using the software ATLAS.ti. The transcriptions were broken down into "quotes", and in a first step, each quote was coded based on the framework which is used to analyse the data (presented in Section 4). More specifically, each quote was coded as a challenge or solution in a specific 'alignment type' (explained in Table 4). For example, the following quote was coded as a 'challenge' in the 'Work system-Context' alignment type because it shows how the regulatory context surrounding the work system needs to be in alignment with the work system:

"...first of all, what we need from a legal perspective is that we need permission from the end user that we can log their data. So this is a constraint, without that the use case is gone ..." (Int-C4)

In a second coding step, challenges and solutions in an alignment type were further grouped into sub-categories. The example above was put into the sub-category 'Data privacy concerns' together with seven other quotes. These sub-categories were elicited by observing commonalities between quotes with the same first level code. This was an iterative process involving all authors and as a final step the interview data was revisited to ensure that all quotes were coded as one of the identified challenges or solutions (second level codes). After this, 19 challenges and 16 solutions remained. hese challenges and solutions are the main results of this research and are presented in Section 4.6.

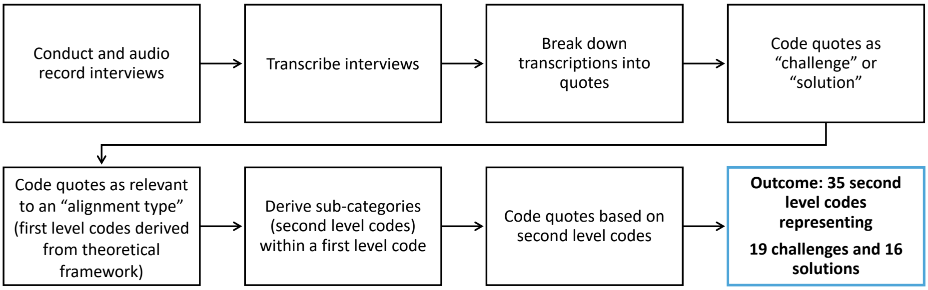


Figure 4.1: Steps in the data analysis process.

4.4. FRAMEWORK DEVELOPMENT

To analyse the cases, we needed a structured representation of (1) the IoT artefact that the companies had to produce to realise CBM and (2) the surrounding organizational and user-related aspects needed to achieve this. This was achieved through adapting and combining two frameworks: the new technology stack (Porter and Heppelmann, 2014) and the work system framework (Alter, 2013). The new technology stack (Figure 4.2) provides a way to describe an IoT artefact as a 'stack' with three main layers: the product layer, the connectivity layer, and the cloud layer. The work system framework (Figure 4.3) provides a frame for describing the system needed to produce a product or a service.

Below, we first briefly present the two frameworks. Then, we describe how we take the work system framework as a starting point, and adapt it by (1) making simplifications where possible, (2) using the new technology stack to detail the product/service to be produced by the work system, and (3) contextualising the descriptions of the work system elements, and the required alignment between them, to fit the context of this paper.

4.4.1. FRAMEWORKS FROM LITERATURE

The new technology stack presented by Porter and Heppelmann (2014) shows the layered nature of IoT artefacts. As depicted in Figure 4.2, Porter and Heppelmann (2014) distinguish between three main layers: the product layer, the connectivity layer, and the product cloud layer. The product layer consists of product hardware and product-level software. The connectivity layer enables communication between the product and the cloud layer. The cloud layer consists of a product data database, an application platform, a data analytics engine, and cloud-level applications (Porter, 2015).

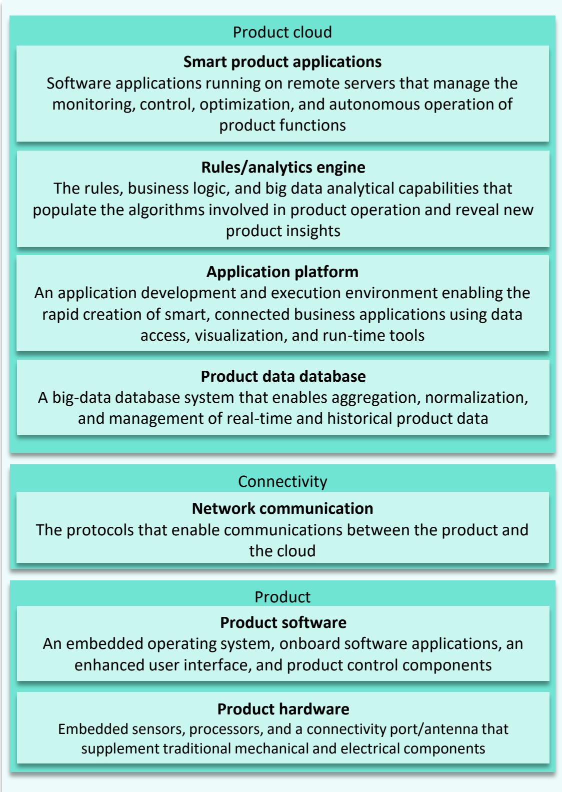


Figure 4.2: The new technology stack, adapted from Porter and Heppelmann (2014).

The work system framework represents a 'work system', defined as a *"system in which human participants and/or machines perform work using information, technology, and other resources to produce specific products/services for specific internal and/or external customers"*. The term 'work' is defined as *"the application of human, informational, physical, and other resources to produce products/services"* (Alter, 2013) [p. 75].

As seen in Figure 4.3, the work system framework includes nine elements: participants, information, technologies, processes/activities, product/service, customers, infrastructure, environment, and strategies. The definitions as given by Alter (2013) for each of the nine elements are presented in Table C.2 in Appendix C.

For a work system to successfully reach its goal, i.e., to produce the product/service for the intended customers, the elements of the work system should be 'in alignment' with each other. Five distinct types of alignment are shown in Figure 4.3 as arrows linking elements together. For example, participant-processes/activities alignment implies that *"the knowledge, skills, interests, and motivation of the participants should fit with the processes and activities in the work system, and the processes and activities* *should be appropriate for attributes of the participants"* (Alter, 2013) [p. 79]. While not explicitly shown in the work system framework, the work system as a whole should also be in alignment with the company-level strategy, infrastructure and environment.

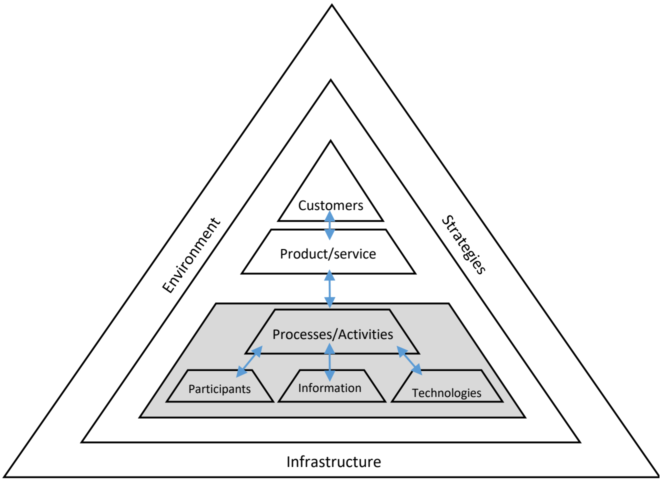


Figure 4.3: The work system framework, adapted from Alter (2013).

4.4.2. INTEGRATED FRAMEWORK

To develop the integrated framework, we take the work system framework as a starting point and adapt it to fit the context of this paper. We first simplify by renaming the element 'Processes/Activities' to 'Activities' and combining the three elements 'Strategies', 'Infrastructure', 'Environment' into one category named 'Context'.

Thereafter, we detail to the 'product/service' to be produced by the work system. We use the new technology stack (Figure 4.2) to represent the IoT artefact needed to enable CBM. In order to also include services produced by the work system, and offered to the users of the IoT artefact, we add a service layer on top of the technology stack. This service layer might include, for example, software maintenance, updates, and support.

Based on the above, we formulate the descriptions of the work system elements according to Table 4.3. We identify the maintenance personnel as the main customers in the work system, since they are the main users of the product/service. This includes roles such as service technicians, service managers, and customer support personnel. However, we acknowledge that there can also be other users of the IoT artefact, for example the end customer (the user of the product to be maintained), or the internal R&D department.

Table 4.3: Elements of the integrated framework, adapted from Alter (2013).

Work system element	Description
Product/Service	An IoT artefact which supports CBM. The IoT artefact has a product layer, a connectivity layer, a cloud layer, and a service layer.
Customers	The main customers of the product/service are service technicians, service management, and customer support. Other customers can be, for example, the end user of the physical product and the R&D department.
Activities	Activities needed to produce the product/service include, but are not limited to, the design and development of cloud applications, data analytics models as well as the setup of data collection, transfer and storage. Activities also include the development of services such as software maintenance, updates, and support.
Participants	Participants involved in the activities are, for example, user interface designers, application developers, data analysts, and embedded software engineers.
Information	Information used by the participants in the activities includes feedback from the customers, as well as data collected by products in the field.
Technologies	Technologies used by the participants when performing the activities include tools for data collection, transfer, and processing.
Context	Using Alter's definitions for Infrastructure, Environment, and Strategies (see Appendix C), the context includes the overarching strategies of the company in which the work system is embedded, the organizational, cultural, competitive, technical, regulatory, and demographic environment surrounding the work system, as well as resources used within the work system, but managed outside it.

The integrated framework distinguishes between six alignment types, numbered 1–6 in Figure 4.4. These alignment types correspond to the five alignment types represented by arrows between work system elements in the work system framework (Figure 4.3), and one extra alignment type corresponding to alignment between the work system and its surrounding context. In the context of this paper, we characterize the six alignments types by explaining what is considered satisfactory alignment within each type, as described in Table 4.4.

Table 4.4: Explanation of satisfactory alignment, for each alignment type in the integrated framework.

Alignment type	Explanation
1. Information-Activities	The information that goes into the activities provides satisfactory input to the participants to perform the activities needed to produce the product/service.
2. Participants-Activities	The participants are able and willing to perform the activities needed to produce the product/service.
3. Technologies-Activities	The technologies available to the participants enable them to perform the activities needed to produce the product/service.
4. Activities-Product/service	The activities are well coordinated and aligned towards the goal of delivering a consistent product/service.
5. Customer-Product/service	The product/service satisfies the needs of all relevant customers, and the customers are able and willing to use the product/service as intended.
6. Work system-Context	The environment, infrastructure, and strategies of the company support the goal of the work system.

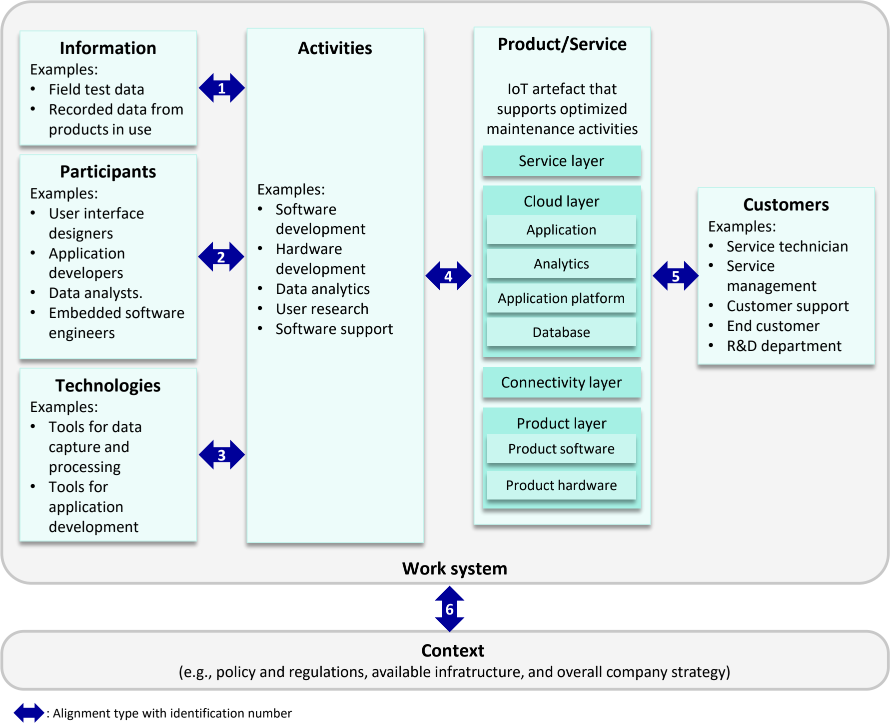


Figure 4.4: Integrated framework for analyzing the company cases, based on Alter (2013) and Porter and Heppelmann (2014).

4.5. CASE DESCRIPTIONS

4.5.1. CASE A: FORKLIFTS

Company A manufactures and sells forklifts to end customers who are operators of, e.g., warehouses and manufacturing facilities. Company A also provides maintenance services to their customers as part of short or long-term rental contracts.

In the recent years, Case A has developed a cloud application that provides the end customers with information about the forklifts they use. Drivers can log in to the application to record driving times, and managers can see productivity data. The application can also be used by maintenance and support personnel to support troubleshooting (IntA3). Through the application, the maintenance personnel can extract reports which show how many hours the forklift has run, as well as the recent error codes that the forklift has produced.

Regarding data analytics to support CBM, the company has started to recruit experts, but is still in an early phase of development.

Looking forward, the interviewees saw the need to develop a failure model, which could prescribe maintenance activities to minimise breakdowns (IntA1). This will require additional data collection from the forklift's operational phase (IntA2), (IntA1). The future vision for the cloud application also includes a stronger focus on service planning and coordination, such as automatic dispatching of jobs to service technicians based on their location and competence (IntA2).

4.5.2. CASE B: INDUSTRIAL ROBOTS

Company B manufactures and sells industrial robots to a broad range of customers, e.g., in the automotive industry. The company has in-house service technicians who provide maintenance services to the end customers who have opted for that. There is also a support organization, which assists customers remotely.

The company has offered services based on connectivity as an add-on to the robots for about 10 years (IntB4). They have developed a web-based application where both the end customer and internal maintenance personnel can log in and get information about the connected robots including alarms and error codes (IntB4). Internally, the main user of the application is the support personnel, who can log in to see and download recent alarms recorded by the robot.

Regarding data analytics, several research projects have been carried out to develop failure diagnostics and prognostics for CBM (IntB3). Moreover, a central data analytics team has been formed to support the different business units.

Looking forward, there is an ongoing project to update the application. The project will make sure that the application is transferred to a new company-central cloud platform and that the user experience is improved (IntB4). Moreover, the vision for the future includes an increased focus on failure predictions, and on prescribing timely maintenance actions (IntB4). Also, there is an ambition to extend the scope of CBM to include the tools used by the robot, or even the whole production line made up of multiple robots.

4.5.3. CASE C: HEAT PUMPS

Company C manufactures and sells heat pumps to both property managers, and individual households. The company does not offer maintenance-as-a-service directly, but has a long (ca 10 years) warranty which covers maintenance costs. Third party installers perform the actual maintenance activities, with help from company C's support organization (IntC1). There is a drive in the company to reduce maintenance costs, and increase customer satisfaction through increased uptime.

Almost all heat pumps currently sold can be connected to the internet. However, the company only collects data from customers if the service technicians cannot solve the problem and therefore contact customer support. Then, the company sends a request to the customer asking for permission to monitor their system for fault diagnosis purposes (IntC1). If accepted, the customer support can see the error codes produced by the heat pump. It is also possible to activate additional data logging, if needed (IntC4).

Regarding data analytics, the company has started to move towards predictive analytics, by putting together a specific team in charge of developing data-driven models to predict failures (IntC4).

Looking forward, there is an ongoing project to develop an application for the service technicians to be able to troubleshoot more easily, receive alarms remotely, and better plan and prepare for maintenance visits (IntC1). The project also involves extending the data available to the customer support team (IntC2).

4.6. RESULTS

A total of 19 challenges and 16 solutions were extracted from the case data. The challenges and solutions are distributed across the six alignment types in the framework, as seen in Figure 4.5 and Figure 4.6, respectively. Below, we describe the observed challenges and solutions per alignment type, illustrated by examples from the cases.

4.6.1. INFORMATION-ACTIVITIES ALIGNMENT

The challenges within this alignment type relate to collecting the right data at an appropriate quality. In all three cases, data is being collected from products in use. However, the data is not always appropriate and useful for the purpose of CBM (IntA1). Limited accuracy and time resolution of the collected data were mentioned as specific challenges (IntC2, IntB1), as was the fact that the data did not include all the parameters known to affect the product's condition (IntA1, IntB3, IntC3). In Case C, the latter issue has partly been solved through a strategy to collect more data than initially needed (IntC1, IntC4). However, this solution is difficult to scale up since it requires large amount of data to be transferred, stored, and processed (IntC4).

Moreover, both high quality metadata and labelled data are difficult to collect. Metadata here refers to information about a product in the field other than the actual monitoring parameters (e.g., the size of a house in which a heat pump is installed), and can be important for interpreting the data recorded by the system (IntC2, IntB1). Labelled data is a dataset that contains 'labels' about what actually happened in the field (e.g., if the product stopped working). Such labels are needed to perform supervised machine learning and build data-driven prognostic models (IntB3, IntC4). A specific issue is that metadata and data labels often need to be entered manually, for example by an installer or the end user. The interviewees pointed out a lack of ability and/or incentive among installers and end users to input this information accurately, and in a format that would allow for automatic processing (IntC2).

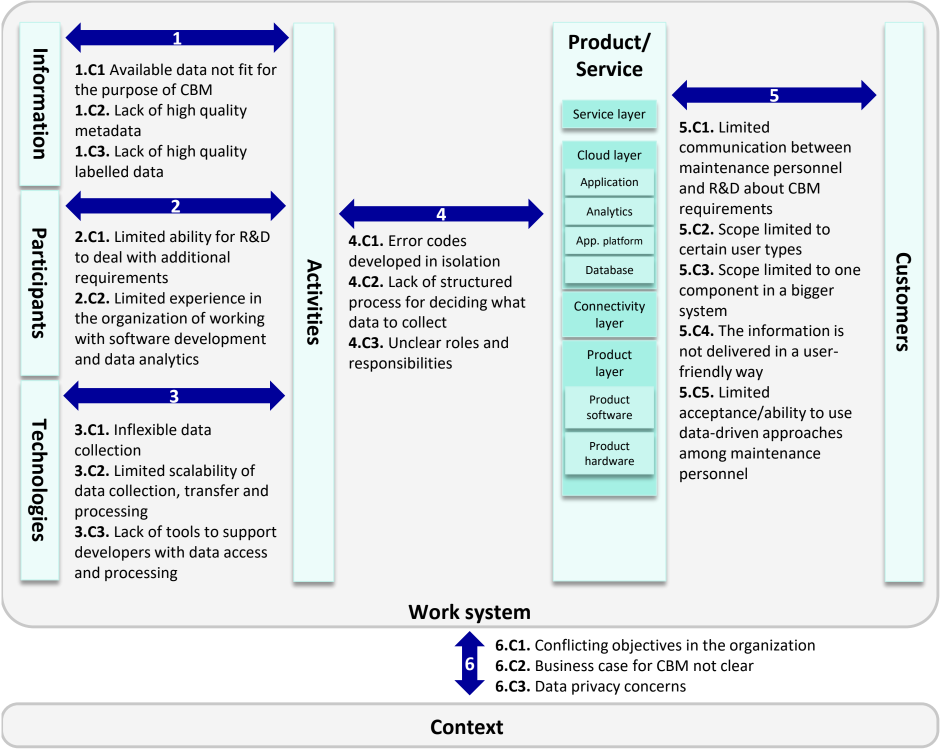
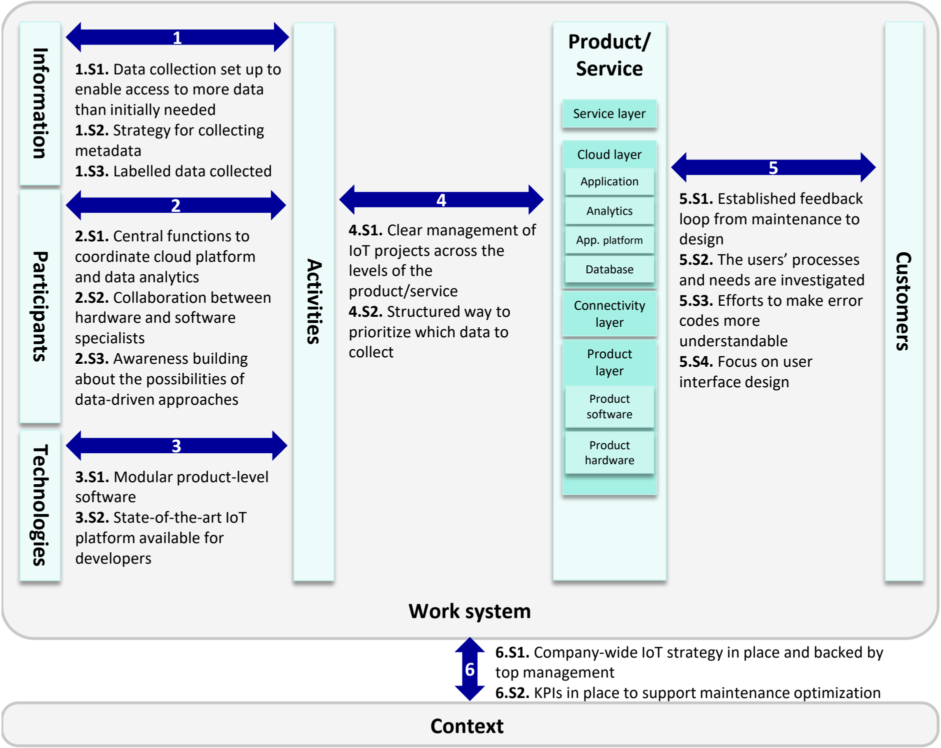


Figure 4.5: Challenges per alignments type, as extracted from the studied cases. The numbering used is ‘X.CY’, where X is the number of the alignment type (1–6), ‘C’ stands for challenge, and Y is the number of the specific challenge.

In Case C, the company has partly solved the challenge of lacking metadata, by asking installers to input metadata through a mobile application when an installation is registered to the warranty program (IntC2, IntC4). Still, many installers either do not report any metadata at all, or report inaccurate information. To collect labelled data, Case A and B monitors products in their own operations, for which they have insight into the products’ condition (IntA6, IntB3). Case B also performs tests of their products in lab environments (IntB3). For Case B, faults that happen at the customer site during the warranty period are well documented (IntB3) and Case C performs field tests at customer sites when new products are released (IntC1, IntC2). However, to understand product degradation over time, it would be necessary to collect labelled data from the field throughout the whole life of the product. Case C has tried to achieve this through building a web application for service technicians to enter labels about products’ condition during maintenance activities. However, the technicians often do not use it, or do not input the data accurately enough (IntC4).



1.S1. Data collection set up to enable access to more data than initially needed
1.S2. Strategy for collecting metadata
1.S3. Labelled data collected

2.S1. Central functions to coordinate cloud platform and data analytics
2.S2. Collaboration between hardware and software specialists
2.S3. Awareness building about the possibilities of data-driven approaches

3.S1. Modular product-level software
3.S2. State-of-the-art IoT platform available for developers

4.S1. Clear management of IoT projects across the levels of the product/service
4.S2. Structured way to prioritize which data to collect

5.S1. Established feedback loop from maintenance to design
5.S2. The users' processes and needs are investigated
5.S3. Efforts to make error codes more understandable
5.S4. Focus on user interface design

6.S1. Company-wide IoT strategy in place and backed by top management
6.S2. KPIs in place to support maintenance optimization

Figure 4.6: Solutions per alignment type, as extracted from the studied cases. The numbering used is 'X.SY', where X is the number of the alignment type (1–6), 'S' means solution, and Y is the number of the specific solution.

4.6.2. PARTICIPANTS-ACTIVITIES ALIGNMENT

The challenges within this alignment type relate to a lack of time, resources, and experience in the organization needed to meet CBM-specific requirements. CBM requirements are sometimes overlooked if the R&D department is already overloaded with other product requirements (IntB3, IntA3, IntA7). It is especially difficult for the R&D team to develop new infrastructure, such as a cloud platform, while working on sharp development projects (IntB3). Moreover, due to lacking experience with data-driven approaches, some employees do not even consider that these technologies could be of interest (IntB3, IntA1). One way to improve this situation is to work actively with awareness-building in the organization, supporting employees in seeing the value and opportunities of data (IntB3).

In Case B and C, time and resource issues in the R&D team have been reduced by appointing a specific group to manage the cloud platform centrally in the organization. This way, each business unit can build applications in the cloud platform, get support from the central function, and learn from each other (IntC1, IntB3). Similarly, Case B and C have established specialised data analysis teams who support and share knowledge between different business units (IntB3, IntC1).

Another identified solution is to ensure sufficient collaboration between people with more traditional product expertise, and people with data-specific competences. One example is that, when developing failure models, data analysts are supported by product experts about known causes for failure, and important parameters influencing degradation (IntB2, IntB3, IntC4). Another example is that collaboration between hardware development and software development is necessary when software-related requirements imply a need for additional data collection, which in turn leads to a need for changes to the physical product (IntB1).

4.6.3. TECHNOLOGY-ACTIVITIES ALIGNMENT

The challenges within this alignment type relate to limited flexibility and scalability of data collection and to a lack of tools available for developers. Limited flexibility in data collection means that it would be difficult to change what data was collected from the products over time. An interviewee from Case B mentioned that if they wanted to add another parameter to be monitored from products in the field, it would require an update of the complete product-level software. This might not be accepted by the end customers, since software updates always involve a risk of introducing new errors. This challenge has been partly solved in Case A, where the data handling unit on the products can be updated separately from other product-level software, enabling collection of additional data without impacting other functionality (IntA6). In Case B, there is an ongoing program to modularize the product-level software (IntB3).

As the number of connected products increase, the scalability of data collection, transfer and processing also becomes a challenge (IntC4). Moreover, one interviewee from Case B highlighted the lack of easy-to-use technical tools and developer environments which could help simplify data access and analysis (IntB3). Both these challenges have been partly solved in both Case B and Case C, through the development of a central IoT platform. The IoT platforms can be used by different business units to build the applications they need. The platforms also offer benefits such as increased data security (IntC2), higher sampling rate, and real time data availability (IntB4).

4.6.4. ACTIVITIES-PRODUCT/SERVICE ALIGNMENT

The challenges within this alignment type relate to a lack of processes, roles, and responsibilities in the organization to effectively deliver a CBM solution. For example, one interviewee mentioned that there is *“no real ownership of the delivery of useful information to the maintenance team”*, and that this responsibility should be made explicit, and assigned to a certain role in the development process (IntA1). More specifically, we found a lack of structure in deciding what data to collect for CBM. Data collection is mainly driven by what is technically possible rather than what is actually needed (IntB4, IntA4, IntA1, IntA2). Similarly, the error codes coming from the products in Case A and C are not developed to guide service personnel when assessing a product's condition, or to propose maintenance actions (IntA1). Instead, the error codes are defined by the software developers for the purpose of testing certain programmed functions (IntA1, IntC3).

The above-mentioned challenges have been partly addressed in Case B by appointing a project manager to lead CBM projects across business functions. Requirements from users of the cloud-level application are collected in a common 'backlog' and sent to the respective teams who implement the request, ensuring feedback of user needs to both software and hardware development (IntB4). Case B and C have started to address the challenge of lacking structure for deciding what data to collect by (1) prioritizing data from components which fail more often, and which are known to have a high impact for the customers if they fail (IntB3) and (2) by involving the customer support department to help decide which data to collect based on their experience of common issues in the field (IntC3).

4.6.5. CUSTOMER-PRODUCT/SERVICE ALIGNMENT

The challenges within this alignment type relate to a lack of user understanding and to a limited acceptance among users to adopt CBM solutions. A core challenge is to translate the needs of the service personnel to the data engineers. Reasons for this lacking understanding are, for example, limited interest and ambition of responsible individuals (IntA7), or that actors are 'stuck' in established ways of working (IntA1). In Case A, the service team expressed that the data engineers do not take the time to understand how they work (IntA2). On the other hand, the data engineers pointed out that communication was hindered by the fact that the service technicians do not fully understand the specificities of big data analytics (IntC4). One interviewee highlighted that service technicians do not even think about setting requirements for the usefulness of the information that they receive, because they are used to their current way of troubleshooting products (IntA1).

Some solutions were found in relation to these problems. In Case B, the application development team perform dedicated user observations and interviews in order to understand the users' needs and pain points. This way, insights are extracted about what information would be useful, and how it should best be presented to the user (IntB4). In Case A and C, the service organization and the development organization hold regular meetings to discuss how to improve product maintainability (IntA3, IntA2, IntC3). While this provides a platform for communication about design for maintenance, the requirements discussed are mainly related to physical product features and not CBM-specific.

A specific challenge is that the CBM solutions do not deliver information in a user-friendly way (IntA3). For example, the service personnel might not understand why certain error codes appear, what they mean, or what action to take based on this information (IntA2, IntA1, IntB4). The same error code can also mean different things for different product models (IntA7). Moreover, support technicians are overloaded with alarms and have difficulties prioritizing between them (IntB4). The interviewees discussed ways to make error codes more understandable. In Case A, the embedded software developers include an information file to all software packages, explaining the error codes. They also use a certain structure for numbering the error codes, and try to keep this structure across product models (IntA7). In Case C, an interviewee mentioned that they always try to make error messages as self-explanatory as possible (IntC2). Case B have focused on reducing unnecessary terminology, using more visuals, and using more consistent terminology (IntB4).

With regards to the limited acceptance and ability among service technicians to adopt data-driven approaches (IntB4), a specific challenge is the limited trust in failure detection and prediction algorithms (IntC4). An interviewee highlighted the importance of keeping the number of ‘false alarms’ from algorithms low, in order to enable higher acceptance rates among service technicians. Interviewees also mentioned that some service technicians are lacking the skills to take advantage of data-driven approaches (IntC2), pointing out a need for additional training (IntA3).

Another challenge is to properly identify and target all relevant users of the IoT artefact. For Case A, a cloud-level application was initially developed for the end customer, partly disregarding the needs of the service organization (IntA5, IntA6). In Case B, a cloud-level application was developed to serve the customer service team (IntB3, IntB4), assuming that they would be the main users. This assumption turned out to be true for small customers, who did not perform any maintenance themselves, but not for big customers (IntB3). Further, there might be other potential users of the IoT artefacts, who are not yet considered. For example, an interviewee from Case A saw the need to add a specific interface towards the back-office service department (IntA2), and in both Case A and B, interviewees saw an opportunity to develop a specific interface towards R&D (IntA5, IntB3).

In Case B, interviewees also discussed that the current CBM solution only monitors the condition of the core part of the product. However, to provide real value to the end customer, the CBM solution should include the whole product, and even the system in which it operates. In Case B, this would mean a solution which considers the condition of the robot itself, the different tools that the robot uses, and potentially even multiple robots in a production line (IntB1, IntB3, IntB4).

4.6.6. WORK SYSTEM-CONTEXT ALIGNMENT

The challenges within this alignment type relate to conflicting objectives in the organization, uncertainty about the business case for CBM, and data privacy issues. All three cases have an IoT strategy in place at the top-management level. On this level, the companies are thus committed to ensuring that their products can be connected to the internet (IntC1, IntB1, IntA4). However, this top-level vision does not always translate into actual changes in work practices regarding CBM. Conflicting objectives manifest themselves through, for example, that CBM advocates struggle to get buy-in from the organization (IntA1, IntC2) and that reducing production costs is prioritized over reducing maintenance costs (IntA2, IntA1). In Case A, some customers also still pay per service visit, and per spare parts exchanged (IntA3). This creates a mind-set among people in the organization that they make money when they replace parts for customers, which dis-incentivized maintenance optimization.

A possible solution to these issues is to introduce organization-wide key performance indicators (KPIs) that steer toward maintenance optimization and CBM. Case C has introduced a KPI to minimise the number of maintenance visits per installed product (IntC1) while Case A has a KPI to minimise downtime in their customers' operations (IntA5, IntA6).

The challenge of finding a business case for CBM relates to how customers perceive the value of the service (IntC2). Many customers are, for example, more concerned about the buying price of a product than the maintenance costs (IntA2). In Case C, the interviewees said that since their products do not have regulated scheduled service events, many customers do not see the value of optimized maintenance (IntC2). It is especially challenging to communicate the customer value of prescribed, precautionary maintenance activities, which take place before the customer detects any issues with the product (IntC4).

Another challenge for CBM implementation is that data privacy regulations are becoming stricter. Interviewees from all cases describe that they work carefully to comply with data privacy regulations. In Case C, an interviewee highlighted that the changing regulations create a careful attitude, among both employees and customers, which might prevent the use of data which could be compliant and useful (IntC2). This was especially true for large customers, who are particularly concerned about IT security and confidentiality of data (IntB3).

4.7. DISCUSSION AND RECOMMENDATIONS

The results show that CBM implementation comes with a wide range of challenges, confirming the previously noted importance of taking a broad and systemic perspective when studying CBM in practice (Golightly et al., 2018; Veldman et al., 2011). It is noteworthy that all three cases display challenges within each of the six alignment types. Moreover, the challenges and solutions within an alignment type are sometimes interrelated with challenges and solutions in another alignment type. As such, targeted interventions within one alignment type can also impact other parts of the system.

Below, we discuss the findings, per alignment type, in relation to previous literature. We combine the challenges and solutions found into a set of 17 recommendations for OEMs aiming to implement CBM (Figure 4.7). Each recommendation is formulated to be concise and actionable. Figure 4.7 shows how each recommendation links to the challenges and solutions identified in the cases. This way, interrelations within and across alignment types are made explicit. As such, Figure 4.7 could support companies in taking concrete action towards more successful CBM implementation, without losing the 'big picture'.

Firstly, the results show that conflicting objectives in the organization is a challenge in CBM implementation (6.C1). This has also been noted by Bokrantz et al. (2020) who saw a need for clear leadership, visions and goals. Rastegari et al. (2013) further pointed out management support as one of the main challenges in CBM implementation. We found that a company-wide strategy for IoT in general is helpful for CBM implementation (6.S1), but that CBM-specific goals and KPIs are important additions (6.S2), confirming similar conclusions by Bouskedis et al. (2020). Based on these insights, we formulate two recommendations:

1. Create a common vision in the organization for CBM.
2. Put in place KPIs which support CBM.

The case companies also struggled to clarify the business case for CBM (6.C2), due to uncertainty about how the CBM solution would benefit themselves and their customers. This challenge has been reported previously by, e.g., van de Kerkhof et al. (2016) and March and Scudder (2017). We further note that the CBM offering might have to be adapted to the needs of different customer types. Specifically, some customers might, for data privacy reasons, prefer to manage their own data storage and processing. As data privacy issues among customers is increasing, and as data privacy regulations are becoming stricter (6.C3), companies need build expertise in this area. Based on the above, we formulate the following recommendations:

3. Clarify the businesses case for CBM.
4. Build expertise in data privacy.

The results further display a need to improve the usefulness of CBM solutions (5.C2, 5.C3, 5.C4, 5.C5). The case companies struggled to identify and sufficiently target all relevant users of the IoT artefact (5.C2) and to decide on a suitable scope the CBM solution in relation to the context in which it operates (5.C3). The latter contextualises the argument made in CBM literature about the importance of developing CBM solutions for multi-component systems (e.g., Alaswad and Xiang, 2017; Olde Keizer et al., 2017). Moreover, we found a challenge in making the IoT artefact's interfaces user friendly (5.C4), indicating a need for more focus on user interface design (5.S4).

This confirms previous findings from, e.g., Golightly et al. (2018) who highlighted the importance of user interface design for CBM. Questions about how to make more intuitive interfaces toward service technicians in CBM have also been explored in the field of augmented reality (e.g., Egger and Masood, 2020).

The layered view of the IoT artefact presented in our framework further highlights the need to translate insights from user research into design decisions at each layer of the technology stack. Specifically, we identified a need for improved communication between maintenance personnel and data engineers about CBM requirements (5.C1). This relates to the challenge within the activities-product alignment type, which showed a lack of coordination of CBM projects across the layers of the IoT artefact (4.C1). Based on the above-mentioned insights, we formulate the following recommendations:

5. Ensure sufficient communication between data engineers and maintenance personnel.
6. Investigate the processes and needs of all relevant users of the IoT artefact.
7. Actively decide on a suitable scope for the CBM solution.
8. Ensure that the IoT artefact delivers information in a user-friendly way.

An interesting challenge found with regards to usability of the CBM solution was the barrier among service personnel to trust data-driven approaches (5.C5). Akkermans et al. (2016) observed a similar challenge, noting that data-driven approaches are “not in the genes” of service technicians. In our study, we found that increased transparency and explicability of algorithms might be important for acceptance, something that has also been mentioned by Bokrantz et al. (2020). Our results did not expose any clear solutions here, but we note that this challenge relates to the identified solution about continuously spreading awareness in the organization about the possibilities of data-driven approaches (2.S3). Based on these insights, we formulate the following recommendation:

9. Combine algorithm explicability efforts with training of maintenance staff to lower the acceptance barrier for data-driven approaches.

The companies also faced challenges related to developing the IoT artefact as one entity. The development of solutions at different layers of the technology stack were generally not well-coordinated (4.C1, 4.C2, 4.C3). We also found a need to clarify roles and responsibilities among the actors in this process (4.C3), something that has been previously noted by, e.g., Ciocoiu et al. (2017). Based on this, we formulate the following recommendation:

10. Set up clear roles and responsibilities for CBM projects, across the layers of the IoT artefact.

Moreover, our results showed a lack of structured processes for deciding which data should be collected (4.C2). This challenge has been noted by multiple other authors (e.g., Lee et al., 2009; Tiddens, 2018; Rastegari et al., 2013) and relates directly to challenges of the information-activities alignment type, indicating that the data collected is not always fit for the purpose of CBM (1.C1). Based on this, we formulate the following recommendation:

11. Establish a structured process for deciding which data to collect, and at what quality.

We saw that CBM implementation can be facilitated by building technical solutions which allow for flexible data collection over time (3.C1, 3.S1), and to provide easy-to-use tools for developers (3.C3, 3.S2). Flexible data collection solutions are important as they allow for learning through trial and error, and for adding new parameters to be monitored when needed (3.S1). Moreover, a flexible data collection solution can help companies avoid the sub-optimal solution of collecting more data than they really need (1.S1), a strategy which has limited scalability (3.C2), and can lead to data overload (Akkermans et al., 2016; Jonsson et al., 2010. Based on the above, we formulate the following recommendations:

12. Build flexible and scalable data collection solutions that allow for adaptability over time.
13. Provide easy-to-use tools to support developers with data access and processing.

We also found that the R&D departments struggled to find the time to develop CBM solutions (2.C1), and that they had limited experience of working with software development and data analytics (2.C2). To overcome these challenges, companies can focus on awareness-building around data-driven approaches (2.S3), and ensure collaboration between data analysts and product experts (2.S2). The latter has been mentioned previously by, e.g., Åkerman et al. (2018) and Hiruta et al. (2019). Based on these insights, we formulate the following recommendations:

14. Build data competences and awareness among employees, customers and partners.
15. Ensure collaboration between specialized data analysts and people with deep domain knowledge.

Finally, we found that the data collected by the case companies was not always fit for the purpose of CBM (1.C1). This relates directly to the lack of structured processes for decided what data to collect (4.C2, covered in recommendation 11). Specifically, high quality metadata and labelled data was lacking (1.C2, 1.C3), partly due to a lack of ability and incentive among installers, service technicians and end customers to input metadata and data labels with sufficient accuracy. As such, this relates to the need to increase the awareness about the value of data-driven approaches (2.S3, covered in recommendation 14) and to the challenge of limited acceptance among maintenance personnel for data-driven approaches (5.C5, covered in recommendation 9). Based on these insights, we add two final recommendations to the list:

16. Incentivise and facilitate metadata collection.
17. Incentivise and facilitate data labelling.

Having presented these recommendations, two important limitations of the research should be mentioned. Firstly, the results build on insights from three company cases. This is a limited data set and more research is thus needed to confirm the findings in other cases. Secondly, the case selection criteria were formulated so that the companies should have an at least a partly implemented CBM solution in place. Had the selection been more strictly limited to advanced cases of CBM implementation, it is possible that other or additional insights could have been captured.

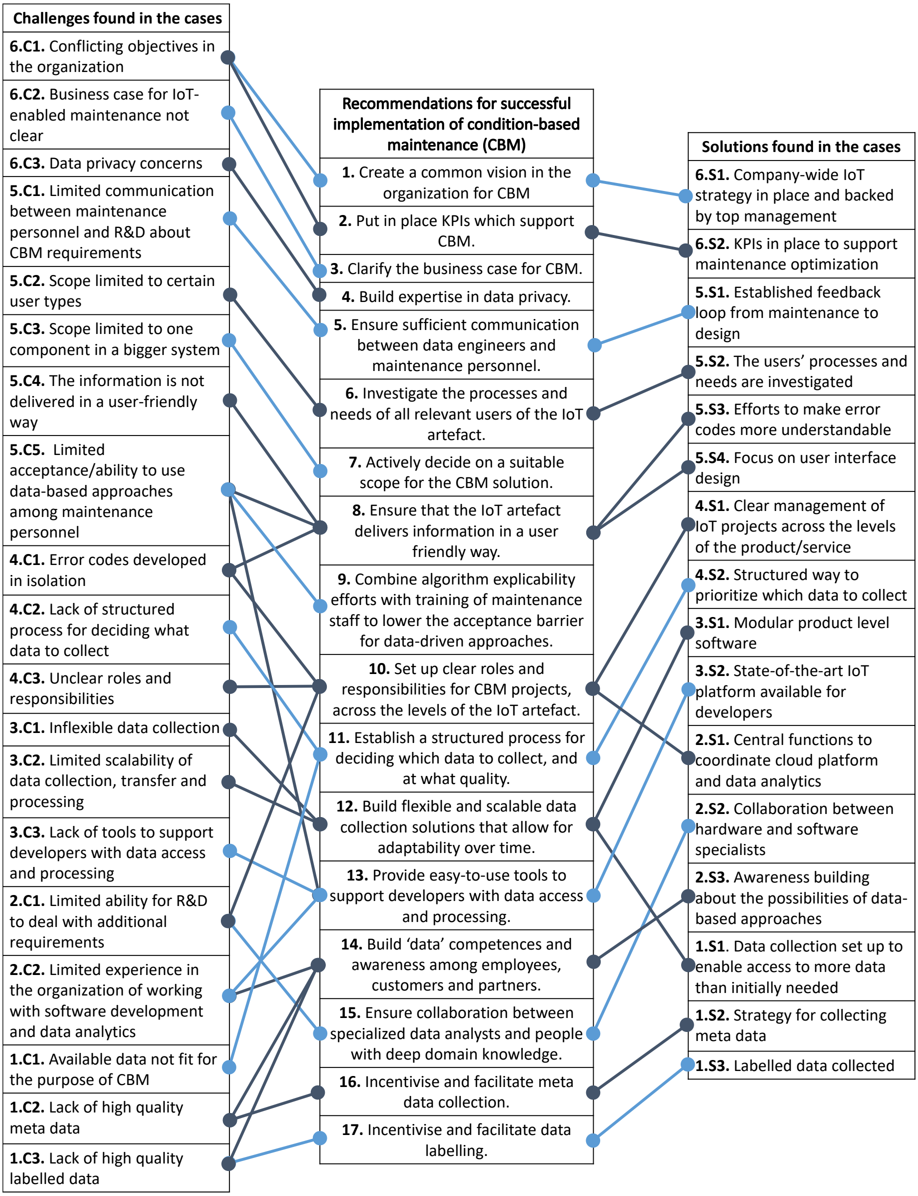


Figure 4.7: 17 recommendations for companies wanting to implement CBM, based on the challenges and solutions found from the cases in this research (alternating colouring of the connecting lines for readability).

]

4.8. CONCLUSIONS AND FUTURE RESEARCH

The aim of this research was to understand the challenges related to CBM implementation in practice and to extract solutions which companies have applied to address these challenges. Towards this aim, we conducted a multiple case study at three manufacturers who had partly implemented CBM. We proposed an integrated framework, which takes a broad perspective on CBM implementation, integrates technological, organizational and user-related elements, and explicitly considers the need for alignment between these elements. Using the framework to analyse the three cases, we identified 19 challenges and 16 solutions, spanning across the different alignment types. Based on this, we proposed a set of 17 actionable recommendations for practice. Moreover, we showed that some challenges and solutions are interrelated across the different alignment types. This implies that, when proposing a solution to a specific CBM implementation challenge, it is important to also assess its effects on other parts of the system. In the discussion of our findings, we facilitated this by making the interrelations between challenges and solutions explicit.

Our study contributes to the field of CBM with a comprehensive view of implementation challenges and solutions in real-world implementation, from the OEM's point of view. It also contributes with an analysis framework that can be used to derive such insights in other cases. Further, we contribute to CE research by adding a concrete case study to the emerging literature about IoT-enabled circular strategies, which has so far predominantly focused on opportunities rather than implementation.

Future research could build on the findings presented here to study more cases of IoT-enabled circular strategy implementation, eventually building a knowledge base around how to best realise the opportunities of IoT for CE in practice. In particular, given the strong analogies between maintenance and reuse/remanufacturing, the recommendations proposed here might also be relevant for OEMs aiming to implement condition-based reuse and/or remanufacturing. To verify this, future research is needed to understand specific challenges and solutions of such strategies.

Author Contributions:
Emilia Ingemarsdotter: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original draft. Marianna Lena Kambanou: Investigation, Methodology, Project administration, Writing Review and Editing. Tomohiko Sakao: Project administration, Supervision, Funding acquisition, Writing Review and Editing. Ella Jamsin: Supervision, Writing Review and Editing. Ruud Balkenende: Supervision, Funding Acquisition, Writing Review and Editing.

Acknowledgements:
This work was funded by the Circular European Economy Innovative Training Network, Circeuit, an action funded by the European Commission under the Horizon 2020 Marie Sklodowska Curie Action 2016 (Grant Agreement number 721909). The authors would like to thank all the interviewees for their participation in the study, and the contact persons at the case companies for support in planning and coordinating data collection.

Conflicts of Interest:
The authors declare no conflict of interest.

REFERENCES

R. Ahmad and S. Kamaruddin (2012). An overview of time-based and condition-based maintenance in industrial application. *Computers and Industrial Engineering* **63**, 135.

M. Åkerman, C. Lundgren, M. Bärring, M. Folkesson, V. Berggren, J. Stahre, U. Engström, and M. Friis (2018), Challenges Building a Data Value Chain to Enable Data-Driven Decisions: A Predictive Maintenance Case in 5G-Enabled Manufacturing, in *Procedia Manufacturing 28th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2018)*, Columbus, OH, USA.

H. Akkermans, L. Besselink, L. van Dongen, and R. Schouten (2016), *Smart moves for smart maintenance*, World Class Maintenance. Available from: https://www.worldclassmaintenance.com/publicaties/.

S. Alaswad and Y. Xiang (2017). A review on condition-based maintenance optimization models for stochastically deteriorating system. *Reliability Engineering and System Safety* **157**, 54.

A. Alcayaga, M. Wiener, and E. G. Hansen (2019). Towards a framework of smart-circular systems: An integrative literature review. *Journal of Cleaner Production* **221**, 622.

S. Alter (2013). Work System Theory: Overview of Core Concepts, Extensions, and Challenges for the Future. *Journal of the Association for Information Systems* **14**, 72.

M. Antikainen, T. Uusitalo, and P. Kivikytö-Reponen (2018), Digitalisation as an Enabler of Circular Economy, in *10th CIRP Conference on Industrial Product-Service Systems*, Linköping, Sweden.

V. Atamuradov, K. Medjaher, P. Dersin, B. Lamoureux, and N. Zerhouni (2017). Prognostics and Health Management for Maintenance Practitioners-Review, Implementation and Tools Evaluation. *International Journal of Prognostics and Health Management* p. 60.

J. Baum, A. Skoogh, B. Oeser, C. Laroque, and M. Subramaniyan (2018). Applications of Big Data analytics and Related Technologies in Maintenance - Literature-Based Research. *Machines* **6**, 54.

J. Bokrantz, A. Skoogh, C. Berlin, T. Wuest, and J. Stahre (2020). Smart Maintenance: a research agenda for industrial maintenance management. *International Journal of Production Economics* **224**, 107547.

A. Bouskedis, D. Apostolou, and G. Mentzasm (2020). Predictive Maintenance in the 4th Industrial Revolution: Benefits, Business Opportunities, and Managerial Implications. *IEEE Engineering Management Review* **48**, 57.

G. Bressanelli, F. Adrodegari, M. Perona, and N. Saccani (2018). Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies. *Sustainability* **10**, 639.

British Standard Institution (2017), *BS EN 13306:2017 Maintenance - Maintenance terminology*. Available from: www.bsigroup.com.

G. Cattelan Nobre and E. Tavares (2017). Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study. *Scientometrics* **111**, 463.

D. Chinese and G. Ghirardo (2010). Maintenance management in Italian manufacturing firms matters of size and matters of strategy. *Journal of Quality in Maintenance Engineering* **16**, 156.

L. Ciocoiu, C. E. Siemieniuch, and E. M. Hubbard (2017). From preventative to predictive maintenance: The organisational challenge. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* **231**, 1174.

C. Coleman, S. Damofaran, and E. Deuel (2017), *Predictive maintenance and the smart factory*, Deloitte.

J. Egger and T. Masood (2020). Augmented reality in support of intelligent manufacturing A systematic literature review. *Computers and Industrial Engineering* **140**, 106195.

Ellen MacArthur Foundation (2016), *Intelligent assets: Unlocking the Circular Economy Potential*, Cowes, UK.
Available from: https://www.ellenmacarthurfoundation.org/publications.

Ellen MacArthur Foundation, McKinsey & Company, and Google (2019), *Artificial Intelligence and The Circular Economy*, Ellen MacArthur Foundation McKinsey & Co Google. Available from: https://www.ellenmacarthurfoundation.org/publications.

European Commission (2008), *Directive 2008/122/EC of the European Parliament and of the Council on Waste.*
Available from: https://ec.europa.eu/environment/waste/framework/.

K. Fraser, H. H. Hvolby, and T. L. B. Tseng (2015). Maintenance management models: A study of the published literature to identify empirical evidence a greater practical focus is needed. *International Journal of Quality and Reliability Management* **32**, 635.

D. Golightly, G. Kefalidou, and S. Sharples (2018). A cross-sector analysis of human and organisational factors in the deployment of data-driven predictive maintenance. *Information Systems and e-Business Management* **16**, 627.

D. Goyal and B. S. Pabla (2015). Condition based maintenance of machine tools-A review. *CIRP Journal of Manufacturing Science and Technology* **10**, 24.

A. Heng, S. Zhang, A. C. Tan, and J. Mathew (2009). Rotating machinery prognostics: State of the art, challenges and opportunities. *Mechanical Systems and Signal Processing* **23**, 724.

T. Hiruta, T. Uchida, S. Yuda, and Y. Umeda (2019). A design method of data analytics process for condition based maintenance. *CIRP Annals* **68**, 145.

E. Ingemarsdotter, E. Jamsin, and R. Balkenende (2020). Opportunities and challenges in IoT-enabled circular business model implementation—A case study. *Resources, Conservation and Recycling* **162**.

E. Ingemarsdotter, E. Jamsin, G. Kortuem, and R. Balkenende (2019). Circular strategies enabled by the Internet of Things—A framework and analysis of current practice. *Sustainability* **11**, 5689.

A. K. Jardine, D. Lin, and D. Banjevic (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing* **20**, 1483.

X. Jin, B. A. Weiss, D. Siegel, and J. Lee (2016). Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing. *International Journal of Prognostics and Health Management* **7**, 012.

N. Johansson, E. Roth, and W. Reim (2019). Smart and Sustainable eMaintenance: Capabilities for Digitalization of Maintenance. *Sustainability* **11**, 3553.

K. Jonsson, J. Holmström, and P. Levén (2010). Organizational dimensions of e-maintenance: A multi-contextual perspective. *International Journal of Systems Assurance Engineering and Management* **1**, 210.

R. M. van de Kerkhof, H. A. Akkermans, and N. G. Noorderhaven (2016). Knowledge Lost in Data: Organizational Impediments to Condition-Based Maintenance in the Process Industry. in *Logistics and Supply Chain Innovation*, edited by H. Zijm, M. Klumpp, U. Clausen, and M. ten Hompel. Springer International Publishing, Cham, Switzerland.

J. Kirchherr, D. Reike, and M. Hekkert (2017). Conceptualizing the Circular Economy: An analysis of 114 definitions. *Resources, Conservation and Recycling* **127**, 221.

A. Kumar, C. P. Gandhi, Y. Zhou, R. Kumar, and J. Xiang (2020). Latest developments in gear defect diagnosis and prognosis: A review. *Measurement* **158**, 107735.

D. Kwon, M. R. Hodkiewicz, J. Fan, T. Shibutani, and M. G. Pecht (2016). IoT-Based Prognostics and Systems Health Management for Industrial Applications. *IEEE Access* **4**, 3659.

J. Lee (2020). How to Establish Industrial AI Technology and Capability. in *Industrial AI: Applications with Sustainable Performance*, Chap. 5. Springer, Singapore.

J. Lee (2020). Killer Applications of Industrial AI. in *Industrial AI: Applications with Sustainable Performance*, Chap. 4. Springer, Singapore.

J. Lee, Y. Chen, H. A. Atat, M. AbuAli, and E. Lapira (2009). A systematic approach for predictive maintenance service design: methodology and applications. *International Journal of Internet Manufacturing and Services* **2**, 76.

J. Lee, H.-A. Kao, and S. Yang (2014). Service Innovation and Smart Analytics for Industry 4.0 and Big Data Environment. *Procedia CIRP* **16**, 3.

Y. Lei, N. Li, L. Guo, N. Li, T. Yan, and J. Lin (2018). Machinery health prognostics: A systematic review from data acquisition to RUL prediction. *Mechanical Systems and Signal Processing* **104**, 799.

H. W. Lightfoot, T. Baines, and P. Smart (2011). Examining the information and communication technologies enabling servitized manufacture. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **225**, 1964.

S. T. March and G. D. Scudder (2017). Predictive maintenance: strategic use of IT in manufacturing organizations. *Information Systems Frontiers* **21**, 327.

D. Mourtzis, V. Siatras, and J. Angelopoulos (2020). Real-time remote maintenance support based on augmented reality (AR). *Applied Sciences (Switzerland)* **10**.

W. Mulder, J. Blok, S. Hoekstra, and F. Kokkeler (2012), *Design for Maintenance - guidelines to enhance maintainability, reliability and supportability of industrial products*, Enschede, The Netherlands.

M. C. Olde Keizer, S. D. P. Flapper, and R. H. Teunter (2017). Condition-based maintenance policies for systems with multiple dependent components: A review. *European Journal of Operational Research* **261**, 405.

O. Ondemir and S. M. Gupta (2014). Quality management in product recovery using the Internet of Things: An optimization approach. *Computers in Industry* **65**, 491.

A. Pagoropoulos, D. C. Pigosso, and T. C. McAloone (2017), The Emergent Role of Digital Technologies in the Circular Economy: A Review, in *Procedia CIRP 9th CIRP IPSS Conference: Circular Perspectives on PSS*, Copenhagen, Denmark.

M. E. Porter (2015). How smart, connected products are transforming companies. *Harvard Business Review* Available from: https://hbr.org/archive-toc/BR1510.

M. E. Porter and J. E. Heppelmann (2014). How smart, connected products are transforming competition. *Harvard Business Review*
Available from: https://hbr.org/archive-toc/BR1411.

J. Potting, M. Hekkert, E. Worrell, and A. Hanemaaijer (2017), *Circular Economy: Measuring innovation in the product chain - Policy report*, PBL Netherlands Environmental Assessment Agency. Available from: https://www.pbl.nl/en/publications.

A. Rastegari, A. Salonen, M. Bengtsson, and M. Wiktorsson (2013). Condition based maintenance in manufacturing industries: Introducing current industrial practice and challenges. *22nd International Conference on Production Research, ICPR 2013* .

S. Ren, Y. Zhang, Y. Liu, T. Sakao, and D. Huisingh (2019). A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework , challenges and future research directions. *Journal of Cleaner Production* **210**, 1343.

A. Rymaszewska, P. Helo, and A. Gunasekaran (2017). IoT powered servitization of manufacturing-an exploratory case study. *International Journal of Production Economics* **192**, 92.

S. Selcuk (2017). Predictive maintenance, its implementation and latest trends. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **231**, 1670.

Y. Shimomura, S. Tanigawa, Y. Umeda, and T. Tomiyama (1995). Development of Self-Maintenance Photocopiers. *AI magazine* **16**, 41.

M. Spring and L. Araujo (2017). Product biographies in servitization and the circular economy. *Industrial Marketing Management* **60**, 126.

J. S. Stecki, S. Rudov-Clark, and C. Stecki (2014). The rise and fall of CBM (condition based maintenance). *Key Engineering Materials* **588**, 290.

A. Stetco, F. Dinmohammadi, X. Zhao, V. Robu, D. Flynn, M. Barnes, J. Keane, and G. Nenadic (2019). Machine learning methods for wind turbine condition monitoring: A review. *Renewable Energy* **133**, 620.

S. Takata, F. Kimura, F. J. Van Houten, E. Westkämper, M. Shpitalni, D. Ceglarek, and J. Lee (2004). Maintenance: Changing role in life cycle management. *CIRP Annals - Manufacturing Technology* **53**, 643.

W. W. Tiddens (2018), *Setting sail towards predictive maintenance - Developing tools to conquer difficulties in the implementation of maintenance analytics*, Ph.D. thesis, University of Twente, Enschede, The Netherlands.

J. Veldman, W. Klingenberg, and H. Wortmann (2011). Managing condition-based maintenance technology: A multiple case study in the process industry. *Journal of Quality in Maintenance Engineering* **17**, 40.

K. Webster (2015), *The Circular Economy - A wealth of flows*, Ellen MacArthur Foundation Publishing, Cowes, UK.

R. K. Yin (2014), *Case Study Research: Design and Methods*, 5th ed., SAGE Publications, Thousand Oaks, CA, USA.

T. Ylipää, A. Skoogh, J. Bokrantz, and M. Gopalakrishnan (2017). Identification of maintenance improvement potential using OEE assessment. *International Journal of Productivity and Performance Management* **66**, 126

5

QUANTIFYING THE NET ENVIRONMENTAL IMPACT OF USING IOT TO SUPPORT CIRCULAR STRATEGIES —THE CASE OF HEAVY-DUTY TRUCK TIRES IN SWEDEN

This chapter has been submitted and is under review as:
E. Ingemarsdotter, D. Diener, S. Andersson, C. Jonasson, A-C. Mellquist, T. Nyström, E. Jamsin, and R. Balkenende (2021) Quantifying the Net Environmental Impact of Using IoT to Support Circular Strategies —The Case of Heavy-Duty Truck Tires in Sweden. *Circular Economy and Sustainability* **xx**, xx.

Abstract: The idea of leveraging the Internet of Things (IoT) to support strategies in line with the circular economy (CE) has been gaining traction in literature. However, previous work has predominantly focused on the opportunities that these technologies can bring, and few studies have critically assessed the environmental viability of the proposed strategies. In this study, we assess the net environmental impact of IoT-enabled circular strategies in a specific case, in order to gain insight into when and how it makes environmental sense to embed IoT hardware, such as sensors and communication devices, into products to support circular strategies. We quantify (1) the potential environmental savings in the different life cycle phases made possible through access to sensor data, and (2) the environmental impact from the added technology needed to provide and process the data. Life cycle assessment (LCA) is used to evaluate the difference in impact between the current state and an 'IoT scenario'. We find that the IoT scenario gives a 4% lower weighted life cycle impact than the current state. Through sensitivity analysis, we show that the conclusions are sensitive to assumptions made about the expected benefits of adding IoT, which depend on the technological context as well as the current and IoT-induced behavior of stakeholders along the product life cycle. The results are also sensitive to assumptions about the environmental impact of the IoT hardware components, implying that design decisions at this level can be important for ensuring a net environmental impact reduction from IoT-enabled circular strategies.

Keywords:
Circular Economy, Digitalization, Internet of Things, Life cycle Assessment

5.1. INTRODUCTION

By connecting products to the internet, and monitoring them over time, actors along the supply chain can get insights into products' performance and condition in the field. This information can be used to support strategies which are in line with the vision of a circular economy (CE), such as efficiency measures in the use phase, product lifetime extension, reuse, remanufacturing, and recycling (Ingemarsdotter et al., 2019). Several recent publications focus on these opportunities, and how companies might use them to their advantage (e.g. Alcayaga et al., 2019; Bressanelli et al., 2018; Ellen MacArthur Foundation, 2016).

However, few studies have investigated the actual environmental performance of such IoT-enabled circular strategies, accounting for the potential environmental savings as well as the obvious environmental downsides of IoT, such as increased use of toxic substances and/or critical raw materials, energy use for data collection and processing, and increased amounts of electronic waste. As of yet, literature about the environmental impact of circular strategies (e.g., Linder et al., 2020; Nussholz, 2019; Böckin et al., 2020) is largely separated from the literature about the environmental impact of IoT-related components and technologies, such as RFID tags (Kanth et al., 2015), wireless sensor networks (Bonvoisin et al., 2012), mobile networks (Malmodin et al., 2012; Scharnhorst, 2006), and cloud-level data storage and processing (Baliga et al., 2010; Chen et al., 2012; Knottnerus, 2019; Shehabi et al., 2018; Uchechukwu et al., 2014). Combining these two fields is important in order to understand the net impact of IoT-enabled circular strategies and support companies in making more conscious decisions about if and how to develop an IoT solution to their CE problem.

Through a dedicated search for literature focusing on the environmental effects of IoT in the context of CE, a small number of previous studies were identified. Lelah et al. (2011) studied the environmental consequences of an IoT solution which aims to reduce unnecessary transportation in a glass waste collection system. They compare the improvements gained from reduced transport to the added impact from using 'machine-to-machine' technologies. They point out that the production of the IoT system leads to increased impact in some impact categories, most notably raw material depletion and hazardous waste production, while impacts related to energy depletion, global warming, and air toxicity decrease. They also found that the production and use of the telecommunications infrastructure needed to support the IoT system did not significantly affect the net environmental impact.

Bonvoisin et al. (2014) presented a framework for evaluating the environmental impacts of 'optimization services' enabled by ICT. They applied this framework to the case of smart waste bins, and found, like Lelah et al. (2011), that for global warming potential, the benefits outweighed the drawbacks, but for raw material depletion the IoT case performed worse. They discuss that there is often a risk for 'impact shifting' between impact categories when introducing IoT-enabled optimizations, and emphasize the importance of including multiple impact categories in the assessment.

Kumar and Mani (2017) estimated the net energy conservation that could be achieved from installing occupancy sensors in office buildings so that the light automatically switches off when nobody is in the room. They concluded that adding the sensors did not conserve energy, due to the high energy requirements in the life cycle of occupancy sensors. In a more recent conference paper, Dekoninck and Barbaccia (2019) conducted a 'streamlined LCA' of a smart fridge, only focusing on the use phase and using global warming potential (GWP) as the sole indicator for environmental impact. They found that the smart fridge was environmentally preferable since the use-phase GWP impact associated with adding IoT (mainly caused by energy use for browsing the internet) was smaller than the savings achieved through reduced food waste and increased levels of online grocery shopping (rather than traveling to the store). Moreover, they noted that the use phase impact reduction depended strongly on the ability of the 'smart system' to steer user behavior in a more sustainable direction, mainly to reduce food waste. Yuli et al. (2019) studied the net GWP reduction from an IoT-enabled irrigation system compared to a conventional irrigation system and concluded that the savings outweighed the impacts. The savings were estimated by the potential for the IoT solution to reduce water and fertilizer consumption in the irrigation system's use phase, while added impacts from the IoT solution itself (sensors, control unit, gateway) were analyzed cradle-to-grave.

The available literature also presents recommendations for how designers might increase the environmental benefit of the respective IoT solutions, both about how to maximize the environmental savings enabled by the IoT solution and how to minimize the environmental impacts from the IoT solution itself. Focusing on the first aspect, i.e., how to achieve environmental savings, Dekoninck and Barbaccia (2019) emphasize the need to design user interfaces that can actually change user behavior. Kumar and Mani (2017) recommend prioritizing use contexts for which the potential for impact reduction is high. In the case of indoor lighting systems, they recommend only using occupancy sensors in areas with low occupancy levels, such as corridors and restrooms.

With regards to minimizing the impact from the IoT solution itself, Lelah et al. (2011) suggest that designers should choose small and low-impact components. Moreover, they discuss that the impact could be reduced if different IoT services in the city (e.g., smart waste collection, smart lighting, water monitoring systems) would share the same gateways. Bonvoisin et al. (2014) recommend a closed-loop approach to electronics design, focusing on longevity, reusability and remanufacturability of IoT components. Moreover, they highlight the need to apply eco-design thinking to ICT infrastructure and to the generation of information, including data collection, transmission, and analysis. Kumar and Mani (2017) recommend local production of sensors, low-impact packaging for sensors, improved reuse of electronic components, and improved recycling techniques for electronics. Dekoninck and Barbaccia (2019) note that the on-fridge web-browsing system should be designed carefully to minimize added impacts from Internet browsing.

We note that the current understanding of the environmental performance of IoT-enabled circular strategies builds on a small number of papers and a limited range of products. Moreover, none of the identified papers address the potential of IoT solutions to extend the lifetime of products, or to increase their recovery rate. Since product lifetime extension and post-use recovery are core strategies in the CE and IoT is seen as an enabler for such strategies (Alcayaga et al., 2019; Bressanelli et al., 2018; Ingemarsdotter et al., 2019), we see a need for additional studies that take these aspects into account.

This paper aims to address some of the above-mentioned research gaps by posing the following research question: *Which factors are important to ensure a net reduction of environmental impact from IoT-enabled circular strategies?* We study the specific case of heavy-duty truck tires in the Swedish context, for which opportunities have been identified for IoT to support fuel efficiency, longer tire lifetimes, and a larger share of used tires being retreaded, i.e., remanufactured through replacement of the outermost part of the tire (the tread) (Andersson and Diener, 2019; Diener et al., 2019; Mellquist et al., 2020). We assess the net environmental effect of using IoT to support circular strategies, considering all life cycle stages of the tires as well as the IoT components. We estimate the environmental improvements that can be achieved by using IoT, as well as the added impact from the technology itself, and compare this 'IoT scenario' to the current state. In order to identify potential 'impact shifting', impact is measured across a range of impact categories.

5.2. METHODOLOGY

This study builds on insights collected during a research project which gathered stakeholders from a truck tire business ecosystem in Sweden with the aim to investigate what a future circular ecosystem for heavy-duty truck tires could look like. Results from the project have previously been presented in (Andersson and Diener, 2019; Diener et al., 2019; Mellquist et al., 2020).

In this study, Life Cycle Assessment (LCA) is used to compare the environmental impact of heavy-duty truck tires in the current Swedish system with a scenario in which IoT is used to support improved circularity. As presented in the ISO14040 standard (International Organization for Standardization, 2006), *"LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to -grave) from raw material acquisition through production, use, and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences."* As such, LCA supports the learning and understanding of environmental problems caused by product systems, from raw materials to end of life (Klöpffer and Grahl, 2014).

5.2.1. GOAL

The goal of the LCA is to compare the environmental impact of heavy-duty truck tires in the current Swedish system with an 'IoT scenario' in which circular improvements are enabled by IoT. The IoT scenario is modeled as a hypothetical scenario in the present-time tire system. As such, the model does not include a temporal shift between the two alternatives. The 'IoT scenario' includes the three following opportunities for IoT to support circular strategies: (1) IoT supports more optimal tire pressure during use and thereby reduces fuel consumption, (2) IoT allows for prolonged tire use times, based on a better understanding of the individual tire's condition as well as minimized wear due to improved pressure monitoring, and (3) IoT increases the rate of retreading through more accurate assessment of the 'reatreadability' of used tires.

5.2.2. DATA SOURCES, SOFTWARE, AND ASSESSMENT METHOD

The software SimaPro 9.0 (Pré Sustainability B.V., 2020) is used to model the system. The Ecoinvent database v.3.5 (Ecoinvent, 2018) is used as the main source of inventory data. Modeling choices about tires are partly based on literature and partly on direct communication with stakeholders in the Swedish tire system: a truck manufacturer, a retreading company, and a recycling company. Assumptions about the components included in the IoT solution (in the IoT scenario) are based on results from the project detailed in (Mellquist et al., 2020), in which different sensor systems for monitoring tire condition were tested. Data about the weight of different components in the Tire Pressure Monitoring System (TPMS) is collected from a TPMS manufacturer (El-watch, 2019). Data about the composition of RFID tags and about the impact of data transfer and processing is collected from previous literature. The data source for each modeling choice is specified in Section 5.3.

All assumptions come with a level of uncertainty, and we deal with this by performing sensitivity analysis to test how the results change by varying key parameters within appropriate uncertainty ranges. The uncertainty ranges are specified per parameter in Section 5.3.

The ReCIPe 2016 method (hierarchist perspective) (Huijbregts et al., 2016) is used to assess the environmental impact. We present impacts both as a weighted single score and per impact category. SimaPro 9.0 includes global normalization factors for the reference year 2010 and weighting sets copied from ReCiPe 2008 (Goedkoop et al., 2009).

5.2.3. FUNCTIONAL UNIT

The function provided by the truck tires is that they enable a truck to drive a certain distance. According to the truck manufacturer, two types of trucks are commonly used in the Swedish system: ‘tractors/semi-trailers’ (10 tires/truck) and ‘trucks with trailer’ (24 tires/truck). In our model, we assume that the tires are used on a ‘tractor/semi-trailer’, but we also include the ‘truck with trailer’ option in our sensitivity analysis. According to the truck manufacturer, the average yearly driving distance for a truck is $2 \cdot 10^5$ km. Given that a ‘tractor/semi-trailer’ has 10 tires, we use a reference distance of $2 \cdot 10^6$ ‘tire-kilometers’ for calculating the impacts.

5.2.4. SCOPE AND SYSTEM DIAGRAM

Figure 5.1 presents a system diagram describing the scope of the LCA and the flow of materials needed to enable the function provided by the tires. We consider the whole life cycle of the tires, from production to end of life, including retreading and multiple use phases. We also include the production of the treads added in retreading, as well as the production, use, and disposal of IoT hardware. Impact from the fuel used by the truck is included ‘well-to-wheel’. New tires are assumed to be produced somewhere in Europe, and transported to a hauler company in Sweden. Tires deemed unsuitable for retreading are sent to end of life (EoL) management (detailed in Section D.1). The grey boxes in the system diagram are IoT specific, and are therefore only included in the IoT scenario.

The scope does not include:

- The production of machines used in the tire life cycle, e.g. in manufacturing, retreading, or recycling.
- The production of data transmission infrastructure, or servers in data centers where the data is processed.

- Emissions from tire maintenance activities (e.g., transport to service point).
- Packaging.
- Personnel-related emissions, such as commuting to work.

5.2.5. MULTI-FUNCTIONAL PROCESSES

System expansion is used to model the multi-functional EoL processes for tires, i.e., incineration and recycling processes. As an example, the incineration of tires for district heating is multi-functional as it both takes care of the waste tires and produces heat. System expansion deals with multi-functionality by expanding the system under study to include additional functions than initially specified in the functional unit (Guinée et al., 2019). As such, we assume that the production of heat from the incineration of tires replaces the production of heat from other sources. Hence, the tires receive 'credits' for the avoided emissions which would otherwise have been caused by burning fuel to produce heat. Similarly, the tires receive credits when substituting other materials, e.g., as drainage material in landfills. For transparency, such negative impact numbers ('credits') are presented separately in the results.

5.3. DATA COLLECTION AND MODELING

5.3.1. EQUATIONS DESCRIBING SYSTEM FLOWS

Here, we introduce the key equations describing the resource flows in our model, and how they depend on whether IoT is used or not. If the value of a function, f, depends on whether IoT is used or not, this is denoted as $f(IoT)$.

In the current Swedish tire system, where retreading takes place up to three times, the reference distance of $2 \cdot 10^6$ km (D_{tot}) is covered by a mix of new tires (N_0) and retreaded tires (N_k, where $k = 1,2,3$ is the number of times the tire has been retreaded). To calculate N_0, N_1, N_2, and N_3, we start by estimating the share of post-use tires that are currently retreaded, and thus used again, as opposed to being sent to EoL management (material recycling or incineration). Based on discussions with the retreading company, we identify four decision points where post-use tires are sorted as 'retreadable' or 'not retreadable', as shown in Figure 5.1. These decision points are: (1) at the tire exchange workshop, (2) at the first inspection point in the retreading process, (3) mid-way through the retreading process, and (4) at the final inspection point after the retreading process. Again, based on discussions with the retreading company, we estimate the current values for the shares X_1, X_2, X_3, and X_4 of incoming tires which are sorted as 'retreadable' at each decision point. As seen in Equation 5.1, the shares X_1, X_2, X_3, and X_4 relate N_k to N_{k+1}. Moreover, as IoT improves the accuracy of the retreadability assessment (see Section 5.2.1), the shares X_1, X_2, X_3, and X_4 depend on whether IoT is used or not.

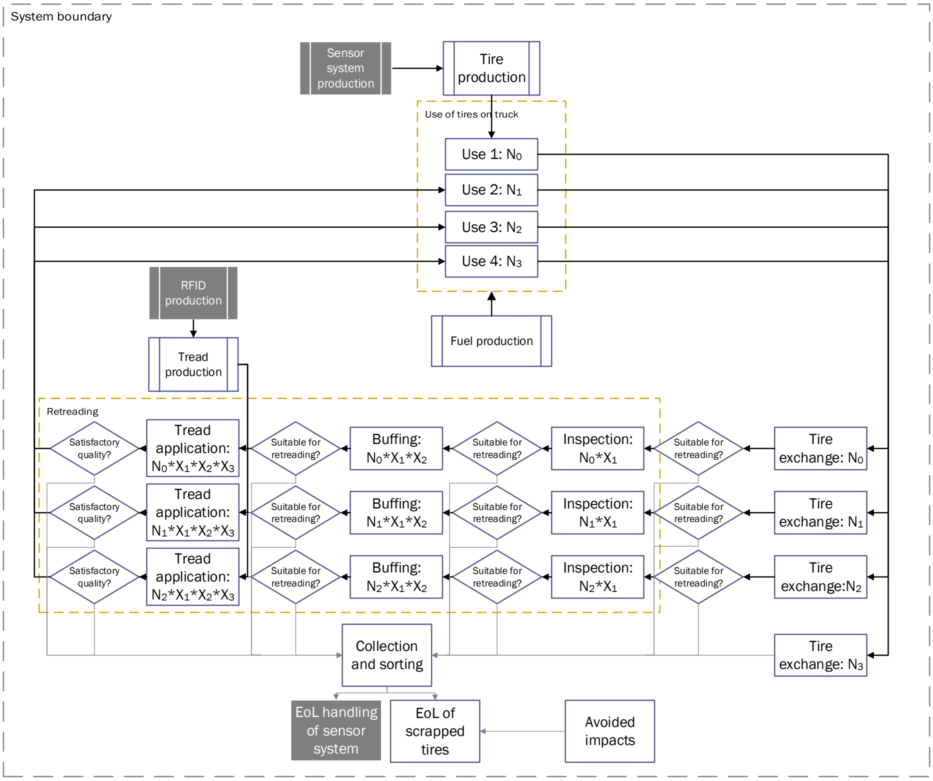


Figure 5.1: System diagram. For readability, arrows going to EoL processes have a lighter color. Filled grey boxes are IoT specific, and thereby only included in the IoT scenario. Transportation steps are not shown in the diagram, but are included in the analysis.

N_0, N_1, N_2, and N_3 can be derived from Equations 5.1 and Equation 5.2. Here, we have considered the possibility that the distance, D_0, that a tire can cover before it has to be exchanged is different for new tires compared to retreaded ones. However, we assume that the distance $D_{1,2,3}$ that a retreaded tire can cover is the same irrespective of the number of retreading cycles. Further, as IoT can delay tire replacement (see 'Goal'), the distance that can be covered by a (new or retreaded) tire depends on whether IoT is used or not.

As seen in Equation 5.3, the total volume of fuel that is needed to cover the distance D_{tot} relates to N_0, N_1, N_2, N_3, D_0, and $D_{1,2,3}$ via the fuel consumption that can be allocated to a new or retreaded tire (FC_{k} [l/km]). Again, we have considered the possibility that the fuel consumption, FC_0, that can be allocated to a new tire is different from that of a retreaded tire. Since the fuel consumption depends on the tire pressure, and since IoT allows for keeping tire pressure at an optimal level (see 'Goal'), the fuel consumption depends on whether IoT is used or not.

$$N_{k+1}(\mathrm{IoT})[\#] = N_k(\mathrm{IoT}) \cdot X_1(\mathrm{IoT}) \cdot X_2(\mathrm{IoT}) \cdot X_3(\mathrm{IoT}) \cdot X_4(\mathrm{IoT}) \tag{5.1}$$

$$D_{\mathrm{tot}}[\mathrm{km}] = D_0(\mathrm{IoT}) \cdot N_0(\mathrm{IoT}) + D_{1,2,3}(\mathrm{IoT}) \cdot \sum_{k=1}^{3} N_k(\mathrm{IoT}) \tag{5.2}$$

$$V_{\mathrm{tot}}(\mathrm{IoT})[\mathrm{l}] = D_0(\mathrm{IoT}) \cdot N_0(\mathrm{IoT}) \cdot FC_0(\mathrm{IoT}) + D_{1,2,3}(\mathrm{IoT}) \cdot FC_{1,2,3}(\mathrm{IoT}) \cdot \sum_{k=1}^{3} N_k(\mathrm{IoT}) \tag{5.3}$$

5.3.2. TIRE AND TREAD PRODUCTION

MATERIAL COMPOSITION

According to the truck manufacturer, a typical heavy-duty truck tire weighs 63 kg. Based on specifications for tire material composition used by the truck manufacturer, we assume a typical material composition for the tires according to Table D.4 in Appendix D. The material composition of treads added in the retreading step is assumed to be the same as for the rubber part of a tire, see Table D.5 in Appendix D. The weight of the tread is estimated to be 10.7 kg, based on communication with the retreading company.

MANUFACTURING

The tire manufacturing process is modeled using data from the production of passenger car tires (Sun et al., 2016, pp. 1752). The data as given in Sun et al. (2016) is presented in Table D.6 in Appendix D, and the data used to describe tire and tread production is presented in Table D.7 and Table D.8, respectively. Process waste from tread and tire production is assumed to be handled as follows: rubber waste is incinerated, steel waste sold as scrap steel, and tire waste processed according to the EoL options described in Section D.1 in Appendix D.

5.3.3. USE

DRIVING DISTANCE BEFORE TIRE EXCHANGE

According to the representatives from the truck manufacturing company, a long-haul truck tire can be driven for about $2.5 \cdot 10^5$ km but is typically exchanged when there is still approximately 20% of mileage left in the tire. We thus assume that new tires are exchanged after $2 \cdot 10^5$ km (D_0 in Equation 5.2). The representatives from the truck manufacturing company also indicated that the maximum distance that a retreaded tire can cover is about 80% compared to a new tire. The retreading company, on the other hand, claims that the quality of the retreaded tire is the same as new, as long as the process is done properly. External data sources also provide different numbers for the possible difference between the distance that a new and a retreaded tire can cover before it has to be exchanged. For example, Michelin claim on their website that their retreaded tires can cover 90% of the distance specified for new tires (Michelin, 2019). In a previously published LCA study, the authors state that the maximum distance for retreaded tires is in the range of 75% to 100% compared to new ones (Boustani et al., 2010). In this study, we use the truck manufacturer's estimation that retreaded tires are exchanged after 80% of the distance compared to new tires, i.e. after $1.6 \cdot 10^5$ km ($D_{1,2,3}$ in Equation 5.2). In the sensitivity analysis, we test values for $D_{1,2,3}$ (in the current state) between $1.5 \cdot 10^5$ km and $2.0 \cdot 10^5$ km, i.e. between 75% and 100% of D_0.

As explained in Section 5.2, the distances D_0 and $D_{1,2,3}$ also depend on whether IoT is used or not. This can be explained by two different effects. Firstly, based on discussions with the truck manufacturer, we found that tire replacement is based on time-in-use rather than the actual condition. By using IoT to monitor the actual condition of the tire, it might thus be possible to only replace the tires when it is really needed, i.e. when the condition is measured as unsatisfactory. As stated above, tires currently have approximately 20% of distance left in them when exchanged. However, based on discussions with the retreading company, it is not obvious that the truck drivers would delay tire exchange even if they had data about the tire condition, since the timing of the tire exchange also correlates with the change of season. We thus estimate this effect of IoT on D_0 and $D_{1,2,3}$ to be in the range of 0% to 20%. Secondly, IoT-enabled pressure monitoring could reduce unnecessary wear since the tire would always be used at optimal pressure. Based on discussions with the truck manufacturer, the distance that a tire can cover before it has to be replaced is reduced by 25% if driven at 80% of optimal tire pressure. We thus estimate this effect of IoT on D_0 and $D_{1,2,3}$ to be in the range between 0% and 25%.

Combining the two effects presented above, we assume that D_0 and $D_{1,2,3}$ are all increased by 25% if IoT is used. In our sensitivity analysis, we test values between 0% and 50%.

ABRASION DURING USE

Based on Pehlken and Roy (2006), abrasion results in a 15% weight loss of the tire during use. We assume that the material lost through abrasion is tread material (i.e., not steel). Further, we assume that the abrasion percentage is the same for new and retreaded tires and that it is not dependent on whether IoT is used or not.

FUEL CONSUMPTION

Based on discussions with the truck manufacturer, the average fuel consumption is 0.32 l/km for a tractor/semi-trailer and 0.48 l/km for a truck with trailer. The fuel consumption depends on the tire pressure, which should be checked and corrected regularly. According to Brigdestone (2012), the fuel consumption of a truck increases close to linearly in the time interval between zero and 48 weeks, if the tire pressure is not checked and adjusted. The fuel consumption, $FC(t)$, can thus be described according to Equation 5.4, where A is a constant and FC_{min} is the minimal fuel consumption corresponding to optimal tire pressure. Brigdestone (2012) further reports that the fuel consumption typically increases by 14% if the tire pressure is not checked for 48 weeks. Based on this, we can formulate Equation 5.5, and derive the relationship between FC_{min} and A according to Equation 5.6.

$$FC(t) = FC_{min} + A \cdot t \tag{5.4}$$

$$FC(\text{t=48}) = FC_{min} \cdot 1.14 \tag{5.5}$$

$$A = FC_{min} \cdot 0.0029 \tag{5.6}$$

Based on discussions with the truck manufacturer, we estimate the time between tire pressure checks, t, to be eight weeks in the current state. For a tractor/semi-trailer, we thus get $FC(t/2) = 0.32$ l/km, and can calculate FC_{min} according to Equation 5.7. This is the value of the fuel consumption when driving at optimal tire pressure.

$$FC_{min} = \frac{FC(\Delta t/2)}{A \cdot \Delta t/2} = \frac{0.32[\text{l/km}]}{1 + 0.0029[\frac{1}{\text{weeks}}] \cdot 4[\text{weeks}]} = 0.3163[\text{l/km}] \tag{5.7}$$

To get the fuel consumption per tire (Equation 5.8 for a new tire and Equation 5.9 for a retreaded tire), we introduce a ‘rolling resistance fraction’ which defines the share of the truck’s fuel consumption that can be allocated to the tires (as opposed to other parts of the truck). This is based on Gutowski et al. (2011), who reported a range for the rolling resistance fraction between 13% and 47%, and used an average of 24%. We follow their example and use 24% in our calculations, but test values between 13% and 47% in our sensitivity analysis.

Equations 5.8 and 5.9 also include a term to describe the above-mentioned increase in fuel consumption caused by sub-optimal tire pressure ($\Delta FC_{\text{pressure}}$). This term depends on how often the tire pressure is currently checked (Δt). Note that in the IoT scenario we assume optimal tire pressure, i.e. that $\Delta FC_{\text{pressure}} = 0$.

In Equation 5.9 (for retreaded tires), we also add a term to account for a possible increase in fuel consumption due to higher rolling resistance for retreaded tires compared to new ones ($\Delta FC_{\text{pressure}}$). This risk for higher rolling resistance for retreaded tires has been highlighted by e.g., Gutowski et al. (2011). Tire manufacturer Continental have reported an increase in rolling resistance between 3-10% (Krömer et al., 1999). However, that report was published 20 years ago, so it might be outdated.

The value for the rolling resistance of retreaded tires is uncertain, especially as it depends on the quality achieved in the retreading process (Boustani et al., 2010), which can vary between different retreading companies and tire types. According to the retreading company, the rolling resistance of the tires they retread is the same as for new tires. Previous LCAs (e.g. Boustani et al., 2010) have also estimated that the rolling resistance is the same for new and retreaded tires (i.e., $\Delta FC_{\text{pressure}}$=0). In our LCA, we set $\Delta FC_{\text{pressure}}$=0 as the base case assumption. In our sensitivity analysis, we test values for $\Delta FC_{\text{pressure}}$ between 0% and 10% of FC_{min}. This range is based on the fuel efficiency grades defined by EU regulations, labeling truck tires from grade A to E (EU, 2020). According to Volvo Trucks (2020), each increase in grade corresponds to an increase in fuel consumption by 2.5%. Using E-grade tires would thus cause a 10% increase in fuel consumption compared to using A-grade tires.

Note that $\Delta FC_{\text{pressure}}$ and $\Delta FC_{\text{pressure}}$ are fully allocated to the tires, i.e., these terms are not multiplied with the rolling resistance fraction. The reason for this is that this additional fuel consumption is seen as directly caused by the tires.

$$FC_0 = \frac{(FC_{\text{min}} \cdot \text{Rolling resistance fraction}) + \Delta FC_{\text{pressure}}(\Delta t)}{\text{Number of tires on truck}} \tag{5.8}$$

$$FC_{1,2,3} = \frac{(FC_{\text{min}} \cdot \text{Rolling resistance fraction}) + \Delta FC_{\text{pressure}}(\Delta t) + \Delta FC_{\text{pressure}}}{\text{Number of tires on truck}} \tag{5.9}$$

FUEL TYPE

Based on discussions with the truck manufacturer, MK1 diesel is often used as fuel for trucks in Sweden. On the Swedish market, biofuels are added to the MK1 giving a mix of fossil diesel (77 vol.%), Hydrotreated vegetable oil (HVO) (17 vol.%) and Fatty Acid Methyl Esters (FAME) (5.5 vol.%) (Energimyndigheten, 2019). MK1 diesel has a density of 0.815 kg/l and a heat value of 35.8 MJ/l (Hallberg et al., 2013). The Ecoinvent entries that we use to describe the fuel mix are presented in Table D.9 in Appendix D. Since no specific Ecoinvent entries were available for FAME or HVO, these were both modeled as 'Vegetable oil, refined'. Emissions to air from burning MK1 diesel in the truck are based on (Hallberg et al., 2013) using Euro6 values when data is available, and otherwise Euro5. The emissions are specified in Table D.10 in Appendix D.

5.3.4. RETREADING

Based on input from the retreading company, we here describe the retreading process and how it might be optimized if IoT were to be used. As explained in Section 5.2 and depicted in Figure 5.1, there are four decision points where tires are scrapped and we use the notation X_1, X_2, X_3, X_4 to describe the share of tires passing through each decision point.

When a tire is due for exchange, the tire is demounted at a truck service point. A quick visual inspection is performed at the service workshop to evaluate the tire's condition. If the tire is deemed to be in satisfactory condition, it is sent for retreading. If not, the tire is sent to EoL management (described in Section D.1) in Appendix D.

The retreading process starts with an inspection step, in which tires of unsatisfactory condition are scrapped. Thereafter, the tire enters the 'buffing' step, in which the old tread is removed. Then, a second inspection is done, whereby a small number of tires are scrapped. Subsequently, the tire is sprayed with cement to fill holes, and a tread is applied. After the tread application, the tire is left in a vacuum chamber for some time and is then vulcanized. Finally, the tire painted, and inspected again. A small share of tires is scrapped at this point due to insufficient quality.

The shares X_1, X_2, X_3, X_4 in the current state were estimated based on discussions with the retreading company and are listed in Table 5.1. The effect of IoT on X_1, X_2, X_3, X_4 was estimated as follows. We assume that IoT brings a more accurate assessment of retreadability, and thus that scrapping decisions are done as early as possible. As such, in the optimal case, no tires are discarded after the first decision point (X_2=X_3=X_4=1). We then estimate X_1 in the IoT scenario according to the following logic: given an accurate assessment of retreadability, we can assume that no tires which could have been retreaded are wrongly sorted as 'not retreadable' and no tires which are not suitable or retreading are wrongly sorted as 'retreadable'. Tires that are currently wrongly scrapped (N_{ws}) are instead accepted at decision point 1 and tires that are currently wrongly accepted (N_{wa}) are scrapped at decision point 1 (rather than later). We estimate N_{wa} as the tires which are currently scrapped at decision point 3 and 4. We further assume that the current error rate for wrongly scrapping a tire is the same as the current error rate for wrongly accepting a tire ($N_{wa} = N_{ws}$). In total this gives:

$$N \cdot X_{1,\text{IoT}} = N \cdot X_{1,\text{current}} + N \cdot X_{2,\text{current}} + N_{ws} - N_{wa} \tag{5.10}$$

$$N_{wa} = N_{ws} \rightarrow X_{1,\text{IoT}} = X_{1,\text{current}} \cdot X_{2,\text{current}} \tag{5.11}$$

where N is the total number of incoming tires to the retreading process. Based on this, we get the shares X_1, X_2, X_3, and X_4 in the IoT scenario as presented in Table 5.1. In our sensitivity analysis we test values for $X_{1,\text{IoT}}$ between 0.7 and 1, while keeping the other values constant.

Table 5.1: Shares of tires accepted for retreading at the four decision points, in the current state and in the IoT scenario.

	X_1 (service point)	X_2 (first inspection)	X_3 (buffing)	X_4 (final inspection)
Current state	1	0.7	0.95	0.95
IoT scenario	0.7	1	1	1

Retreading process data, such as water and energy use, amount of incoming material, and emissions from the retreading process, was provided by the retreading company, and is presented in Table D.11. Tire shreds that are scraped off the used tire before a new tread is applied are assumed to be sent to incineration (district heating generation).

5.3.5. TRANSPORTS

See Table D.12 in Appendix D for all assumptions about transportation distances and modes of transport. For the transports where no direct reference is available, the following assumptions were made:

- Transport of raw material to tire/tread production is assumed to be within the country or close region where tire production takes place, with an estimated distance of 500 km.
- The transportation distance for tires from a producer in Europe to a user in Sweden is assumed to be 1500 km.
- The transportation distance for materials produced in Europe and used in the retreading plant in Sweden is assumed to be 1500 km.
- The transportation distance between the service workshop and the retreading facility (both in Sweden) is assumed to be 150 km.
- IoT components are assumed to be produced in China and shipped to Sweden, with an estimated distance of 20 000 km.

5.3.6. ADDED IMPACTS FROM IOT

To calculate the added impacts from the life cycle of the IoT solution itself, we include hardware production, energy use for data collection, transfer, storage and processing on the cloud, as well EoL management of the hardware.

In order to support the IoT-enabled improvements included (reduced fuel consumption, delayed tire exchange, and more increased retreading), we model the hardware to include the following sub-units: (1) a Tire Pressure Monitoring System (TPMS) which allows for monitoring the tire pressure and transferring the data to the cloud (2) a piezoelectric sensor system which allows for monitoring of sudden impacts on the tires (from for example uneven pavement) and transferring the data to the cloud (3) RFID tags which allow for unique identification of each cord (the main body of the tire) and each tread. Each sub-unit is described in more detail below, as are our estimations of energy requirements in the sensor units, the gateways, and the cloud. In the sensitivity analysis, we test values for the combined weight of all electronic components between 50% of the base value to 300% of the base value (+200%). The large span is chosen because of the lack of specific Ecoinvent data for electronic components. All hardware components are assumed to be treated as electronic scrap at their EoL.

TPMS

The TPMS includes a sensor unit, a gateway, and a cable to supply the gateway with power (El-watch, 2019). The sensor unit is attached to the tire using a magnet, making it easy to mount and dismount. The lifetime of the TPMS sensor unit is assumed to be limited by the lifetime of its battery. The battery lifetime is noted as 5 years in the datasheet from a TPMS manufacturer (El-watch, 2019). Based on this, we assume that the TPMS can be reused throughout all three retreading steps. Assumptions about the material composition of the TPMS is based on the same datasheet (El-watch, 2019), and on direct communication with the TPMS manufacturer. The hardware composition as well as the Ecoinvent entries used to describe each component is detailed in Table D.13 in Appendix D.

PIEZOELECTRIC SENSOR SYSTEM

The piezoelectric sensor system includes a sensor unit, a gateway, and a cable to supply the gateway with power. The sensor unit is assumed to be passive, which means that it does contain a battery. As batteries are often the limiting component for the lifetime of sensor units, we assume that the sensor unit can be reused throughout all three retreading steps. Assumptions about the material composition of the piezoelectric sensor system is based on the system presented and tested in (Mellquist et al., 2020). The hardware composition as well as the Ecoinvent entries used to describe each component is detailed in Table D.14 in Appendix D.

RFID TAGS

RFID tags are made up of an RFID chip and an RFID antenna (RFID4U, 2020). Here, we also assume that the RFID tag has a plastic casing. Assumptions about the material composition of the RFID tag are based on (Kanth et al., 2015), as presented in Table D.15 in Appendix D.

ENERGY REQUIREMENTS FOR DATA COLLECTION, TRANSMISSION, STORAGE AND ANALYSIS

We estimate the energy needed for data transfer, storage and processing in the same way for both the TPMS and the piezo sensor system, see Table D.16 in Appendix D. We use data from (1) the power consumption of the TPMS stated in the technical datasheet from a TPMS manufacturer (El-watch, 2019), (2) literature about the energy requirements of mobile data transfer (Pihkola et al., 2018) and (3) literature about the energy requirements of cloud computing (Baliga et al., 2010). To calculate the total time during which the sensors are used, we assume an average speed of the truck throughout its use of 70 km/h. In order to calculate the speed of data transfer, we assume that each transfer contains 4 bytes (32 bits) of information, which is the equivalent to a so-called float number, i.e. a floating-point number which is accurate up to approximately seven decimals (MariaDB, 2019). Based on the datasheet from the TPMS manufacturer, the TPMS system transfers data from the tire once every 2 minutes, leading to a data transfer rate of 16 bits per minute, i.e. 0.267 bits per second.

To calculate the energy requirements for cloud computing, we assume that the data from the sensors is processed according to the ‘storage-as-a-service’ model as defined by Baliga et al. (2010). This means that the data is stored on the cloud and can be downloaded by a user for viewing or processing. No computing-intense tasks take place in the cloud. As the system modeled here is mainly meant to monitor the pressure and the impacts on the tire, this ‘storage-as-a-service’ type was deemed an appropriate estimation. Using this assumption, the energy requirements can, according to (Baliga et al., 2010), be calculated using Equation D.1 in Appendix D.

5.4. RESULTS

5.4.1. DIFFERENCE IN IMPACT BETWEEN CURRENT STATE AND IOT SCENARIO

Using the ReCIPe single score, the environmental impact associated with the reference distance, D_{tot} ($2 \cdot 10^6$ tire-kilometers), in the current state and the IoT scenario is shown in Figure 5.2. The impact is presented per life cycle phase and with IoT-specific impacts shown separately. Credits for avoided impacts in EoL management of tires are also shown separately.

The total weighted life cycle impact is about $6.64 \cdot 10^{-2}$ kPt lower in the IoT scenario than in the current state, corresponding to a net impact reduction of approximately 4%. This is thus the net effect of, on the one hand, impact reduction effects brought about by adding IoT ($-8.37 \cdot 10^{-2}$ kPt, combined) and, on the other hand, added impact from IoT hardware production, IoT energy use, IoT EoL management, and reduced credits from tire EoL management ($+1.73 \cdot 10^{-2}$ kPt, combined).

The impact reduction stems from (1) lower fuel consumption ($-6.53 \cdot 10^{-2}$ kPt, by far the largest effect); (2) a reduced need for new tires and thereby less impact from tire manufacturing ($-1.37 \cdot 10^{-2}$ kPt); (3) a reduced need for EoL management of tires and thereby less direct impact from EoL management ($-2.70 \cdot 10^{-3}$ kPt); and (4) a reduced need for retreading ($-2.00 \cdot 10^{-3}$ kPt). The fact that there is a reduced need for retreading might seem counter-intuitive since the share of tires that are accepted for retreading is higher in the IoT scenario. The reason is that, since IoT increases the distance that each tire can cover before it has to be exchanged, the total amount of tires that are needed to cover the reference distance is lower, also resulting in a lower absolute number of tires being retreaded. The number of new and retreaded tires that

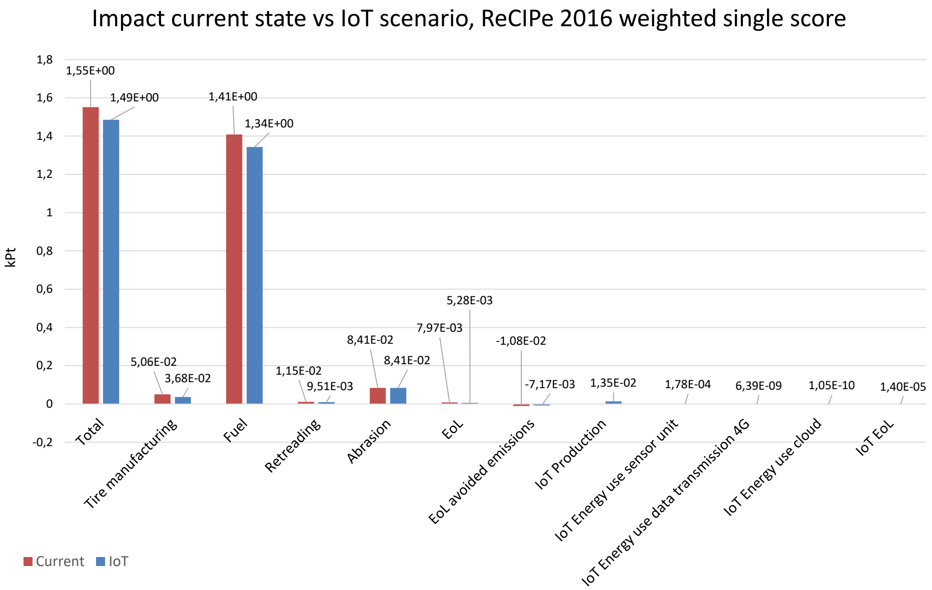


Figure 5.2: Weighted impact per life cycle phase, current state vs IoT scenario. Note that impacts related to the life cycle of the IoT hardware (production, energy use, EoL) are presented separately and are only applicable for the IoT scenario.

are needed to cover the reference distance is shown in Table 5.2.

The added impacts in the IoT scenario are mainly a result of IoT hardware production ($+1.35 \cdot 10^{-2}$ kPt) followed by a reduction of EoL credits assigned to the tires from avoided impacts in tire recycling and incineration ($+3.61 \cdot 10^{-3}$ kPt). The energy requirements and EoL management of the IoT system do not add any significant impact ($+0.19 \cdot 10^{-3}$ kPt, combined).

If the weighted impact in the two scenarios is compared per life cycle phase, the impact from tire manufacturing is reduced by 27%, the impact from fuel consumption is reduced by 5%, the impact from retreading is reduced by 17%, and the direct impact from EoL management is reduced by 34%. If credits from avoided impacts in EoL management are included, the impact from EoL management increases by 108% in the IoT scenario compared to the current state.

So far, we have only presented weighted impact. Figure 5.3 adds additional detail by presenting the impact difference between the current state and the IoT scenario for each impact category in the ReCIPe 2016 method. We see that for most impact categories, the impact is lower in the IoT scenario. However, in the following four categories, the IoT scenario has a significantly larger impact: Freshwater eutrophication, Freshwater ecotoxicity, Marine ecotoxicity, Human non-carcinogenic toxicity. The added impact in these categories mainly stems from the production of the IoT

Table 5.2: Number of tires that are needed to cover the reference distance, $2 \cdot 10^6$ tire-kilometers (D_{tot})

	Number of tires	
	Current state	IoT scenario
New tires (N_0)	4.9	3.6
One time retreaded tires (N_1)	3.1	2.5
Two times retreaded tires (N_2)	2.0	1.8
Three times retreaded tires (N_3)	1.2	1.2
Total number of tires (N_{tot})	11.2	9.1

hardware.

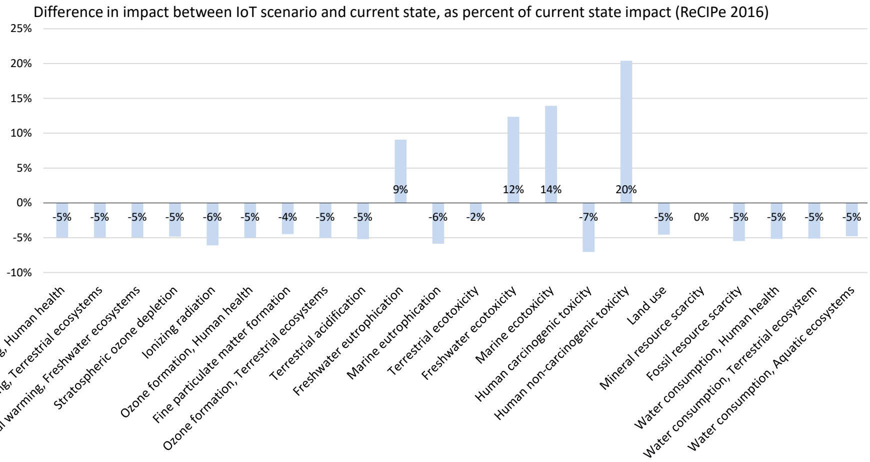


Figure 5.3: Difference in impact between IoT scenario and current state, for all impact categories in the ReCIPe method. Negative values mean that the impact is smaller in the IoT scenario than in the current state.

5.4.2. SENSITIVITY ANALYSIS

We test the sensitivity of the results by varying the values of nine key parameters. Table 5.3 presents how the total life cycle impact changes when varying one parameter at a time. Figure 5.4 shows the ranges within which the relative impact difference between the current state and the IoT scenario, calculated in relation to the total current state impact, varies per parameter.

Parameter A (the rolling resistance fraction) and parameter I (the type of truck) have the largest effect on the total life cycle impact. Parameter A affects the current state and the IoT scenario equally, i.e., varying this assumption does not change the absolute difference in impact. However, it has a significant effect on the relative impact difference, as seen in Figure 5.4. Parameter I affects the total life cycle impact significantly but has a small effect on the relative difference.

Parameter E (weeks between pressure checks in the current state) has a moderate effect on the total life cycle impact, but a large effect on the relative impact difference. Parameters D (the weight of the IoT components), F (the share of tires that are retreaded in the IoT scenario), and G (the increase in distance that can be achieved through adding IoT) show small effects on the total impact, but moderate effects on the relative difference. Parameter C (the increase in rolling resistance for a retreaded tire compared to a new one) has a moderate effect on both the total impact and the relative difference. Parameters B (the reduction in distance that a retreaded tire can cover compared to a new one) and H (whether EoL credits are assigned or not) have small effects on both the total impact and the relative difference.

To get a total range of possible values for the relative impact difference between the current state and the IoT scenario, we construct two extreme cases: the ‘most favorable case for IoT’ and the ‘least favorable case for IoT’. This is done by combining parameter values that maximize the relative impact difference (as percent of total current state impact) between the current state and the IoT scenario. Figure 5 shows the impact in these two extreme cases. In the most favorable case for IoT, the IoT scenario leads to a 16% impact reduction compared to the current state. In the least favorable case, the IoT scenario performs 5% worse than the current state. Hence, while the base case presented in Section 5.4.1 showed that adding IoT leads to a 4% net impact reduction, the sensitivity analysis shows that, in the most favorable case for IoT, the reduction could be significantly larger, while in the least favorable case, the IoT scenario could actually be worse than the current state.

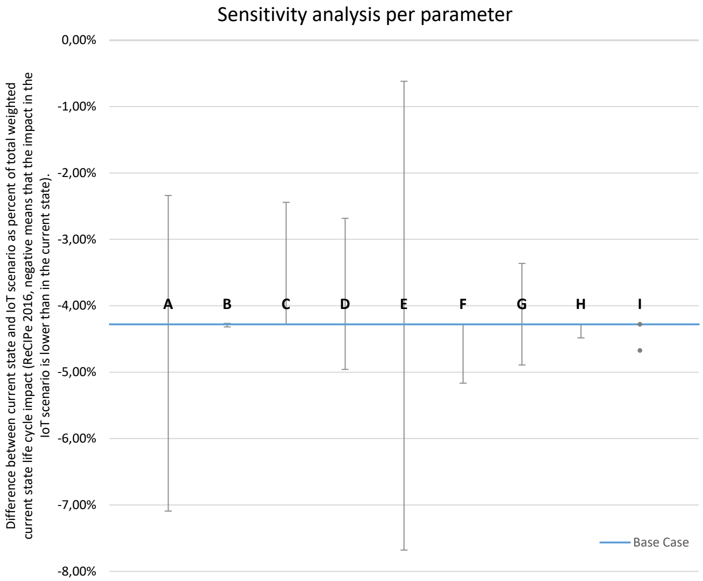


Figure 5.4: How the relative difference in impact (as percent of current state impact) between the current state and the IoT scenario varies per parameter. Parameters A to I and their respective value ranges are explained in Table 5.3

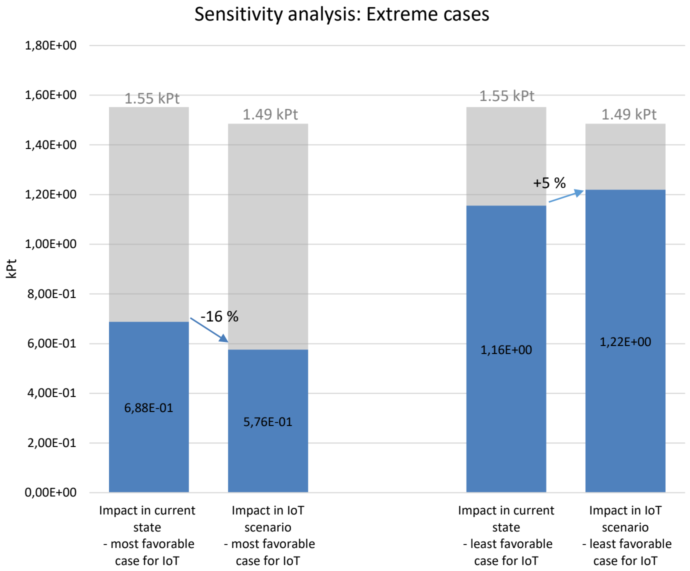


Figure 5.5: Combining the nine parameter values to maximize the relative difference (as percent of current state impact) between the current state and the IoT scenario results in a maximum impact reduction of 16% and a maximum impact increase of 5%.

Table 5.3: Sensitivity analysis per key parameter. The impacts should be compared to the base case (Current state: 1.55 kPt, IoT scenario: 1.49 kPt, diff.: $6.64 \cdot 10^{-2}$ kPt).

Parameter	Value used in base case	Lowest value	Highest value	Impact range for current state, per parameter (-/+ compared to base case)	Impact range for IoT scenario, per parameter (-/+ compared to base case)	Effect on *total life cycle impact* and on *absolute impact difference* between current state and IoT scenario
A. Rolling resistance fraction	24%	13%	47%	$9.36 \cdot 10^{-1}$ –2.84 kPt ($-6.16 \cdot 10^{-1}$/+1.29 kPt)	$8.7 \cdot 10^{-1}$ –2.77 kPt ($-6.16 \cdot 10^{-1}$/+1.29 kPt)	Significant effect on the total life cycle impact, no effect on the absolute impact difference.
B. Reduction of the distance that a retreaded tire can cover compared to a new one	20%	0%	25%	1.55 –1.55 kPt ($-6.54 \cdot 10^{-3}$/$+1.90 \cdot 10^{-3}$)	1.48 –1.49 kPt ($-6.89 \cdot 10^{-3}$/$+2.03 \cdot 10^{-3}$)	Small effect on the total life cycle impact and on the absolute impact difference.
C. Increase of the rolling resistance for retreaded tires compared to new ones	0%	0%	10%	1.55 –1.84 kPt (-0.00/$+2.87 \cdot 10^{-1}$ kPt)	1.49 –1.79 kPt (-0.00/$+3.08 \cdot 10^{-1}$ kPt)	Moderate effect on the total life cycle impact and on the absolute impact difference.
D. Weight of electronics in the IoT system	See all weights in Tables D.13, D.14 and D.15 in Appendix D	-50% for all weights	+200% for all weights	Constant at 1.55 kPt (-0.00/+0.00 kPt)	1.48 –1.51 kPt ($-6.38 \cdot 10^{-3}$/$+3.26 \cdot 10^{-1}$ kPt)	Small effect on the total life cycle impact and moderate effect on the absolute impact difference.
E. Weeks between pressure checks in current state	8 weeks	1 week	15 weeks	1.49 –1.61 kPt ($-5.71 \cdot 10^{-2}$/$+5.71 \cdot 10^{-2}$ kPt)	Constant at 1.49 kPt (-0.00/+0.00 kPt)	Moderate effect on the total life cycle impact but significant effect on the absolute impact difference.
F. Share of tires which are retreaded in IoT scenario (X_1)	70 %	70%	100%	Constant at 1.55 kPt (-0.00/+0.00 kPt)	1.47 –1.49 kPt ($-1.38 \cdot 10^{-2}$/+0.00 kPt)	Small effect on the total life cycle impact and moderate effect on the absolute impact difference.
G. Extension of distance a tire can cover when IoT is used	25 %	0%	50%	Constant at 1.55 kPt (-0.00/+0.00 kPt)	1.48 –1.51 kPt ($-1.02 \cdot 10^{-1}$/$+1.53 \cdot 10^{-2}$ kPt)	Small effect on the total life cycle impact and moderate effect on the absolute impact difference.
H. Credits assigned in EoL phase or not	Yes	No	Yes	1.155 –1.56 kPt (-0.00/$+1.08 \cdot 10^{-2}$ kPt)	1.49 –1.49 kPt (-0.00/$+7.17 \cdot 10^{-3}$ kPt)	Small effect on the total life cycle impact and small effect on the absolute impact difference.
I. Type of truck	Tractor/semi-trailer	Truck with trailer	Tractor/semi-trailer	1.02 –1.55 kPt ($-5.28 \cdot 10^{-1}$/+0.00 kPt)	$9.76 \cdot 10^{-1}$ –1.49 kPt ($-5.10 \cdot 10^{-1}$/+0.00 kPt)	Significant effect on the total life cycle impact but moderate effect on the absolute impact difference.

5.5. DISCUSSION

Previous studies have investigated the potential for IoT to reduce environmental impacts in the use-phase of products (e.g., Dekoninck and Barbaccia, 2019; Yuli et al., 2019). In this study, we add to this by showing that IoT can also bring significant impact reductions in the production phase, since it can enable both product lifetime extension and increased product recovery. The results show that under base case assumptions, the IoT scenario brings a 4% net reduction of total life cycle impact of truck tires compared to the current state. Since the use-phase emissions dominate, a relatively small impact reduction in the use phase (-5%) makes the largest contribution to the difference between the current state and the IoT scenario. The impact reduction in the tire production phase is significant (-27%), but has a smaller effect on the total life cycle impact. It should be noted that these relative contributions between life cycle stages are specific for tires and would be different for products with a larger share of the impacts stemming from production.

In case the studies here, the largest added impact in the IoT scenario comes from the production of the IoT hardware. This could also be different for other types of products, especially if large amounts of data need to be transferred and processed, resulting in increased energy demand.

As seen in Section 5.4, when looking at each ReCIPe impact category separately (Figure 5.3), the IoT scenario brings impact reductions for most impact categories. For four impact categories, however, the IoT scenario performs worse than the current state. This is an example of what Bonvoisin et al. (2014) refer to as 'impact shifting', i.e., that the impact in some categories is reduced while it increases in others. The added impacts in these categories are mainly stemming from the production of IoT hardware. It is thus important for designers to be aware of the fact that even in cases where using IoT brings net environmental reductions on a weighted basis, the IoT hardware itself comes with inherent environmental impacts, and efforts should be taken to minimize these.

Our sensitivity analysis showed that the results about the relative impact difference between the current state and the IoT scenario are sensitive to assumptions of three types: (1) assumptions about the use-phase emissions of tires, independent of whether IoT is used or not, (2) assumptions about the actual environmental reductions that IoT will bring about, and (3) assumptions about the hardware components used in the IoT solution.

The first type of assumptions includes parameters A and I. Parameter A describes the share of the total fuel consumption in the truck that should be allocated to the tires because of their rolling resistance. This parameter thus depends on which tires we expect are used. Changing this parameter does not change the absolute difference in impact between the current state and the IoT scenario, but it considerably affects the total life cycle impact of the tire, which is dominated by the use phase. If a low rolling resistance factor is assumed, the total life cycle impact becomes lower, and the relative difference between the current state and the IoT scenario becomes bigger. Parameter I defines which type of truck is used. As stated previously, two options are considered: (1) a fully-loaded 'tractor/semi-trailer' or (2) a fully-loaded 'truck with trailer'. The use-phase impact per tire-kilometer is lower in (2) than in (1) and the relative impact difference between the current state and the IoT scenario is larger in (2) than in (1).

The fact that parameters A and I have a large influence on the total tire life cycle impact suggests that hauler companies should ensure that the tires and trucks that they use are appropriate for the type and amount of goods to be transported. The fuel efficiency that can be achieved in this way is likely to affect the impact per tire-kilometer more than adding IoT. However, based on the analysis done in this study, we cannot draw conclusions about which tires and trucks to use in which situation.

The second type of assumptions includes parameters E (how often the tire pressure is checked in the current state), F (share of tires which are retreaded in IoT scenario) and G (extension of distance a tire can cover when IoT is used). These parameters indicate to what extent IoT actually brings environmental impact reductions in the tire life cycle.

The difference in impact between the current state and the IoT scenario is especially sensitive to variations in parameter E. This shows that the results are not only dependent on the technological context, but also sensitive to modeling choices about the behavior of different actors. If drivers already have a routine in place to check the pressure quite often (every 1-2 weeks), then the addition of a pressure monitoring system will not bring any significant environmental benefit. Moreover, we cannot know for sure that the availability of up-to-date pressure data will actually lead to a behavioral change among the drivers to adjust the pressure more often.

Similarly, with regards to parameter G, even if the hauler company gets access to data about the condition of each tire, they might still exchange all tires at the same time, if that is more convenient or most cost effective, for example. Further, to actually increase the share of tires that are retreaded (parameter F), the retreading company would need to be willing and able to act on the data supplied by the IoT solution, and adjust their sorting procedure accordingly. These findings echo the discussion in (Dekoninck and Barbaccia, 2019) about the need to design for behavioral change, so that the potential savings that IoT can bring are actually realized through user actions. When assessing IoT-enabled strategies, it is thus important to closely examine the context in which it is going to be implemented, including the current and expected behavior of actors along the product life cycle.

In relation to the third type of assumptions, i.e. about the hardware components used to enable the IoT solution, the primary uncertainty lies in the choice of components and in the lack of reliable data about the impact of specific components. As the Ecoinvent database does not provide specific data for different types of sensors, nor for gateways, we used the Ecoinvent data entry 'unspecified electronic component' to describe these components. To deal with this uncertainty, we used a wide range of values for the weight of IoT components in our sensitivity analysis (parameter D). Varying parameter D has a moderate but non-negligible effect on the weighted impact difference and a large effect on the impact difference in the four impact categories Freshwater eutrophication, Freshwater ecotoxicity, Marine ecotoxicity, Human non-carcinogenic toxicity. This indicates that design decisions at this level can be important for the net environmental impact of IoT-enabled circular strategies. Based on this, as well as the fact that more and more products are being connected to the internet, we argue that more research is needed to produce detailed and reliable data of different electronic components used in connected products.

Another aspect related to the impact of the IoT hardware is the lifetime of the specific hardware components. In the case studied here, the lifetimes of the hardware components were sufficient to last through the multiple lifetimes of the core product (the tire). However, for other longer-lived product types, it is possible that the IoT components become obsolete while the rest of the product is still functioning. This aspect is important to keep in mind, since it could mean that adding IoT shortens the lifetime of the core product, instead of prolonging it.

Lastly, some limitations of this study should be mentioned. We have not included the possibility that IoT might enable additional retreading cycles, i.e., that tires could be retreaded four or five times instead of three. This was excluded since the stakeholders who were interviewed did not see an opportunity for this, mainly because of lacking demand from customers. Similarly, we did not investigate potential IoT-induced improvement (or deterioration) in tire design, production, recycling or incineration, since this was not mentioned by the stakeholders. Moreover, while this study focused on tires, IoT could be used more widely in trucks, for example to support fuel-efficient driving behavior, increased traceability, or optimized maintenance of other important components besides tires [47]. Such opportunities have not been investigated in this study.

Further, our results are based on the Swedish context, and might not be directly generalizable to other countries. Some context-specific aspects should thus be mentioned. Firstly, Sweden has a relatively high use of renewable fuels for transport compared to other countries (e.g., compared to the EU average [48]). Secondly, Sweden has cold winters, implying that Swedish hauler companies are cautious about extending the use time of tires into the winter season. Thirdly, Sweden has a well-developed collection and recycling system for used tires. Altogether, these context-specific aspects likely mean that the IoT-induced environmental impact reduction for tires is smaller in Sweden than in many other countries.

With regards to the methods used, we presented our LCA results both as a single impact score based on weighting and per impact category in the ReCIPe method. While weighting always adds subjectivity, it was meaningful to use weighting in this study as it supported a more direct comparison of total environmental impact of the two scenarios. However, it was also important to present the results per impact category as this allowed for a more nuanced discussion of the findings and showed that the IoT scenario actually performed worse for four impact categories. Finally, the focus of our assessment was entirely on environmental impact, and we did not try to quantify the potential safety and/or cost improvements that might come from adding IoT.

5.6. CONCLUSIONS

The aim of this paper was to assess the net environmental impact reduction of using IoT to support circular strategies in the life cycle of heavy-duty truck tires in Sweden. Doing so, we aimed to gain insights into when and how it makes environmental sense to embed IoT hardware, such as sensors and communication devices, into products to stimulate circular strategies. We compared the environmental impact from tires in the current state with an 'IoT scenario', in which IoT brought about (1) reduced fuel consumption, (2) delayed tire exchange, and (3) increased retreading of tires. The biggest impact reduction in the IoT scenario was found to come from fuel consumption reduction as a result of IoT-enabled tire pressure monitoring. Using the ReCIPe method for impact assessment, we found that the weighted tire life cycle impact was 4% lower in the IoT scenario than in the current state. However, we also found that the IoT scenario performed significantly worse for four ReCIPe impact categories (Freshwater eutrophication, Freshwater ecotoxicity, Marine ecotoxicity, Human non-carcinogenic toxicity). Through sensitivity analysis, we showed that the results are sensitive to the underlying modeling choices. We varied nine key parameters to find the range of possible values for the relative impact difference between the current state and the IoT scenario. In the most favorable case for IoT, the impact reduction was found to be 16%. In the least favorable case for IoT, we found a 5% impact *increase* in the IoT scenario.

The results are sensitive to assumptions about the current and expected behavior of different actors along the life cycle. This indicates that, when exploring or proposing IoT-enabled circular strategies, it is important that designers thoroughly investigate the context in which the strategy is to be implemented and, when needed, design solutions that actually ensure behavioral change. We also found that design decisions at the level of specific IoT components can be important to the net environmental performance of IoT-enabled circular strategies.

Future research should perform similar assessments for other types of products. In addition, efforts should be put into gathering more detailed inventory data about environmental impact of specific IoT components, such as sensors and gateways.

Acknowledgements:
This research was funded by the Circular European Economy Innovative Training Network, Circeuit, an action funded by the European Commission under the Horizon 2020 Marie Sklodowska Curie Action 2016 –Grant Agreement 721909 (authors E.I., E.J., and R.B), and by the Swedish Innovation Agency (Vinnova), under the Innovations for a Sustainable Society call –dnr 2016–03356 (authors D.D., S.A., C.J., A–C.M., and T.N.). We are grateful to the company representatives who provided input to the study and to the anonymous reviewers for valuable feedback.

Conflicts of interest/Competing interests:
The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material:
The data that was used is provided in the Appendix.

Code availability:
The SimaPro file is available upon request.

Author contributions:
Emilia Ingemarsdotter: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original draft. Derek Diener: Methodology, Formal analysis, Investigation, Writing Review and Editing. Simon Andersson: Formal analysis, Investigation. C. Jonasson: Investigation, Writing Review and Editing. A-C. Mellquist: Investigation, Writing Review and Editing. Thomas Nyström: Funding Acquisition, Investigation. Ella Jamsin: Supervision, Writing Review and Editing. Ruud Balkenende: Supervision, Funding Acquisition, Writing Review and Editing.

REFERENCES

A. Alcayaga, M. Wiener, and E. G. Hansen (2019). Towards a framework of smart-circular systems: An integrative literature review. *Journal of Cleaner Production* **221**, 622.

S. Andersson and D. Diener (2019), *Life Cycle Assessment of Resource Effectiveness in a Business Ecosystem of Heavy-Duty Truck Tires*, IVL and RISE Sustainable Business. Available from: https://www.ri.se/en/what-we-do/projects/circular-business-ecosystem-sensors-and-recycling-heavy-vehicle-tyres.

J. Baliga, R. W. A. Ayre, K. Hinton, and R. S. Tucker (2010). Green Cloud Computing: Balancing Energy in Processing, Storage and Transport. *Proceedings of the IEEE* **99**, 149.

D. Böckin, S. Willskytt, H. André, A. M. Tillman, and M. Ljunggren Söderman (2020). How product characteristics can guide measures for resource efficiency - A synthesis of assessment studies. *Resources, Conservation and Recycling* **154**, 104582.

J. Bonvoisin, A. Lelah, F. Mathieux, and D. Brissaud (2012). An environmental assessment method for wireless sensor networks. *Journal of Cleaner Production* **33**, 144.

J. Bonvoisin, A. Lelah, F. Mathieux, and D. Brissaud (2014). An integrated method for environmental assessment and ecodesign of ICT-based optimization services. *Journal of Cleaner Production* **68**, 144.

A. Boustani, S. Sahni, T. Gutowski, and S. Graves (2010), *Tire Remanufacturing and Energy Savings*, Environmentally Benign Manufacturing Laboratory, Sloan School of Management. Available from: http://web.mit.edu/ebm/www/Publications/MITEI-1-h-2010.pdf.

G. Bressanelli, F. Adrodegari, M. Perona, and N. Saccani (2018). Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies. *Sustainability* **10**, 639.

Brigdestone (2012), *Total tyre life brochure*, Bridgestone.
Available from: https://www.bridgestone.co.uk/truck-and-bus/downloads.

F. Chen, J. G. Schneider, Y. Yang, J. Grundy, and Q. He (2012), An energy consumption model and analysis tool for Cloud computing environments, in *2012 1st International Workshop on Green and Sustainable Software, GREENS*, Zurich, Switzerland.

E. Dekoninck and F. Barbaccia (2019), Streamlined assessment to assist in the design of internet-of-things (IoT) enabled products: A case study of the smart fridge, in *Proceedings of the International Conference on Engineering Design, ICED*, Delft, Netherlands.

D. Diener, T. Nyström, A.-C. Mellquist, C. Jonasson, and S. Andersson (2019), The legend of the circular tire : Creating a vision for a more resource productive tire business ecosystem, in *Proceedings of the Product Lifetimes and the Environment (PLATE) Conference*, Berlin, Germany.

Ecoinvent (2018), Ecoinvent 3.5, https://www.ecoinvent.org/database/older-versions/ecoinvent-35/ecoinvent-35.html [accessed 2020-10-15].

El-watch (2019), The Neuron Tyre Health System, https://www.el-watch.com/wp-content/uploads/2019/11/THS-Facts-EN-08.pdf [accessed 2020-08-19].

Ellen MacArthur Foundation (2016), *Intelligent assets: Unlocking the Circular Economy Potential*, Cowes, UK.
Available from: https://www.ellenmacarthurfoundation.org/publications.

Energimyndigheten (2019), *ER 2019:14 Drivmedel 2018*, Energimyndigheten.
Available from: http://www.energimyndigheten.se/statistik.

EU (2020), *Regulation (EU) 2020/740 on the labelling of tyres with respect to fuel efficiency and other parameters*, The European Parliament and the council of the European union.

M. Goedkoop, R. Heijungs, M. Huijbregts, A. de Schryver, J. Struijs, and R. van Zelm (2009), *ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation.* Available from: https://www.rivm.nl/en/life-cycle-assessment-lca/downloads.

J. Guinée, R. Heijungs, and R. Frischknecht (2019). Multi-functionality in Life Cycle Inventory Analysis: Approaches and Solutions. in *LCA Compendium The Complete World of Life Cycle Assessment*, edited by W. Klöpffer and M. Curran, Chap. 4: Life Cycle Inventory Analysis (Arvidsson R., Ciroth A. (eds)). Springer, Dordrecht, Netherlands.

T. G. Gutowski, S. Sahni, A. Boustani, and S. C. Graves (2011). Remanufacturing and energy savings. *Environmental Science and Technology* **45**, 4540.

L. Hallberg, T. Rydberg, L. Bolin, L. Dahllöf, H. Mikaelsson, E. Iverfeldt, and J. Tivander (2013), *Well-To-Wheel LCI Data for Fossil and Renewable Fuels on the Swedish market*, f3 the Swedish Knowledge center for renewable transport fuels. Available from: www.f3centre.se.

M. Huijbregts, Z. J. N. Steinmann, P. M. F. M. Elshout, G. Stam, F. Verones, M. D. M. Vieira, M. Zijp, and R. van Zelm (2016), *ReCiPe 2016 - A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization (RIVM Report 2016-0104)* , Dutch National Institute for Public Health and the Environment, RIVM. Available from: https://www.rivm.nl/en/life-cycle-assessment-lca/downloads.

E. Ingemarsdotter, E. Jamsin, G. Kortuem, and R. Balkenende (2019). Circular strategies enabled by the Internet of Things—A framework and analysis of current practice. *Sustainability* **11**, 5689.

International Organization for Standardization (2006), *Iso 14040:2006 environmental management life cycle assessment principles and framework*, Geneva, Switzerland.
Available from: https://www.iso.org/standard/37456.html.

R. K. Kanth, P. Liljeberg, H. Tenhunen, H. Tenhunen, L. R. Zheng, Y. Amin, and H. Kumar (2015), Study on sustainability and life cycle assessment of RFID antenna, in *Environmental Engineering and Computer Application - Proceedings of the International Conference on Environmental Engineering and Computer Application, ICEECA 2014*, Hong Kong.

W. Klöpffer and B. Grahl (2014), *Life cycle assessment (LCA): a guide to best practice*, 1st ed., Wiley, Weinheim, Germany.

A. Knottnerus (2019), *A Methodology for Energy Analysis of High Performance Cloud users*, Master's thesis, Leiden University and TU Delft.

S. Krömer, E. Kreipe, D. Reichenbach, and R. Stark (1999), *Life cycle assessment of a car tire*, Continental AG. Available from: https://www.continental.com/resource/blob/47500/b64cfd62d7c37b31e0141cb618756f86/oekobilanz-en-data.pdf.

T. Kumar and M. Mani (2017). Life Cycle Assessment (LCA) to Assess Energy Neutrality in Occupancy Sensors. in *Research into Design for Communities, Volume 2. ICoRD 2017. Smart Innovation, Systems and Technologies, vol 66.*, edited by A. Chakrabarti and D. Chakrabarti. Springer, Singapore.

A. Lelah, F. Mathieux, and D. Brissaud (2011). Contributions to eco-design of machine-to-machine product service systems: The example of waste glass collection. *Journal of Cleaner Production* **19**, 1033.

M. Linder, R. H. W. Boyer, L. Dahllöf, E. Vanacore, and A. Hunka (2020). Product-level inherent circularity and its relationship to environmental impact. *Journal of Cleaner Production* **260**, 121096.

J. Malmodin, D. Lunden, M. Nilsson, and G. Andersson (2012), LCA of data transmission and IP core networks, in *Proceedings of Electronics Goes Green 2012+, ECG 2012*, Berlin, Germany.

MariaDB (2019), Data Type Storage Requirements, https://mariadb.com/kb/en/data-type-storage-requirements/ [accessed 2020-08-24].

A.-C. Mellquist, C. Johansson, C. Jonasson, D. Diener, F. Norefjäll, M. Linder, P. Altmann, and T. Nyström (2020), *Circular economy in a business eco-system: Integrated sensors and new recycling technology for heavy vehicle tyres*, RISE AB, Gothenburg, Sweden. Available from: https://www.ri.se/en/what-we-do/projects/circular-business-ecosystem-sensors-and-recycling-heavy-vehicle-tyres.

Michelin (2019), Different Life Stages of Michelin Truck Tyres, https://www.michelin.in/truck-bus-tyres/retread [accessed 2020-10-14].

J. L. K. Nussholz (2019), *Circular Business Model Design: A checklist for creating environmental benefits*. Https://doi.org/10.13140/RG.2.2.14624.12808.

A. Pehlken and G. Roy (2006). Identifying LCA-elements in scrap tire recycling. *WIT Transactions on Ecology and the Environment* **92**, 325.

H. Pihkola, M. Hongisto, O. Apilo, and M. Lasanen (2018). Evaluating the Energy Consumption of Mobile Data Transfer From Technology Development to Consumer Behaviour and Life Cycle Thinking. *Sustainability* **10**, 2494.

Pré Sustainability B.V. (2020), SimaPro, https://simapro.com [access 2020-10-14].

RFID4U (2020), Dig Deep Construction of RFID Tags, https://rfid4u.com/dig-deep-construction-of-rfid-tags [accessed 2020-10-14].

W. Scharnhorst (2006), *Life cycle assessment of mobile telephone networks, with focus on the end-of-life phase*, Ph.D. thesis, École Polytechnique Fédérale de Lausanne.

A. Shehabi, S. J. Smith, E. Masanet, and J. Koomey (2018). Data center growth in the United States: Decoupling the demand for services from electricity use. *Environmental Research Letters* **13**, 124030.

X. Sun, J. Liu, J. Hong, and B. Lu (2016). Comparative life cycle assessment of chinese radial passenger vehicle tire. *International Journal of Life Cycle Assessment* **21**, 1749.

A. Uchechukwu, K. Li, and Y. Shen (2014). Energy Consumption in Cloud Computing Data Centers. *International Journal of Cloud Computing and Services Science (IJ-CLOSER)* **3**, 31.

Volvo Trucks (2020), Tyres and how they impact fuel consumption, https://content.volvotrucks.com/are-your-trucks-tyres-causing-unnecessary-fuel-consumption [accessed 2020-08-24].

M. Yuli, R. Puig, M. A. Fuentes, D. Civancik-Uslu, and M. Capilla (2019). Eco-innovation in garden irrigation tools and carbon footprint assessment. *International Journal of Environmental Science and Technology* **16**, 2937

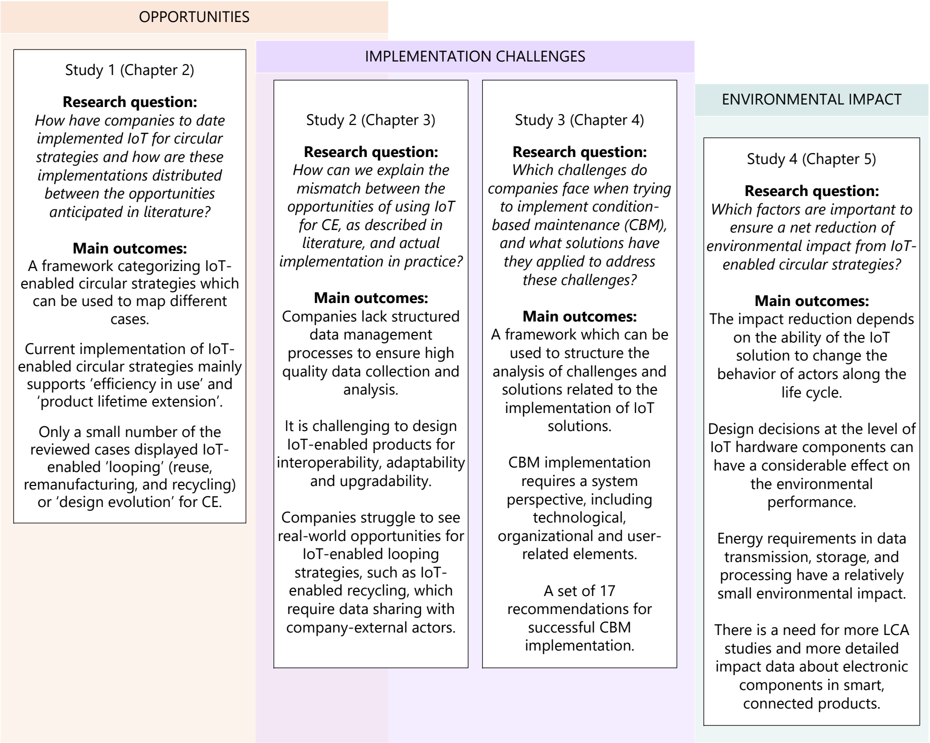
6

CONCLUSIONS

THE aim of this thesis was to study how companies can use IoT for circular strategies and to provide guidance to companies in making effective and responsible use of IoT to support the transition to a circular economy. Focus was placed on understanding the opportunities, implementation challenges, and environmental impact of IoT-enabled circular strategies. Throughout this thesis, I have discussed ‘circular strategies’ as product and service design strategies related to efficiency in use, increased product utilization, product lifetime extension, reuse, remanufacturing, or recycling.

Towards this aim, four research projects were conducted, as presented in Chapter 2-5. Each study posed a specific research question related to the wider thesis topic. The first study (Chapter 2) aimed to understand the opportunities of IoT for CE as well as to what extent companies are currently exploring these opportunities. The second study (Chapter 3) investigated a particular case of IoT-enabled circular business model implementation, with the aim to understand context-specific opportunities and challenges. The third study (Chapter 4) focused on one particular IoT-enabled circular strategy, namely condition based maintenance (CBM). Here, the aim was to understand implementation challenges as well as solutions that companies have applied in order to overcome such challenges. Finally, the fourth study (Chapter 5) assessed the net environmental impact of IoT-enabled circular strategies in a particular case, with the aim to derive insights into design factors that are important to ensure net environmental impact reductions. The four studies and their respective main outcomes are presented in Figure 6.1.

In this final chapter, I first shortly present the rationale for conducting the four studies (Section 6.1), including intermediate results which guided the research direction along the way. The findings from all four studies are then synthesized into overall conclusions according to the three main topics of interest: opportunities (Section 6.2), implementation challenges (Section 6.3), and environmental impact (Section 6.4). Thereafter, I reflect on the implications of the findings for research and practice (Sections 6.5 and 6.6). Finally, I present suggestions for future research at the intersection between IoT and CE (Section 6.7).



Study 1 (Chapter 2)

Research question:
How have companies to date implemented IoT for circular strategies and how are these implementations distributed between the opportunities anticipated in literature?

Main outcomes:
A framework categorizing IoT-enabled circular strategies which can be used to map different cases.

Current implementation of IoT-enabled circular strategies mainly supports 'efficiency in use' and 'product lifetime extension'.

Only a small number of the reviewed cases displayed IoT-enabled 'looping' (reuse, remanufacturing, and recycling) or 'design evolution' for CE.

Study 2 (Chapter 3)

Research question:
How can we explain the mismatch between the opportunities of using IoT for CE, as described in literature, and actual implementation in practice?

Main outcomes:
Companies lack structured data management processes to ensure high quality data collection and analysis.

It is challenging to design IoT-enabled products for interoperability, adaptability and upgradability.

Companies struggle to see real-world opportunities for IoT-enabled looping strategies, such as IoT-enabled recycling, which require data sharing with company-external actors.

Study 3 (Chapter 4)

Research question:
Which challenges do companies face when trying to implement condition-based maintenance (CBM), and what solutions have they applied to address these challenges?

Main outcomes:
A framework which can be used to structure the analysis of challenges and solutions related to the implementation of IoT solutions.

CBM implementation requires a system perspective, including technological, organizational and user-related elements.

A set of 17 recommendations for successful CBM implementation.

Study 4 (Chapter 5)

Research question:
Which factors are important to ensure a net reduction of environmental impact from IoT-enabled circular strategies?

Main outcomes:
The impact reduction depends on the ability of the IoT solution to change the behavior of actors along the life cycle.

Design decisions at the level of IoT hardware components can have a considerable effect on the environmental performance.

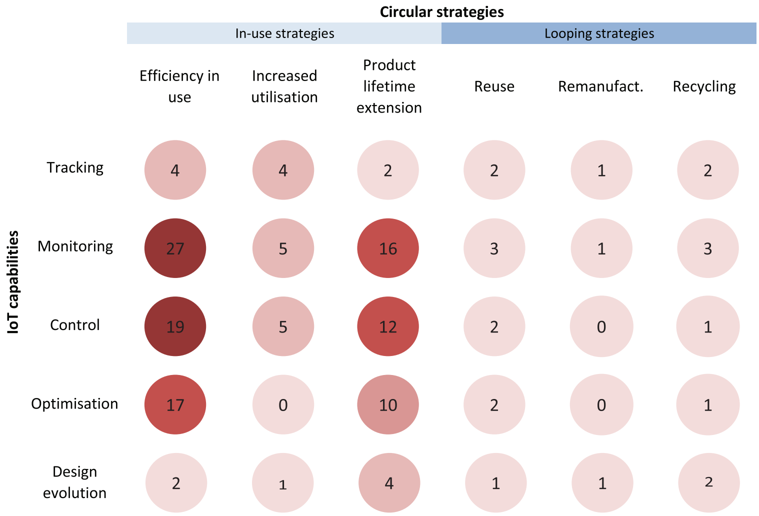
Energy requirements in data transmission, storage, and processing have a relatively small environmental impact.

There is a need for more LCA studies and more detailed impact data about electronic components in smart, connected products.

Figure 6.1: The four studies presented in this thesis, and their main outcomes.

6.1. RATIONALE FOR CONDUCTING THE STUDIES

As previous literature provided limited information about the actual implementation of IoT for CE in practice, the first research question addressed in this thesis was: *How have companies to date implemented IoT for circular strategies and how are these implementations distributed between the opportunities anticipated in literature?* To answer this question, a first step was to create an overview of the opportunities of using IoT for CE as anticipated in literature, resulting in a framework that categorizes different types of IoT-enabled circular strategies (Chapter 2). By mapping 40 cases to the framework, a 'heat map' was derived which indicates how current implementations are distributed among the 'theoretical opportunities', i.e. the opportunities for IoT to support circular strategies as anticipated in previous literature. The mapping of the cases to the framework is reproduced in Figure 6.2. It shows that IoT-enabled circular strategies mainly supports efficiency measures in the use phase and product lifetime extension. Few examples were found describing IoT-enabled reuse, remanufacturing, and recycling. Similarly, few of the studied cases had implemented processes to feed back data from products-in-use to help improve product circularity in the design phase (design evolution for CE).



	In-use strategies			Looping strategies		
	Efficiency in use	Increased utilisation	Product lifetime extension	Reuse	Remanufact.	Recycling
Tracking	4	4	2	2	1	2
Monitoring	27	5	16	3	1	3
Control	19	5	12	2	0	1
Optimisation	17	0	10	2	0	1
Design evolution	2	1	4	1	1	2

Figure 6.2: Framework categorizing different types of IoT-enabled circular strategies. Examples from 40 cases have been mapped to the framework, creating a 'heat map' of current implementation of IoT-enabled circular strategies in practice (from Chapter 2).

As the first study revealed a mismatch between the 'theoretical opportunities' of IoT for CE and actual implementation in practice, the next step was to understand the reasons why this mismatch existed. Two types of reasons why a company would not have implemented an IoT-enabled circular strategy were discussed: (1) while the company sees the strategy as an opportunity, they have not yet managed to overcome the associated implementation challenges, and (2) the company does not see the strategy as relevant in their particular context. In order to distinguish between these two types of reasons, in-depth understanding of specific case contexts was needed.

The second study thus posed the following research question: *How can we explain the mismatch between the opportunities of using IoT for CE, as described in literature, and actual implementation in practice?* This question was explored through an in-depth case study with an original equipment manufacturer (OEM) of LED lighting systems who was developing an IoT-enabled circular value proposition (Chapter 3). The case study showed examples of both types of reasons for the mismatch between theory and practice; some IoT-enabled circular strategies in the framework (Figure 6.2) were seen as relevant but associated with challenges, while others were not seen as relevant in the particular case. For the first type, both IoT-specific and non IoT-specific implementation challenges were identified. Most IoT-specific challenges were brought up in relation to developing a solution for condition-based maintenance, but the interviewees expected similar challenges when implementing other strategies which would also require an understanding of product condition, such as optimized reuse/remanufacturing based on remaining lifetime estimations, and design evolution for improved durability.

Building on these results, a multiple case study at three OEMs was conducted (Chapter 4) focusing specifically on condition-based maintenance (CBM) implementation. The focus on CBM was chosen as this is one of the most commonly adopted IoT-enabled circular strategies (as found in Study 1), and because it builds on monitoring the condition of products, which is important also in IoT-enabled looping strategies and for design evolution (as found in Study 2). The following research question was posed: *Which challenges do companies face when trying to implement condition-based maintenance, and what solutions have they applied to address these challenges?* To answer this question, a framework was developed (Figure 6.3) which integrates technological, organizational and user-related aspects of CBM implementation. The framework was then used to analyze the three cases (forklift trucks, industrial robots, heat pumps). The results displayed a wide range of challenges related to the implementation of CBM in practice. Based on the identified challenges and solutions and the interrelations between them, a set of recommendations were formulated for other companies aiming to implement CBM.

Finally, the fourth study was dedicated to understanding the net environmental impact of IoT-enabled circular strategies (Chapter 5). The following research question was addressed: *Which factors are important to ensure a net reduction of environmental impact from IoT-enabled circular strategies?* To answer this question, life cycle assessment (LCA) was performed on a specific case, in which IoT was used to support circular strategies (heavy-duty truck tires). The results showed that the added IoT solution was likely to bring a net environmental impact reduction in the tire's life cycle but that it could also lead to a net impact *increase* if certain design factors were not sufficiently considered.

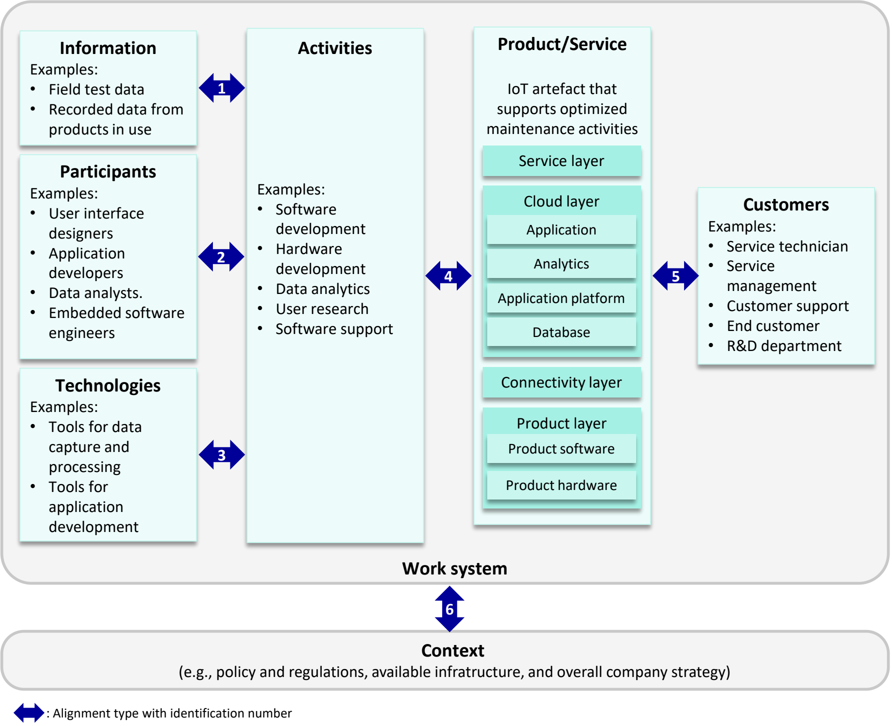


Figure 6.3: Framework describing the work system elements that need to be aligned for successful CBM implementation (from Chapter 4).

6.2. OPPORTUNITIES

The framework introduced in Chapter 2 (and reproduced in Figure 6.2) presents a palette of potential ways in which IoT can support circular strategies, both in the product's use phase and for 'looping strategies', i.e., reuse, remanufacturing or recycling. The IoT solution itself can range from being relatively simple, mainly allowing for identification of products or parts, to being more complex, involving advanced data analytics or data sharing between multiple actors.

Figure 6.2 also indicates how the current implementation of IoT-enabled circular strategies is distributed among the opportunities anticipated in literature. It shows that most examples of IoT-enabled circular strategies in practice display efforts in the use phase, especially related to energy efficiency and maintenance, which are both well-established strategies also in the traditional linear economy. Few examples were found of companies implementing IoT for looping strategies. Similarly, 'design evolution' for CE, i.e., the use of data recorded from products-in-use in the design process to improve the circularity of the product or service, is still underexplored in practice.

The case study results presented in Chapter 3 and 4 suggest that OEMs see opportunities in using the tracking and monitoring capabilities of IoT to offer their products through more service-oriented business models, e.g., 'light-as-a-service' or 'heating-as-a-service'. As discussed in Chapter 3, IoT could also help increase the attractiveness (for the customer) of such service-oriented business models through the addition of data-enabled features which extend the original function of the product. In the case of lighting systems for supermarkets, such add-ons could be, for example, advice on how to redesign the supermarket in order to optimize sales, and evaluations of the effect of events in the store on sales numbers. Such a shift away from transactional sales models to service-oriented business models could then, in turn, incentivize the manufacturer to offer long-lasting products that they take back for reuse, remanufacturing, or recycling at the end of use.

The company representatives interviewed in Chapter 3 and 4 also saw opportunities in using data from products-in-use (at the customer site) to support planning and optimization of maintenance activities. With improved maintenance, the products might, in turn, run more efficiently and last longer. Some of the interviewees in Chapter 3 also acknowledged that IoT could support reuse, remanufacturing, and design evolution, but this was not based on practical experiences.

The focus on use-phase strategies is likely a sign that, to date, companies mainly use IoT to improve on what they already see as part of their core activities, which - more often than not - does not include reuse, remanufacturing or recycling. An important aspect here is the novelty of both IoT and CE. Companies are just starting to understand how they might improve the circularity of their products and services. At the same time, many companies are at the beginning of the process of finding out how they could use IoT to develop and offer new value propositions, be more data-driven, and more efficient. As one of the interviewees put it in Chapter 3, *"IoT is a blurry opportunity field"*. The combination of IoT and CE is thus a relatively unexplored strategic and operational space where companies will need to put time, effort, and resources into identifying what the real opportunities are in their particular context.

Thus, the research presented in this thesis does not suggest that IoT implementation in itself is likely to move companies towards incorporating additional circular strategies into their core activities. However, as in the case of maintenance services in Chapter 4, the results do suggest that IoT can strengthen the delivery of an already established circular strategy. Moreover, it should be noted that many of the circular strategies that are not considered core activities by the manufacturer are still handled somewhere else, by third-party actors (e.g. remanufacturers and recyclers). Here, there could be a real opportunity, from a systems perspective, to use IoT for providing these actors with information that could help them optimize their processes. However, as discussed in Chapter 3, OEMs might not perceive this as an opportunity. This is not surprising since OEMs have traditionally seen third-party remanufacturers as a threat to their own sales and brand image. Even if data sharing would be beneficial from a system's perspective, it might thus not be in the business interest of the OEM. Here, I see an interesting avenue for future research investigating conditions under which OEMs would indeed see an opportunity in sharing product-related, potentially sensitive, information with third party ‘reusers’, remanufacturers and recyclers. This could include research into different kinds of collaboration setups between the OEM and recovery actors. Another interesting and emerging research direction concerns technical solutions for sharing sensitive data in supply chains. For example, several companies are developing Blockchain-based protocols with the aim to enable product life cycle data sharing across supply chains (e.g., Esmaeilian et al., 2020; Licht et al., 2020).

6.3. IMPLEMENTATION CHALLENGES

As discussed in Chapters 3 and 4, the challenges faced by companies when trying to implement IoT-enabled circular strategies cover a wide range of aspects: from creating a common vision, to ensuring collaboration between different parts of the company, understanding user processes, and managing data collection and analysis in a structured way. In addition, they face non IoT-specific challenges related to circular business model implementation, such as limited customer acceptance and financial risk. Companies wanting to implement IoT-enabled circular strategies thus need to take a broad perspective and consider all these kinds of challenges. A too narrow focus on developing a technical solution, without sufficiently understanding the other types of challenges, is not likely to result in successful implementation.

Chapter 4 showed that, for successful implementation of condition-based maintenance (CBM), the organization needs to align the different elements of the ‘work system’ producing the IoT artefact needed for CBM. As presented in Chapter 4, a work system is defined as a *“system in which human participants and/or machines perform work (processes and activities) using information, technology, and other resources to produce specific products/services for specific internal and/or external customers"* (Alter, 2013). The work system producing the IoT artefact for CBM also needs to be aligned with its context, meaning that the company strategy, environment, and infrastructure support the goal of the work system. All four case companies studied in Chapters 3 and 4 experienced challenges in achieving alignment between work system elements and between the work system and its context. While Chapter 4 focused solely on IoT-enabled CBM, similar challenges are expected also for other circular strategies which require an understanding of the product’s condition, such as IoT-enabled reuse/remanufacturing, and design evolution for CE.

Several of the extracted challenges were related to how the organization was set up around CBM implementation. For example, there was a lack of experience in the organization of working with data analytics, and it was unclear who was responsible for different parts of CBM development and implementation.

Another important challenge in CBM implementation is to really understand the user of the CBM system, in most cases the service technician. The CBM solutions need to consider the user's processes and provide effective interfaces which can facilitate desired actions. Moreover, companies need to acknowledge the acceptance barrier that the service technicians (or other users) might have when it comes to using the CBM system. One particular challenge here is to improve the 'explicability' of the IoT artefact and the algorithms it uses.

The results presented in Chapter 3 and 4 further indicate that companies struggle to ensure structured processes for managing data collection and analysis to support monitoring and prediction of products' condition in the field. 'Predictive maintenance' has become a popular term in both business and academic literature, envisioning a new paradigm for maintenance where downtime and unexpected failures can be minimised (Bouskedis et al., 2020; March and Scudder, 2017). However, accurate predictions of failures in the real world is technically challenging, and requires prediction models to be built over time. Moreover, as seen in Chapter 3 and 4, it is difficult to know, from the beginning of an implementation process, what data should be collected and fed to the model. As such, data collection needs to be flexible, i.e., possible to adjust over time. Moreover, the organization needs to ensure the collection of meta data and data labels from the field, which often requires manual data input by service technicians, or even end customers. This brings an additional challenge, since the person inputting the data might not have the incentive, time, or knowledge to do this sufficiently accurately. Again, efforts are needed to facilitate these activities and to design effective interfaces which stimulate actors to perform the desired actions.

Finally, the results from Chapter 3 indicate that there is a risk that adding IoT components might actually reduce the lifetime of products, since IoT technology is developing quickly, potentially rendering the IoT components obsolete faster than other parts of the product. A challenge on the level of product design is thus to ensure that the IoT solution itself is designed for longevity, upgradability, and adaptability.

6.4. ENVIRONMENTAL IMPACT

Chapter 5 showed that, for the case of heavy-duty truck tires in the Swedish context, IoT could reduce the total weighted life cycle impact through fuel consumption reduction, delayed tire exchange, and increased remanufacturing. However, the impact increased for four of the ReCIPe impact categories.

Further, I discussed that the results were sensitive to the assumptions made, both with regards to the impact reduction potential and to the added impacts from IoT hardware. One critical assumption was how much fuel could be saved by introducing a tire pressure monitoring system. This relates to how one expects the truck driver's behavior to change through the access to accurate tire-pressure data. If access to data does not lead to behavioral change, either because the current tire pressure is already close to optimal, or because of some kind of resistance to change, then the fuel consumption will not decrease. Similar assumptions about anticipated IoT-enabled behavioral change are likely to be important when assessing the effect of adding IoT to other products as well.

Another important assumption concerned the design of the actual IoT solution. The results indicated that design decisions at the level of specific IoT components can have a considerable effect on the net environmental impact of IoT-enabled circular strategies. However, current LCA databases do not contain detailed impact data about specific IoT components, such as sensors, gateways, and antennas. As more and more products are becoming connected, it is important that more data is collected about these kinds of components. Another aspect related to the design of the IoT solution itself is the lifetimes of the individual IoT components. In the case of truck tires, the lifetime of the IoT components were sufficiently long to not influence the lifetime of the tire core, but as seen in Chapter 3, this might not be the case for longer-lived products such as LED luminaires. Moreover, if the lifetime of the components were twice as long as that of the tire core, so that they could be reused, then the added impact from IoT would be lower.

Chapter 5 showed that there is no easy answer to the question whether IoT-enabled circular strategies lead to a net reduction of environmental impact. As the net impact depends on both the direct impact from IoT components and the IoT-induced changes to the product life cycle, designers and others proposing and evaluating IoT-enabled circular strategies need to have a thorough understanding of both the current state of the product life cycle and the anticipated state (in which IoT is used). Moreover, practically all IoT solutions include interfaces between people and the data that is being collected. As these interfaces are meant to support and influence decision-making and actions of people, they should be designed carefully based on a thorough understanding of the needs and processes of the envisioned user(s).

Lastly, as seen in Chapter 5, IoT-enabled circular strategies can lead to ‘impact shifting’, i.e., that the impact is reduced within some impact categories but actually increases in others. It is thus important to include a range of impact categories when assessing IoT-enabled circular strategies.

6.5. IMPLICATIONS FOR RESEARCH

The work presented in this thesis contributes to research in the fields of design for circular economy, condition-based maintenance (CBM) implementation, and ICT for sustainability (including environmental assessment of ICT). Previous work on IoT in the design for circular economy literature has mainly focused on the opportunities brought about by the technology, often disregarding both implementation challenges and environmental impact assessment. Similarly, previous work in the field of CBM implementation has mainly focused on technological aspects, rather than ‘softer’ implementation challenges and interrelations between different types of challenges

(Golightly et al. 2018). Previous work in the field of ICT for sustainability has often focused more on energy and material efficiency rather than on other circularity aspects, such as maintenance, increased utilization, and recovery activities (Townsend and Coroama, 2018). In relation to previously available literature, the main contributions of this thesis are thus the following:

- Increased empirical grounding about the opportunities of using IoT for CE and how they could actually be realized by companies.
- An original research framework that supports the analysis of company cases with regards to their current level of implementation and indicated future opportunities they might explore further.
- An overview of how current implementations of IoT-enabled circular strategies are distributed between types of strategies, showing a mismatch between the opportunities as anticipated in literature and current implementation in practice.
- Deepened insights into the challenges of circular business model implementation with a focus on IoT-specific challenges.
- An original research framework describing important elements needed for condition-based maintenance implementation and how these need to be aligned.
- One of the first comprehensive and balanced evaluations of the environmental impact of adding IoT to support circular strategies, leading to insights into design factors that are important to reach net environmental impact reduction.

6.6. IMPLICATIONS FOR PRACTICE

Apart from the academic contributions, the research presented in this thesis can support practitioners aiming to use IoT for circular strategies. Insights into the opportunities of IoT for CE can inform and inspire companies to innovate and test new strategies. Insights into current practice and challenges enable companies to learn from the experiences of others, making them better prepared for their own explorations. Finally, insights into factors which influence the net environmental impact of IoT-enabled circular strategies can spur reflections, at an early stage in the design process, about how to reach real impact reduction. Specifically, this thesis showed that designers should focus on ensuring that the IoT solution actually influences the behavior of actors along the life cycle. The results also indicated that design decisions at the level of specific IoT components can have a considerable effect on the net environmental impact of IoT-enabled circular strategies.

The frameworks presented in this thesis have not (yet) been developed into actual methods or tools, and their usefulness in practice has therefore not been formally evaluated. However, as the frameworks were derived based on examples from practice, I believe that they can already be informative for companies who are interested in IoT-enabled circular strategies. The framework presented in Chapter 2 could be used by companies to map their current state of IoT-enabled CE implementation, and to consider additional opportunities that might be interesting for further exploration. During the interviews conducted for Study 2, the framework provided a useful structure in the discussions about opportunities and challenges related to IoT-enabled circular strategies (Chapter 3).

The framework presented in Chapter 4 gives an overview of the different elements needed to develop and implement a CBM solution. It describes how the elements need to be aligned to successfully produce an integrated IoT artefact which serves the needs of its different users. Finally, Chapter 4 also presented a set of 17 recommendations for companies wanting to implement condition-based maintenance for the products they produce, building on the challenges and solutions found in three case companies. The recommendations span across different strategic levels: from providing suitable technical tools for software developers, to setting up clear roles and responsibilities in CBM projects, and creating a common vision in the company. Chapter 4 also explicitly highlighted interrelations between different challenges and solutions. This can help companies to consider system-level implications of different actions.

6.7. FUTURE RESEARCH

Building on the work presented in this thesis, multiple interesting avenues for future research can be identified. There is a need to further the scientific understanding of IoT-enabled circular strategies, as well as for evidence-based methods and tools which can facilitate their implementation in practice.

Understand challenges and explore solutions related to IoT-enabled looping and design evolution for circular strategies
There is a need to further explore why IoT-enabled reuse, remanufacturing and recycling have not been implemented to scale. Similarly, more research is needed about how design evolution (the feedback of data from products in use to design) could support more circular design. Especially, more work is needed to understand how data sharing between different actors in the product life cycle, including product recovery networks, can be managed and incentivized. Since there is a lack of examples of these strategies in practice, future research projects might set up real-world pilots in relevant sectors.

Conduct environmental assessment studies on IoT-enabled circular strategies
In this thesis, an environmental assessment study was carried out for one specific type of product (tires). For the research community to learn more about the environmental impact of IoT-enabled circular strategies, other product types in other contexts need to be investigated, e.g., products with shorter lifetimes or products

for which condition monitoring would require large amounts of data transfer and processing. Compared to the study presented in Chapter 5, future studies could also extend the scope to include the (positive or negative) effects of IoT on recycling. Moreover, if the assessment is to support design decisions at the IoT hardware level, more detailed inventory data is needed for IoT-specific components, such as sensors, actuators, antennas, and gateways.

Develop tools to support the implementation of IoT-enabled circular strategies
The framework in Chapter 2 could be turned into a tool for structured exploration of opportunities while the framework and recommendations in Chapter 4 could be used to guide implementation of such strategies. Future work is needed to detail such tools and evaluate them with practitioners. Specifically, it would be useful to investigate how the framework from Chapter 4 could be adapted to include other circular strategies beyond maintenance, e.g., IoT-enabled remanufacturing.

Develop tools to guide the design of environmentally sound IoT-enabled products
As seen in Chapter 3, there is a risk that adding IoT actually reduces the lifetime of products. In addition, IoT solutions require production, transport and disposal of hardware as well as energy to transfer, process and store data. As seen in Chapter 5, assessing the net environmental impact of IoT-enabled circular strategies is a complex task, and the outcome depends on assumptions made about added impacts and IoT-induced savings. Specifically, the results presented in Chapter 5 showed that the net impact depends on the ability of the IoT solution to influence the behavior of actors along the product life cycle. To support the design of environmentally sound IoT-enabled products, future work is thus needed to develop (1) guidelines for designers to ensure sufficient longevity of the IoT solution itself, thereby avoiding IoT-induced product obsolescence, (2) easy-to-use assessment tools which can enable designers to scan early ideas about IoT-enabled circular strategies for impact reduction potential, and (3) tools that support the design of interfaces through which actors can interact with product-related data in a way that stimulates desired behavior.

Evaluate additional effects of IoT on social and environmental sustainability
The scope in Chapter 5 did not include potential rebound effects or macro-level impacts related to changes in, e.g., policy or social norms (as introduced in Chapter 1). Future research could thus build on the work presented here and include additional indirect effects, in order to advance the understanding of the environmental impact of IoT-enabled circular strategies. Moreover, as presented in Chapter 1, there are important social and ethical aspects that need to be considered when designing with IoT, related to, for example, data privacy and security. Due to its focus on environmental sustainability, this thesis did not address such concerns. Future research could thus investigate social and ethical risks related to IoT-enabled circular strategies, and how they could be managed.

REFERENCES

S. Alter (2013). Work System Theory: Overview of Core Concepts, Extensions, and Challenges for the Future. *Journal of the Association for Information Systems* **14**, 72.

A. Bouskedis, D. Apostolou, and G. Mentzasm (2020). Predictive Maintenance in the 4th Industrial Revolution: Benefits, Business Opportunities, and Managerial Implications. *IEEE Engineering Management Review* **48**, 57.

B. Esmaeilian, J. Sarkis, K. Lewis, and S. Behdad (2020). Blockchain for the future of sustainable supply chain management in Industry 4.0. *Resources, Conservation and Recycling* **163**, 105064.

D. Golightly, G. Kefalidou, and S. Sharples (2018). A cross-sector analysis of human and organisational factors in the deployment of data-driven predictive maintenance. *Information Systems and e-Business Management* **16**, 627.

J. Licht, T. D. Jong, K. Oudshoorn, and P. Pasotti (2020), Circularise Whitepaper, https://www.circularise.com/technology [accessed 2020-08-19].

S. T. March and G. D. Scudder (2017). Predictive maintenance: strategic use of IT in manufacturing organizations. *Information Systems Frontiers* **21**, 327.

J. H. Townsend and V. C. Coroama (2018). Digital Acceleration of Sustainability Transition: The Paradox of Push Impacts. *Sustainability* **10**, 2816

A

APPENDIX TO CHAPTER 2

Table A.1: Product/service cases analyzed in this paper and how they were categorized according to IoT capabilities and circular strategies.

Company	**Type of Product/ Service**	**Description**	**IoT Capability**					**CE Aspect**	**CE Strategy**						**Primary Source**	**Additional Source(s)**
			Tracking	**Monitoring**	**Control**	**Optimization**	**Design Evo.**		**Eff. in use**	**Inc. utilizat.**	**Life. ext.**	**Reuse**	**Reman**	**Recycl.**		
A.O. Smith	Heaters and boilers	Remote fault monitoring [1]		x				Minimize downtime for repairs and reduce lost revenue caused by interruption in hot water delivery [2]			x				[1] Porter and Heppelmann	[2] http://www.aosmithconnect.com/
ABB	Electric grid equipment	Conditions monitoring (e.g. temperature changes in transformers), sending alerts to control centre to warn for possible overload conditions [1]		x	x			Prevents overload conditions [1].			x				[1] Porter and Heppelmann	
AGCO (Agcommand)	Farm machinery	Monitors use, condition and environment to optimize overall farm performance [1]. Automated machine health alerts to identify problems early [2]		x	x	x		Optimize overall farm efficiency [1] improve machine health. [2]	x		x				[1] Porter and Heppelmann	[2] https://www.agcotechnologies.com/products/detail/agcommand/

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Arup	Bridge	Structural health monitoring systems which gives warnings of structural problems, allows targeted inspections/interventions to ensure smooth operations and prolong the bridge's service life. Approximately 1000 sensors will provide data of the bridge's condition, enabling predictive maintenance. [1]		x	x	x		Enables predictive maintenance and prolongs the bridge's service life [1]			x				[1] EMF	[2] https://www.arup.com/projects/q/queensferry-crossing
Auscott Limited	Irrigation	Monitors water flows, on-the-field-sensing, weather data. [1] optimized irrigation application and direct yield or field productivity increases resulting from reduced water wastage [1] The cotton-bale tracking system allows managers to monitor cotton quality variability [1] remote sensing / control systems are employed with irrigation scheduling based on soil moisture data. [2]	x	x	x	x		Reduced water wastage [1]	x						[1] EMF	[2] http://www.auscott.com.au/Farming/default.aspx

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Big Ass	Ceiling fans	Fans regulate speed on basis of temperature and humidity [1]. Works with air conditioning system to make them more effective [2]		x	x			By incorporating Big Ass Fans into building automation systems and using controls, energy savings become easy and automatic.[2]	x						[1] Porter and Heppelmann	[2] http://docs.bigassfans.com/ae-files/BAS-Energy-Brochure.pdf
Car2Go	Car-sharing service	Car sharing based on tracking of the car, and monitoring of the time the user has used the car. The user can unlock the car through the app.	x	x	x			A larger number of people can reach their destination with fewer assets [1]		x					[1] EMF	[2] https://www.car2go.com/US/en/#152741 [3] https://www.car2go.com/US/en/faq/

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Carrier Corporation (Infinity)	HVAC and building control	The control knows to conserve energy while you are not home.[2]		x	x			The Infinityő System bundles efficient performance with precise energy reporting. It can reduce your utility bills and increase your energy savings. [2]	x						[1] Porter and Heppelmann	[2] https://www.carrier.com/residential/en/us/innovation/#infinity
Cisco	Space management in real estate	Real time occupancy sensing allows for more intense use of building. Provides energy consumption data (e.g. lights, HVAC, blinds). [1]		x				More intense use of the workspace. Energy savings. [1]	x	x					[1] EMF	
Cisco Energy Management (CEM)	Energy management system	Measure and manage energy use (and CO2 emissions) at manufacturing facility [1]		x				Goal of reducing energy consumption by 20%. [1]	x						[1] EMF	
Current by (GE)	Energy management system	Integrates data from the building's systems and responds in real time [1]		x	x	x		Deliver energy savings and operational efficiency improvements. [2]	x						[1] EMF	[2] https://www.currentbyge.com/offices

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Delta Development	Elevators	Conditions monitoring and optimized maintenance. IoT data can help identify products that can be reused in a different setting. [1]		x	x	x		Improved maintenance and reuse. [1]			x	x			[1] EMF	[2] http://www.deltadevelopment.eu/en/sustainability
Diebold	ATM	Status monitoring and analysis. Machine can be serviced remotely [2] or the company deploys a technician who has been given a detailed diagnosis of the problem, a recommended repair process, and, often, the needed parts. Remote updates. [1]		x	x			Fault detection, remote service. Informed repairs. Remote updates. [1]			x				[1] Porter and Heppelmann	[2] http://www.s4growth.com/publications/whitepapers/diebold whitepaper.pdf
DriveNow	Car sharing	Tracks location of cars. User can access the car through the app. Price based on the time the user uses the car.	x	x	x			A larger number of people can reach their destination with fewer assets. [1]		x					[1] EMF [2] Porter and Heppelmann	[3] https://www.drive-now.com/gb/en/london

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Enevo	Smart bin	Automatically generated schedules and optimized routes taking into account future fill level projections, truck availability, traffic information, road restrictions, container and content types the vehicle can collect etc. New schedules and routes are planned not only looking at the current situation, but considering the future outlook as well. [2]		x		x		Collections based on Enevo's smart plans significantly reduces costs, emissions, road wear, vehicle wear, noise pollution, and work hours. [2]	x						[1] EMF	[2] https://www.enevo.com/
Enlighted	Energy management system	IoT- based energy service system, [1] uses sensor data about energy, occupancy and environment. links to a lighting control system and facilitates integration with third-party building automation and demand response systems. [2]		x	x			Claim it saves their clients 6070% on lighting and 2030% on heating/cooling efficiency. [1]	x						[1] EMF	[2] http://www.enlightedinc.com/system-and-solutions/iot-system/energy-manager/

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
GE Aviation (TrueChoice)	Jet engines	Optimize engine performance by identifying discrepancies between expected and actual performance [1]. Remote diagnostics for minimizing maintenance while maximizing fleet efficiency.[3]		x		x	x	Insights from data has resulted in reduced fuel use [1], and it enables efficient maintenance. [3]	x		x				[1] Porter and Heppelmann [2] EMF	[3] https://www.geaviation.com/commercial/truechoice-commercial-services/truechoice-flight-hour

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
GE Wind power	Wind turbines	Wind turbines that automatically change gear according to wind conditions [1] increases wind farm's output by up to 10%, taking into account environmental conditions. [3] backed by data driven insights through intelligent monitoring, detection and diagnostic capabilities. Specialized upgrades, repairs, and exchange techniques to ensure superior turbine performance. [2]		x	x	x		More power output (efficiency) [3] and improved maintenance [2]	x		x				[1] EMF	[2] https://www.ge.com/content/dam/gepogep-renewables/global/ee_US/documents/wiwi-services/_WindServiWin_Brochure.pdf [3] https://www.ge.com/renewableenergy/wind-energy/turbine-services/platform-upgrades

Continuation of Table A.1

Company	**Type of Product/ Service**	**Description**	**IoT Capability**					**CE Aspect**	**CE Strategy**						**Primary Source**	**Additional Source(s)**
			Tracking	**Monitoring**	**Control**	**Optimization**	**Design Evo.**		**Eff. in use**	**Inc. utilizat.**	**Life. ext.**	**Reuse**	**Reman**	**Recycl.**		
HP (Instant ink)	Printing as a service	The printer monitors how it is being used, as well as ink levels in the cartridges. New cartridges are ordered automatically, and the user gets an envelope to send the used one back for recycling. Printer use data helps inform system designs, and future product designs, to improve serviceability, durability [1]		x	x		x	Cartridge recycling [2]			x			x	[1] EMF	[2] http://www.hp.com/hpinfo/global citizenship /09gcreport /enviro /reuse/ programs.html
Hubway (now Bluebikes)	Bike-sharing	Location tracking, real-time bike and dock availability. User can unlock the bike with the app. Collects and shows information about your number of rides and total miles ridden. [2]	x	x	x			More efficient utilization of products that are used intermittently [1]		x					[1] Porter and Heppelmann	[2] www.bluebikes.com

Continuation of Table A.1

Company	**Type of Product/ Service**	**Description**	**IoT Capability**					**CE Aspect**	**CE Strategy**						**Primary Source**	**Additional Source(s)**
			Tracking	**Monitoring**	**Control**	**Optimization**	**Design Evo.**		**Eff. in use**	**Inc. utilizat.**	**Life. ext.**	**Reuse**	**Reman**	**Recycl.**		
IBM	Reuse optimization tool	Tracking location and availability. Conditions monitoring. Integrates data about design specifications, components list and materials. Optimization model to support decision about recovery option. Based on these insight, companies can build a CE business case [1]	x	x			x	Optimal reuse option of a product can be made: weather to refurbish, remanufacture or harvest key components, or recycle materials. [1]				x	x	x	[1] EMF	
JohnDeere (Farmsight)	Farm machinery, irrigation	Monitors yield per hectare, which can be used to optimize irrigation and the use of fertilizers and pesticides. Optimize overall farm performance.		x	x	x		Reduced water, fertilizer, and pesticide use. [1]	x						[1] Porter and Heppelmann, [2] EMF	[3] http://smartagservices.jd-dealer.co.uk/Services/Smart-FarmSight

Continuation of Table A.1

Company	**Type of Product/ Service**	**Description**	**IoT Capability**					**CE Aspect**	**CE Strategy**						**Primary Source**	**Additional Source(s)**
			Tracking	**Monitoring**	**Control**	**Optimization**	**Design Evo.**		**Eff. in use**	**Inc. utilizat.**	**Life. ext.**	**Reuse**	**Reman**	**Recycl.**		
Joy Global	Mining equipment	Machines autonomously coordinate with other equipment to improve mining efficiency. Monitoring of performance and faults. Can be controlled from a control centre on the surface. The system can optimize performance across the fleet of equipment in the mine. [1]		x	x	x		Fault detection and predictive service indicators facilitates maintenance. The system can improve mining efficiency. [1]	x		x				[1] Porter and Heppelmann	
Libelium	Sensor kit and management platform for precision agriculture	Monitoring of environmental factors and condition of crops. [1]		x				Reduce the amount of pesticides, fertilizers and water used. [1]	x						[1] EMF	
Nest	Thermostats	Monitors energy use and energy demand on grid, can be remotely controlled, maximizes comfort while minimizing energy consumption [1]		x	x	x		Minimize energy consumption, and energy use during peak demand periods [1]	x						[1] Porter and Heppelmann [2] EMF	

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Opower (now Oracle)	Energy data management	Stores and analyzes energy use from smart meters in cloud platform [2] from which energy reports can be written. [1]		x				Incentivizing users to reduce their energy bill. [1]	x						[1] EMF	[2] https://www.oracle.com/se/corporate/acquisitions/opower/index.html

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Philips light-as-a-service	Lighting	Optimizes power consumption based on live data of use patterns. Checks system operations and monitors faults. [1]		x	x	x		Lower power consumption [1]. Manage all maintenance and repair work, optimize the installation's performance throughout the life of the contract. [2]	x		x				[1] EMF	[2] http://images.philips.com/is/content/PhilipsConsumer/PDFDownloads/Global/Services/ODLI20170905_001-UPD-en_AA-7035_Philips-Managed_Services_Digi_WTO_01_digital-version.pdf

Continuation of Table A.1

Company	**Type of Product/ Service**	**Description**	**IoT Capability**					**CE Aspect**	**CE Strategy**						**Primary Source**	**Additional Source(s)**
			Tracking	**Monitoring**	**Control**	**Optimization**	**Design Evo.**		**Eff. in use**	**Inc. utilizat.**	**Life. ext.**	**Reuse**	**Reman**	**Recycl.**		
Philips Lighting (CityTouch)	Street lighting	Tracking of products and parts. Monitoring of energy use and environmental factors. Remote control and automatic dimming. Allows managers to optimize asset use time and predictively maintain their system. By increasing the ability to manage heterogeneous use cycles of the different asset components in detail, the model enables the looping of assets or asset components through additional use cycles. [1]	x	x	x	x		Extends the use cycle. Enables looping of components through additional cycles. Increased energy efficiency. [1]	x		x	x			[1] EMF	
Philips Lighting (Hue)	Lighting	Lightbulbs can be controlled via app [1]. Automatically turns on and off based on monitoring presence and daylight.[2]		x	x			Makes your home “smarter, comfortable and energy efficient”.	x						[1] Porter and Heppelmann	[2] http://www2.meethue.com/en-us/about-hue/

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Rolls-Royce (TotalCare)	Jet engines	Engine conditions monitoring gives insight into how to redesign the engine [1] and how to optimize maintenance [2]		x		x	x	More productive and more durable, long-lasting design [1]. Better planned maintenance and repair. [2]	x		x				[1] EMF	[2] https://www.rolls-royce.com/media/our-stories/discover/2017/totalcare.aspx

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Schindler PORT technology	Elevators	Predicting elevator demand patterns, calculating the fastest time to destination, and assigning the appropriate elevator to move passengers quickly. [1] Usage patterns are recorded. The system can learn about passenger needs to optimize flow . If current or forecasted waiting times fall below a defined acceptable value, ECO mode switches the unrequired elevators into standby mode. [2]		x	x	x		More efficient traffic handling means fewer stops and starts, reducing energy demand. Increases traffic handling capacity: Schindler Destination Interface can increase system efficiency by up to 50%. ECO mode allows intelligent reduction of the elevators' energy consumption. [2]	x						[1] Porter and Heppelmann	[2] https://www.schindler.com/content/us/internet/en/mobility-solutions/products/destination-technology/port-technology/_jcr_content/contentPar/downloadlist_464827542/downloadList/8_1471287019098.download.asset.8_1471287019098/schindler-port-brochure.pdf

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Schneider Electric	Building management systems	Gathers data about energy use and other building performance metrics. Uses monitoring and, for some customers, remote control to minimize energy consumption [1]		x	x	x		Minimize energy consumption. [1]	x						[1] Porter and Heppelmann	[2] https://www.schneider-electric.com/en/work/solutions/system/s4/building-systems-smart struxure/
Sensity Systems	Lighting control system	Monitors presence of people and automatically adjusts lighting based on that [1]		x	x			Lighting owners are able to reduce energy costs and implement a variety of “Smart City” applications and services. [2]	x						[1] EMF	[2] http://www.verizon.com/about/news/verizon-accelerates-smart-communities-acquisition-sensity-systems

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Spire	Satellite-based data monitoring	Tracking of e.g. trucks, aircrafts and trains. Spire also collects other kinds of data, about for example weather and climate. [1]	x					Enabling lowered fuel consumption from optimal routing. [1]	x						[1] EMF	[2] https://spire.com/data/
Sunpower	Solar panels	Monitors energy output and performance. Connects to other devices in the home to optimize the timing of activities in a way that matches power generation from the solar power system. [1]		x	x	x		Improved energy management. [1]	x						[1] EMF	[2] https://us.sunpower.com/businessgovernment/largecommercial/sunpowercommercial/
Tesla	Electric vehicles	Fault monitoring. Car can schedules repairs autonomously. Remote service and upgrades. Learn from real world performance in design improvements. [1]		x	x		x	Fault detection, service, repairs, and upgrades. [1]			x				[1] Porter and Heppelmann	

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
TOMRA	Reverse vending machines	Measures material composition and uses decision-making algorithm to separate waste. Can communicate location and load to enable route planning. [1] Notifications if it needs service. [2]	x	x				Precise and efficient recycling. [1] Maintenance of machine. [2]	x		x			x	[1] EMF	[2] https://www.tomra.com/en/collection/reverse-vending/digital
Trane	HVAC	Company as moved from focussing on HVAC equipment production to complete building performance [1]. Mobile platform to control and manage buildings more efficiently, reducing cost and providing a better indoor environment while energy efficiency is maximized. Monitoring of e.g. refrigerant leaks can give remote alarms to control system. [2]		x	x	x		Optimize performance and energy efficiency [2]	x						[1] Porter and Heppelmann	[2] https://www.trane.com/commercial/global/europe/en/controls/building-management-controls.html

Continuation of Table A.1

Company	**Type of Product/ Service**	**Description**	**IoT Capability**					**CE Aspect**	**CE Strategy**						**Primary Source**	**Additional Source(s)**
			Tracking	**Monitoring**	**Control**	**Optimization**	**Design Evo.**		**Eff. in use**	**Inc. utilizat.**	**Life. ext.**	**Reuse**	**Reman**	**Recycl.**		
Whirlpool	Washing machines	Monitors washing cycles. Remote control through app [3]. Maintenance notifications. Connected to NEST to find optimal time for washing. [2]		x	x	x		Predictive maintenance notification. [3] Connected to NEST to plan washing to save energy and avoid grid-peaks. [2]	x		x				[1] Porter and Heppelmann	[2] https://www.whirlpool.com/home-innovations/connected-appliances.html [3] http://www.whirlpool.co.uk/world-of-whirlpool/connectivity.content.html

Continuation of Table A.1

Company	Type of Product/ Service	Description	IoT Capability					CE Aspect	CE Strategy						Primary Source	Additional Source(s)
			Tracking	Monitoring	Control	Optimization	Design Evo.		Eff. in use	Inc. utilizat.	Life. ext.	Reuse	Reman	Recycl.		
Zipcar	Car-sharing service	Vehicle tracking help users find the car when they need it. Vehicle telematics allows Zipcar to monitors driver behaviour and understand how vehicles are being used, ultimately leading to better service availability for members [2]. The cars are unlocked by the user who has reserved it, with mobile application [3].	x	x	x		x	Real-time access to vehicles when needed. [1]		x					[1] Porter and Heppelmann	[2] http://www.zipcar.be/en/static/privacy [3] http://www.zipcar.be/en/how-it-works

B

APPENDIX TO CHAPTER 3

Table B.1: Interviewees per main area of expertise, with professional role, interview date, interview duration and ID used to link the person to the quotes presented in the results section.

Area of expertise	Role	#	Date	Duration	ID
Food retail		3			
	Product manager		2017-09-04	50 min	Int-1
	Segment manager		2017-09-04	40 min	Int-2
	Segment manager		2017-09-04	60 min	Int-3
Circular Economy		5			
	Sustainability strategy manager		2017-09-04	50 min	Int-4
	Marketing manager		2017-09-04	50 min (video link)	Int-5
	Product manager		2017-09-04	40 min	Int-6
	R&D manager		2017-09-04	70 min	Int-7
	Product designer		2017-09-04	50 min	Int-8
Internet of Things		4			
	Business developer		2017-09-04	50 min	Int-9
	Data-enabled services manager		2017-09-04	70 min (video link)	Int-10
	Research manager		2017-09-04	60 min	Int-11
	Data scientist		2017-09-04	50 min	Int-12

Table B.2: The main themes discussed during the interviews, with example questions.

Time perspective	Theme	Example questions
Current state	General strengths and challenges of currently offered product and services	-What are strengths of the current offering in food retail according to you?
	Current level of implementation of CE and IoT	-What are challenges/focus areas from your perspective for development in food retail? -What aspects of circularity are considered in the current proposition in food retail? -What is not yet in place, and why? -How do you see that circularity of lighting in the food retail segment could be improved? -From your perspective, how is IoT relevant for circularity in lighting in food retail?
Future outlook	Opportunities for IoT in CE	-Can you elaborate on how IoT could support the CE improvements that we talked about earlier?
	Challenges of IoT in CE	-Based on the opportunities: do you see any challenges to get there?

Table B.3: Opportunities for IoT to support circular strategies in the studied case as perceived by the interviewees.

Data category	Type of opportunity	Main points put forward by the interviewees	Example quotes
Opportunities			
	IoT supports servitized business models	-IoT allows for monitoring of system performance, enabling performance-based service contracts.	*"We have this beautiful infrastructure that is really omnipresent, it is everywhere. We are looking for ways to use that infrastructure to hook up different sensors to gather data and to come up with different data-enabled services for our customers."* (Int-9)
		-IoT makes service models more attractive through adding digital services beyond the lighting function.	
	IoT supports maintenance	-IoT enables detailed record keeping of installed products and parts, facilitating maintenance and adaptations.	*IoT … helps you in your serviceability, because a lighting system says 'Hey! I am about to fail' and then instead of going there to service one lamp you service all 10 which are about to fail in one go.* (Int-8)

Table B.4: Challenges associated with the implementation of the identified IoT for CE opportunities, as found in the studied case. The challenges are categorised as IoT-specific or General (i.e. not IoT specific).

Data category	Type of challenge	Main points put forward by the interviewees	Example quotes
IoT-specific challenges	Data quality and management	- Lack of data from products that have actually failed	*"The biggest challenge for predictive maintenance I think is that, for me, in order to apply this data science and solve this problem, I need data for luminaires that fail, and they last very long normally …"* (Int-12)
		- Parameters known to influence the condition of the product not collected.	*"The problem now is to get this prediction. It is not so easy … because the data that we have is not so reliable so we really lack some input we would really need some better data … Still making the model will be difficult, but without the right data it is nearly impossible."* (Int-12)

Continuation of Table B.4			
Data category	Type of challenge	Main points put forward by the interviewees	Example quotes
		- Not always clear which data set originated from which product.	*"Another key challenge that we have is that ... if you want to predict that something fails, you need to know for sure when something did actually fail in this data, and the recording of that is also not so well structured as I would like it."* (Int-12)
		- Lack of data about which luminaires actually failed in the field (labeled data).	
	Design for interoperability, adaptability and upgradability	- Design changes might lead to the need for new models for failure prediction and remaining lifetime estimation for every new product version.	*" ... if they do fail then this luminaire will have been released quite some time ago so by the time that I have managed to make a model it is probably for an outdated model of the luminaire because they will have released a new one."* (Int-12)
		- The uncertainty of future technological developments makes it difficult to design for interoperability over time.	*"If you want to keep the system interesting for the shop owner you need to be able to add things over time ... That means that suddenly we need a roadmap for connectivity ... which holds over 10 years! We need to think already about how things in the future ... will interoperate with each other ... Otherwise, the life cycles could even be shorter than in the past."* (Int-11) *"In the ideal luminaire you can put any module in and there is also space for something that is not available yet ... So how are you going to make sure that everything fits ... but that it doesn't look like a big block?"* (Int-7)
General challenges	Financial risk and uncertainty	- The value of used products depends on future market developments that are difficult to predict	*"The topic of residual value is rather complex because ... the actual market situation at that moment [the end of the service contract] will define the residual value. If there is no demand the value is zero, and if there is a huge demand then the value will be higher than the original price. The only thing we can do is to work on the enablers, to keep the residual value as high as possible."* (Int-4)

Continuation of Table B.4

Data category	Type of challenge	Main points put forward by the interviewees	Example quotes
	Customer preferences and behaviour	- The food retailers are used to a transactional way of buying lighting, and might not be willing to accept a service-based business model.	*"I would say that theoretically a service model would suit them [the food retailers]. But we know that they are very conservative. They want to buy and sell that's what they do all day. This 'pay-as-you-go' thing is not in their DNA … The interesting part is to make it attractive for them somehow."* (Int-5)
		- The PSS has to stay relevant over time even if the customer's needs keep changing	*"It is not only about increasing the lifetime of the product so that it last long, it is also about increasing the relevance of the product. Especially in the retail space I think it is important, because … you have a product now which will last for 10 years. During that period, the store would go through at least 3 or 4 changes. So how do you adapt the same product to changes in the store layout, so that you are still able to use it?"* (Int-6)

C

APPENDIX TO CHAPTER 4

Table C.1: Interview guide used to collect data from the cases.

Theme	Example questions
Questions to R&D	
Context	- What was the idea when designing the CBM solution, what should it be able to do, and for whom? - Was the maintenance service already in place before the development of the CBM solution? How did IoT change the service proposition? - Who owns the cost and benefit of the CBM solution? Do end customers pay a fee for the CBM service? - Who owns the data collected from the CBM solution?
Function	- What functionalities does your CBM solution currently have? - How is this functionality supporting improved maintenance, according to you? - What information and knowledge can be obtained from your CBM solution? - Who uses the your CBM solution, and in what way? - Which information and knowledge is used by whom? - What are current limitations to the solution according to you?
Process	- Who initiated the project? - Who was involved in the development process? - Did you use some kind of defined design/development process for developing the CBM solution? If yes, what does that entail? - Which were the main activities in the development process? - Whose needs did you consider when collecting requirements? - How and when did you collect requirements from the users of the CBM solution? - How and when did you collect needs from maintenance personnel to identify requirements? - How did you decide what information to show the users of the system, and how to visualise it? - How did you decide what data to collect and how to analyse it? - How was the solution evaluated throughout the development process? - Did you have to make changes to this after the system had been used for a while? Can you describe that process? - How do you work with continuous improvement of the CBM solution? - What are your future development plans for the CBM solution? Why is this needed?
Questions to maintenance personnel	
Process	- Was the maintenance department involved in the development of the CBM solution? Can you describe how? - Do you think you/your group should have been more involved in the development of the system? Why/Why not? - Do you have a process for providing feedback to R&D about improvements that you would like to see for the CBM solution?
Use of the CBM solution	- What kind of maintenance activities do you do? - How do you use the CBM solution? - Has your work changed since the CBM solution came in place? How?
Improvement potential	- Is the information that you get from the CBM solution relevant? - Is the information that you get from the CBM solution reliable? - Is the information that you get from the CBM solution sufficient for you to make the decisions that you want to make? - Does the solution integrate well with other systems that you are using? - If you could change something about the solution as it is now, what would it be?

Table C.2: Definitions of the nine elements of work systems, directly from Alter (2013) (p. 81)

Processes and activities occur in a work system to produce products/services for its customers. The use of the term 'processes and activities' recognizes that the work being performed may not be a set of clearly specified steps. Many important work systems perform organized activities that rely heavily on human judgment and improvisation, are semi-structured, and are better described as a set of related activities.
Participants are people who perform work within the work system. Customers are often participants in work systems, especially in service systems.
All work systems use or create **information**, which in the context of work system analysis is expressed as informational entities that are used, created, captured, transmitted, stored, retrieved, manipulated, updated, displayed, and/or deleted by processes and activities.
Technologies include both tools that are used by work system participants and automated agents; that is, hardware/software configurations that perform totally automated activities.
Products/services consist of information, physical things, and/or actions produced by a work system for the benefit and use of its customers.
Customers are recipients of a work system's products/services for purposes other than performing work activities within the work system. Customers of a work system often are also participants in the work system.
Environment includes the relevant organizational, cultural, competitive, technical, regulatory, and demographic environment within which the work system operates, and that affects the work system's effectiveness and efficiency. Organizational aspects of the environment include stakeholders, policies and procedures, and organizational history and politics, all of which are relevant to the operational efficiency and effectiveness of many work systems.
Infrastructure includes relevant human, information, and technical resources that are used by the work system but are managed outside of it and are shared with other work systems. From an organizational viewpoint rather than a purely technical viewpoint, infrastructure includes human infrastructure, informational infrastructure, and technical infrastructure.
Strategies that are relevant to a work system include enterprise strategy, department strategy, and work system strategy. In general, strategies at the three levels should be in alignment, and work system strategies should support department and enterprise strategies.

D

APPENDIX TO CHAPTER 5

D.1. DATA COLLECTION ABOUT THE TIRE'S END OF LIFE

Tires that are deemed unsuitable for retreading are sent to EoL processing. Below, we first present how scrapped tires are divided between different EoL streams. Then, we present more details about the processes in each such EoL stream. As mentioned in Section 5.2, we use system expansion to account for impacts that can be avoided elsewhere when tires are recycled or incinerated. The 'credits' received by the tires because of these avoided impacts depend on assumptions made about the recycling and incineration processes. In the sensitivity analysis, we deal with this uncertainty by showing the total results both with and without credits from the EoL phase.

D.1.1. DISTRIBUTION OF SCRAPPED TIRES INTO EOL STREAMS

In January 2019, the biggest tire recycling company in Sweden estimated that, out of the tires that they receive, 60% is sent for energy recovery in incineration (either in cement production or in district heating generation), while 39% is sent for material recycling and 1% is exported (Ragnsells Däckåtervinning AB, 2019). Material recycling included three streams: production of rubber granulates for artificial turfs (12%), cutting into blasting mats used on construction sites (22%), and shredding into drainage material to be used in construction or in landfills (5%) (Ragnsells Däckåtervinning AB, 2019).

In August 2019, the same recycling company announced that they will stop producing rubber granulates for artificial turfs (Ragnsells Däckåtervinning AB, 2019). Based on correspondence with the recycling company, we assume that this share instead goes to incineration. Thus, we estimate the current incineration percentage to be 72%. Based on (SDAB, 2019) we estimate that about half of this (36% of total) goes to the cement industry. The other half (again, 36% of total) is expected to go to district heating generation.

The percentages of scrapped tires going in the different EoL streams, as used in our calculations, are presented in Table D.1. Here, we disregard the 1% of tires that are exported and instead add 0.25% to each waste stream to reach 100%.

Table D.1: Share of scrapped tires going to each EoL option.

End of life options	wt%
Cement kiln incineration	36.25%
District heating incineration	36.25%
Blasting mats	22.25%
Drainage material	5.25%

All EoL options require that the tires are cut or shredded. (Alongi Skenhall et al., 2012) reported that the shredding process can be powered by electricity (20 kWh/ton tire) or diesel fuel (108 MJ diesel/ton tire). We assume that electricity used since this the most common option.

D.1.2. ENERGY RECOVERY IN CEMENT KILN INCINERATION

Based on a previous LCA study (Hallberg et al., 2006), tire shreds that are incinerated in cement kilns replace fuel (coal and pet-coke) as well as iron ore, which is used as an additive in cement production. While the referenced study is 14 years old, coal is still used in the cement production at the largest Swedish cement producing company (Cementa, 2018). We follow the calculations by Hallberg et al. (2006) who estimate that other emissions than CO_2 from cement kiln incineration can be neglected (both when burning tire shreds, and when burning coal/pet-coke). The amount of replaced fuel per tire mass, and the emissions from incinerating tire shreds, are based on Hallberg et al. (2006) and presented in Table D.2.

Table D.2: Data used to model incineration of tires in cement kiln.

	Amount	**Reference**	**Modeled as (Ecoinvent entry)**
Emissions to air: CO_2, fossil	2.55 $\mathrm{kg/kg_{tire,\ excluding\ natural\ rubber}/kg_{tire}}$	(Hallberg et al., 2006)	Carbon dioxide, fossil
Emissions to air: CO_2, biogenic	$\mathrm{2.55kg/kg_{tire} \cdot 0.37\ kg_{natural\ rubber}/kg_{tire}}$	(Hallberg et al., 2006)	Carbon dioxide, biogenic
Electricity use, tire shredding	20 $\mathrm{Wh/kg_{tire}}$	(Alongi Skenhall et al., 2012)	Electricity, medium voltage {SE}| market for | Cut-off, S
Replaced fuel: coal	0.75 $\mathrm{kg_{coal}/kg_{tire}}$	(Hallberg et al., 2006)	Hard coal {Europe, without Russia and Turkey} market for hard coal | Cut-off, S
Replaced fuel: pet-coke	0.25 $\mathrm{kg_{coal}/kg_{tire}}$	(Hallberg et al., 2006)	Petroleum coke {GLO}| market for | Cut-off, S
Replaced material: iron ore	0.16 $\mathrm{kg_{iron}/kg_{tire}}$	(Hallberg et al., 2006)	Iron ore, beneficiated, 65% Fe {GLO}| market for | Cut-off, S
Avoided emissions to air: CO_2 released from burning coal	2.888 $\mathrm{kg_{CO_2}/kg_{coal}}$	(Hallberg et al., 2006)	Carbon dioxide, fossil
Avoided emissions to air: CO_2 released from burning pet-coke	3.0 $\mathrm{kg_{CO_2}/kg_{pet\text{-}coke}}$	(Hallberg et al., 2006)	Carbon dioxide, fossil

D.1.3. ENERGY RECOVERY IN DISTRICT HEATING INCINERATION

The tire shreds in this EoL stream replace fuel that would otherwise have been used to produce district heating. Based on Hallberg et al. (2006), tire shreds that are incinerated for district heating replace coal or bio mass from wood. That study estimates that, in 2006, 57% of the tires were incinerated in a bio burner, replacing bio mass, and 43% in a coal burner, replacing coal. These numbers were based on the district heating plant ‘Händelöverket’, which in 2011 reported that 95% of their fuel is either renewable or waste-based (e.g., tires), only using coal at peak demand (Eon, 2011).

Based on this, we instead assume the tires replace 95% solid biomass and 5% coal. The amount of replaced fuel per tire mass, and the emissions from incinerating tire shreds, are based on Hallberg et al. (2006) and presented in Table D.3.

Table D.3: Data used to model incineration of tires in district heating production

	Amount	**Reference**	**Modeled as**
Electricity use, tire shredding	20 Wh/kg_{tire}	(Hallberg et al., 2006)	Electricity, medium voltage {SE}| market for | Cut-off, S
	Tires incinerated in coal burner		
Emissions to air: CO	0.738 g/kg_{tire}	(Hallberg et al., 2006)	Carbon monoxide
Emissions to air: CO_2, fossil	2.55kg/$kg_{\text{tire, excluding natural rubber}}$	(Hallberg et al., 2006)	Carbon dioxide, fossil
Emissions to air: CO_2, biogenic	2.55kg/$kg_{\text{natural rubber in tire}}$	(Hallberg et al., 2006)	Carbon dioxide, biogenic
Emissions to air: N_2O	0.54 g/kg_{tire}	(Hallberg et al., 2006)	Dinitrogen monoxide
Emissions to air: NH_3	0.0364 g/kg_{tire}	(Hallberg et al., 2006)	Ammonia
Emissions to air: NO_x	2.83 g/kg_{tire}	(Hallberg et al., 2006)	Nitrogen oxides
Emissions to air: Particles	0.041 g/kg_{tire}	(Hallberg et al., 2006)	Particulates
Emissions to air: SO_2	10.7 g/kg_{tire}	(Hallberg et al., 2006)	Sulfur dioxide
Replaced heat (otherwise generated from burning coal)	4.333 [kWh_{heat}/kg_{coal}] · 1.17 [kg_{coal}/kg_{tire}]	(Hallberg et al., 2006)	Heat, district or industrial, other than natural gas {RoW}| heat production, at coal coke industrial furnace 1-10MW | Cut-off, S
	Tires incinerated in bio boiler		
Emissions to air: CO	0.0764 g/kg_{tire}	(Hallberg et al., 2006)	Carbon monoxide
Emissions to air: CO_2, fossil	2.55/$kg_{\text{tire, excluding natural rubber}}$	(Hallberg et al., 2006)	Carbon dioxide, fossil
Emissions to air: CO_2, biogenic	2.55/$kg_{\text{natural rubber in tire}}$	(Hallberg et al., 2006)	Carbon dioxide, biogenic
Emissions to air: N_2O	0.33 g/kg_{tire}	(Hallberg et al., 2006)	Dinitrogen monoxide
Emissions to air: NH_3	0.000765 g/kg_{tire}	(Hallberg et al., 2006)	Ammonia
Emissions to air: NO_x	2.6 g/kg_{tire}	(Hallberg et al., 2006)	Nitrogen oxides
Emissions to air: Particles	0.0211 g/kg_{tire}	(Hallberg et al., 2006)	Particulates
Emissions to air: SO_2	2.62 g/kg_{tire}	(Hallberg et al., 2006)	Sulfur dioxide

Continuation of Table D.3

	Amount	**Reference**	**Modeled as**
Electricity use, tire shredding	20 $\mathrm{Wh/kg_{tire}}$	(Hallberg et al., 2006)	Electricity, medium voltage {SE}| market for | Cut-off, S
Replaced heat (otherwise generated from burning bio mass)	1.519 $[\mathrm{kWh_{heat}/kg_{biomass}}] \cdot 3.33$ $[\mathrm{kg_{biomass}/kg_{tire}}]$	(Hallberg et al., 2006)	Heat, district or industrial, other than natural gas {SE}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, S

D.1.4. RECYCLING AS DRAINAGE MATERIAL

For this EoL stream, 1 kg of tire shreds are estimated to replace 2.5 kg crushed stone which would otherwise have been used as drainage material in landfills or construction (Hallberg et al., 2006).

D.1.5. RECYCLING AS BLASTING MATS

For this EoL stream, the tires are used as blasting mats in road and construction work. We did now find specific data about the impacts of blasting mats. As a rough approximation, we assume that cutting the tires and binding them into a blasting mat is similar to the electricity requirement for shredding tires. Blasting mats are generally made from old tires, thus no replacement credits are assigned to the tires for this secondary use. At the end of a blasting mat's life, it is assumed to be incinerated.

D.2. OTHER DATA TABLES

Table D.4: Raw materials in tires, based on interviews with representatives from truck manufacturer.

Raw materials in tires	**Assumed wt%**	**Weight [kg]**
Total tire	100%	63
Natural rubber	37%	23.3
Synthetic rubber	9%	5.7
Carbon black	24%	15.1
Organic chemicals	8%	5
Steel	22%	13.9

Table D.5: Raw materials in treads, based on the assumption that treads have the same material composition as the rubber part of tires.

Raw materials in tires	**Assumed wt%**	**Weight [kg]**
Total tire	100%	10.7
Natural rubber	47%	5.0
Synthetic rubber	12%	1.3
Carbon black	31%	3.3
Organic chemicals	10%	1.1

Table D.6: Inputs, emissions and wastes in tire production process as given in Sun et al. (2016) per 1 passenger car tire à 9.497 kg. The data is given per step in the tire production process: 'compound blending', 'rolling and extrusion', 'cutting and forming', 'vulcanizing and testing'. However, for emissions, the data is only given as a total (not per step). Moreover, a certain amount of electricity and water is reported for 'other three processes'. This refers to electricity and water used in the three processes 'rolling and extrusion', 'cutting and forming' and 'vulcanizing and testing' collectively, i.e. the available data does not indicate how much originate from which of the three processes.

	Compound blending	**Rolling & extrusion**	**Cutting & forming**	**Vulcanizing & testing**	**'Other three processes'**	**Total**
Electricity [MJ/tire]	14.44	4.57	1.7	3.01	11.13	34.85
Water [kg/tire]	6.96	0	0	0	16.56	23.52
Steam [kg/tire]	0.76	0.2	0.39	15.89	0	17.24
Emissions to air: PM [g/tire]	-	-	-	-	-	243.51
Emissions to air: VOCs [g/tire]	-	-	-	-	-	0.005
Emissions to water: COD [g/kg_{tire}]	-	-	-	-	-	1.73
Emissions to water: NH4+-N [g/tire]	-	-	-	-	-	0.19
Emissions to water: suspended solid [g/tire]	-	-	-	-	-	0.69
Waste wire cord fabric (kg/tire)	0	0.002	0.015	0.001	0	0.018

Continuation of Table D.6

	Compound blending	**Rolling & extrusion**	**Cutting & forming**	**Vulcanizing & testing**	**'Other three processes'**	**Total**
Waste fiber fabric (kg/tire)	0	0.001	0.02	0.001	0	0.022
Waste cord thread (kg/tire)	0	0.001	0	0	0	0.001
Waste rubber (kg/tire)	0.001	0.001	0	0	0	0.002
Waste steel wire (kg/tire)	0	0.001	0.003	0	0	0.004
Waste tire (kg/tire)	0	0	0	0.073	0	0.073

Based on the data given in Table D.6, we derive process input and emission values for tire as presented in Table D.7, and for a tread as presented in Table D.8. To model tire production, we use the total values. To model tread production, we use the data for the first two steps given in Sun et al. (2016), i.e., 'compound blending', and 'rolling and extrusion'. When the data from Sun et al. (2016) is only given as a total, we allocate one fourth of these values to each of the four process steps. For the data reported in the column 'other three processes', we allocate one third of the values to each of the three steps ('rolling and extrusion', 'cutting and forming' and 'vulcanizing and testing'). Since the tread is assumed to not contain steel, no steel scrap is modeled in tread production. 'Fabric' and 'thread' waste is neglected for both tires and tread, as it is also not included in the assumed tire/tread composition.

Table D.7: Data used to model tire production (per kg tire), based on Sun et al. (2016).

Input/output	**Amount**	**Modeled as**
Input: Electricity [MJ/kg_{tire}]	3.67	Electricity, medium voltage {SE}| market for | Cut-off, S
Input: Water [kg/kg_{tire}]	2.48	Tap water {Europe without Switzerland}| market for | Cut-off, S
Input: Steam [kg/kg_{tire}]	1.82	Steam, in chemical industry {GLO}| market for | Cut-off, S
Emissions to air: PM [g/kg_{tire}]	25.64	Particulates, SPM
Emissions to air: VOCs [g/kg_{tire}]	0.00053	VOC, volatile organic compounds, unspecified origin
Emissions to water: COD [g/kg_{tire}]	0.18	COD, Chemical Oxygen Demand
Emissions to water: NH4+-N [g/kg_{tire}]	0.02	Ammonia
Emissions to water: suspended solid [g/kg_{tire}]	0.073	Suspended solids, unspecified
Waste: Rubber [kg/kg_{tire}]	0.0002	District heating incineration (described in Section D.1)
Waste: Steel wire [kg/kg_{tire}]	0.0004	Scrap steel {GLO}| market for | Cut-off, S
Waste: tires [kg/kg_{tire}]	0.0077	Described in Section D.1.

Table D.8: Data used to model tread production (per kg tread), based on Sun et al. (2016).

Input/output	**Amount**	**Modeled as**
Input: Electricity [MJ/kg_{tread}]	2.392	Electricity, medium voltage {SE}| market for | Cut-off, S
Input: Water [kg/kg_{tread}]	1.314	Tap water {Europe without Switzerland}| market for | Cut-off, S
Input: Steam [kg/kg_{tread}]	0.101	Steam, in chemical industry {GLO}| market for | Cut-off, S
Emissions to air: PM [g/kg_{tread}]	12.82	Particulates,SPM
Emissions to water: COD [g/kg_{tread}]	0.091	COD, Chemical Oxygen Demand
Emissions to water: NH4+-N [g/kg_{tread}]	0.01	Ammonia
Emissions to water: suspended solid [g/kg_{tread}]	0.036	Suspended solids, unspecified
Waste: Rubber [kg/kg_{tread}]	0.00021	District heating incineration (described in section D.1)

Table D.9: Content in the MK1 diesel, which is assumed to be used in the trucks, and data entries used for each fuel type, based on Energimyndigheten, (2019)

Fuel	**Share (vol%)**	**Modeled as**
Fossil diesel	77%	Diesel {Europe without Switzerland}| market for | Cut-off, S
HVO	17%	Vegetable oil, refined {GLO}| market for | Cut-off, S
FAME	5.5%	Vegetable oil, refined {GLO}| market for | Cut-off, S

Table D.10: Emissions [g/liter] from burning MK1 diesel mix including 4% FAME and 17% HVO, based on Table 7 in (Hallberg et al., 2013), using Euro VI values when available, otherwise Euro V.

	Amount [g]	**Modeled as**
CO_2	2000	Carbon dioxide, fossil
CO	17	Carbon monoxide
NO_x	2	Nitrogen oxides
NMVOC	0.62	NMVOC, non-methane volatile organic compounds, unspecified origin
SO_2	0.005	Sulfur dioxide, {SE}
N_2O	0.21	Dinitrogen monoxide
PM, unspecified	0.07	Particulates, unspecified
CH_4	0.04	Methane

Table D.11: Retreading process data and how these inputs/outputs were modeled in this study. Based on primary data from the retreading company.

	Unit	**Amount as given [unit/23000 retreaded tires]**	**Amount [unit/1 retreaded tire]**	**Modeled as**
Input				
Treads	t	245	0.010652174	See Table D.5 and D.8.
Unvulcanized/raw rubber	t	25	0.001086957	Natural rubber (61.98%), Synthetic rubber (15.07%), Carbon black (17.50%), Organic chemicals (4.20%), Zinc oxide (1.25%)
Cement spray	t	4.24	0.000184348	Heptane {GLO} | market for
Rubber sealer	l	15.04	0.000653913	Chemical, organic {GLO} | market for
Water-based paint	l	2400	0.104347826	Alkyd paint, white, without solvent, in 60% solution state {RER} | market for
Water use				
Water	m3	263	0.011434783	Tap water {Europe without Switzerland} | market for
Energy use				
Electricity	kWh	489619	21.28778261	Electricity, medium voltage {SE}
Emissions to air				
Fumes from cement spray step	t	3.56	0.000154783	Heptane

Table D.12: Transportation data.

			Transport 1		Transport 2 (if applicable)			
Cargo	*Origin*	*Destination*	*Est. distance [km]*	*Ecoinvent dataset*	*Est. distance [km]*	*Ecoinvent dataset*	*Reference and/or explanation of assumption*	
							Transport 1	Transport 2
Transport related to Tire production								
Raw materials	Raw material production plants	Tire production plant	500	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: within a country or nearby region	N/A
Tire	Tire production plant	Truck production plant	1500	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: Europe-Sweden	N/A
Transport related to Retreading								
Raw materials, for tread	Raw material production plants	Tread production plant	500	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: within a country or nearby region	N/A
Tread	Tread production plant	Retreading	1500	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption Europe-Sweden	N/A

Continuation of Table D.12

			Transport 1		Transport 2 (if applicable)			
Cargo	*Origin*	*Destination*	*Est. distance [km]*	*Ecoinvent dataset*	*Est. distance [km]*	*Ecoinvent dataset*	*Reference and/or explanation of assumption*	
							Transport 1	Transport 2
Non-vulcanized rubber	Rubber production plant	Retreading	1500	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption Europe-Sweden	N/A
Other raw materials used in retreading	Raw material production plants	Retreading	1500	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption Europe-Sweden	N/A
Used tire	Tire workshop	Retreading	150	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: Within southern Sweden	N/A
Retreaded tire	Retreading	Workshop/User	150	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: Within southern Sweden	N/A

Continuation of Table D.12

			Transport 1		Transport 2 (if applicable)			
Cargo	*Origin*	*Destination*	*Est. distance [km]*	*Ecoinvent dataset*	*Est. distance [km]*	*Ecoinvent dataset*	*Reference and/or explanation of assumption*	
							Transport 1	Transport 2
Tire scrap	Retreading	Recycling facility	150	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: Within southern Sweden	N/A
Transport related to Tire recycling								
Used tire	Tire workshop	Tire shredding	150	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: Within southern Sweden	N/A
Tire cuts	Cutting plant	Cement kiln	26	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	560	Transport, freight, inland waterways, barge tanker {GLO}| market group for transport, freight, inland waterways, barge tanker | Cut-off, S	(Hallberg et al., 2006) Truck from cutting plant to harbour	(Hallberg et al., 2006) Medium-sized freight ship from one of the cutting plant in Sweden to the island Gotland where the cement factory is located
Tire cuts	Cutting plant	District heating plant	305	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	(Hallberg et al., 2006)	N/A

Continuation of Table D.12

			Transport 1		Transport 2 (if applicable)			
Cargo	*Origin*	*Destination*	*Est. distance [km]*	*Ecoinvent dataset*	*Est. distance [km]*	*Ecoinvent dataset*	*Reference and/or explanation of assumption*	
							Transport 1	Transport 2
Tire cuts (to be used as drainage material or blasting mats)	Cutting plant	Landfill or construction site	200	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	(Alongi Skenhall et al., 2012) Average distance from tire cutting plant to landfill site within Sweden	N/A
Transport replaced materials								
Hard coal	Hard coal production	Cement kiln	3860	Transport, freight train {GLO}| market group for | Cut-off, S	1300	Transport, freight, inland waterways, barge {RER}| market for transport, freight, inland waterways, barge | Cut-off, S	(Hallberg et al., 2006) Train from mine/production site to harbor within Russia	(Hallberg et al., 2006) Medium-sized freight ship from a harbor in Russia to to the island Gotland where the cement factory is located.
Petrol coke	Petrol coke production	Cement kiln	10058	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, S	587	Transport, freight, inland waterways, barge {RER}| market for transport, freight, inland waterways, barge | Cut-off, S	(Hallberg et al., 2006) Large freight ship from New Orleans	(Hallberg et al., 2006) Medium-sized freight ship from Malmö to the island Gotland where the cement factory is located.

Continuation of Table D.12

			Transport 1		Transport 2 (if applicable)			
Cargo	*Origin*	*Destination*	*Est. distance [km]*	*Ecoinvent dataset*	*Est. distance [km]*	*Ecoinvent dataset*	*Reference and/or explanation of assumption*	
							Transport 1	Transport 2
Hard coal	Hard coal production	District heating plant	3860	Transport, freight train {GLO}| market group for | Cut-off, S	1600	Transport, freight, inland waterways, barge {RER}| market for transport, freight, inland waterways, barge | Cut-off, S	(Hallberg et al., 2006) Train within Poland or Russia	(Hallberg et al., 2006) Boat from Poland/Russia to Norrköping
Biomass	Biomass suppliers	District heating plant	254	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	(Hallberg et al., 2006) Within Sweden	N/A
Crushed stone	Crushed stone production	Landfill	300	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	(Hallberg et al., 2006) Within Sweden	N/A
Transport related to Sensor System production								
Electronic components	Component manufacturer	Piezoelectric sensor system manufacturer	20000	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, S	N/A	N/A	Assumption: China to Sweden	N/A

Continuation of Table D.12

			Transport 1		Transport 2 (if applicable)			
Cargo	*Origin*	*Destination*	*Est. distance [km]*	*Ecoinvent dataset*	*Est. distance [km]*	*Ecoinvent dataset*	*Reference and/or explanation of assumption*	
							Transport 1	Transport 2
Electronic components	Component manufacturer	TPMS manufacturer	20000	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, S	N/A	N/A	Assumption: China to Sweden	N/A
Piezoelectric sensor system	Piezoelectric sensor system manufacturer	Tire manufacturer	500	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: Europe to Sweden	N/A
TPMS	TPMS manufacturer	Tire manufacturer	500	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	N/A	N/A	Assumption: Europe to Sweden	N/A
RFID	RFID manufacturer	Tire manufacturer	20000	Transport, freight, sea, transoceanic ship {GLO}| market for | Cut-off, S	N/A	N/A	Assumption: China to Sweden	N/A

Table D.13: Data for Tire Pressure Monitoring System (TPMS).
* Direct communication with the TPMS manufacturer
** Technical datasheet from the TPMS manufacturer (El-watch, 2019)
*** Estimation by authors

Components and their lifetimes, TPMS				
Component	**Count**	**Amount per count**	**Modeled as:** Material [‘Selected EcoInvent entry’]	**Lifetime**
Sensor unit, including casing, battery, and magnet	**1 per new tire****	**35g***	*See per component below*	Limited by battery lifetime***
Sensor unit casing	1 per sensor unit**	5g***	Polyurethane* [‘Polyurethane, rigid foam {RER}’]	-
Sensors	1 per sensor unit**	5g***	Unspecified electronics passive*** [‘Electronic component, passive, unspecified {GLO}’]	-
Battery	1 per sensor unit**	5g***	Li-ion battery***[‘Battery cell, Li-ion {GLO}’]	3-5 years **
Magnet	1 per sensor unit**	20g***	NdFeB*** [‘Permanent magnet, for electric motor {GLO}’]	-
Gateway with 4G, 3G and 2G connection, including casing	**1 per truck****	**200g***	*See per component below*	At least as long as sensor unit lifetime***
Electronics	-	100g***	Unspecified electronics active*** [‘Electronic component, active, unspecified {GLO}’]	-
Casing	-	100g***	Nylon* [‘Nylon 6-6 {GLO}’]	-
Cable	**1 per truck****	**14** meters**	Unspecified cable material*** [‘Cable, unspecified {GLO}’]	At least as long as sensor unit lifetime***

Table D.14: Modeling data for Piezoelectric sensor system
* As reported in Mellquist et al. (2020)
** Estimation by authors

Components and their lifetimes, Piezoelectric sensor system				
Component	**Count**	**Amount per count**	**Modeled as:** Material ['Selected EcoInvent entry']	**Lifetime**
Sensor unit	**1**	**50g****	*See per component below*	Same as tire**
Antenna	2* per sensor unit	5g**	Copper** ['Copper {GLO}| market for']	-
Piezoelectric film sensor	1* per sensor unit	5g**	Unspecified electronics passive** ['Electronic component, passive, unspecified {GLO}']	-
Casing	1** per sensor unit	40g**	Polyurethane** ['Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam']	-
Gateway	**1* per truck**	**300g****	*See per component below*	At least as long as sensor unit**
Casing	1 per gateway	150g**	Polyurethane** ['Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam']	-
Electronics	1 per gateway	150g**	Unspecified electronics active** ['Electronic component, active, unspecified {GLO}']	-
Cable	**1 per truck**	**14** meters**	Unspecified cable material** ['Cable, unspecified {GLO}']	At least as long as sensor unit lifetime**

Table D.15: Data for RFID tag
* As reported in Kanth et al. (2015)
** Estimation by authors

Component	**Count**	**Weight per count**	**Modeled as:** Material ['Selected ecoinvent entry']	**Lifetime**
RFID tag	**1 per new tire and 1 per added tread**	**10g****	*See per component below*	Same as tire**
Antenna	1 per RFID tag	1.22 g*	*See per component below*	Same as tire**
Substrate	1 per antenna	0.98 g*	Plastic film* ['Extrusion, plastic film {GLO}']	Same as tire**
Ink	1 per antenna	0.24 g*	Silver Ink* ['Silver {GLO}']	Same as tire**
Chip	1 per RFID tag	4.4 g**	Unspecified electronics passive** ['Electronic component, passive, unspecified {GLO}']	Same as tire**
Casing	1 per RFID tag	4.4 g**	Polyurethane** ['Polyurethane, rigid foam {RER}']	Same as tire**

Table D.16: Data used to model energy requirements of the added technology in the IoT scenario
* Technical datasheet from TPMS manufacturer (El-watch, 2019)
** Estimation by authors
*** As reported in Pihkola et al. (2018)
**** As reported in Baliga et al. (2010)

	Assumption	**How total was calculated**	**Unit**	**Modeled as**
Energy requirements data collection by sensors	1W typical power*	$1/1000[kW]$ · total hours in use$[h]$	kWh	Electricity, low voltage {SE}]
Gateway energy requirements for data transfer	Sends data every 2 minutes via 4G LTE network*	$\frac{1}{2}$*[transfers/minute] · 4**[bytes/transfer] · 10^{-9} [GB per byte] · 0.3***[kWh/GB]*** · total minutes or tire use [minutes]	kWh	[Electricity, low voltage {SE}]
Cloud-side energy requirements	Sends data every 2 minutes*, 4 bytes per transfer**	Equation D.1****	kWh	[Electricity, medium voltage {SE}]

$$E_{cloud} = \frac{B_d \cdot D}{3600}\left(E_T + 1.5\frac{P_{st,SR}}{C_{st,SR}}\right) + 2B_d\frac{1.5P_{SD}}{B_{SD}}\,[\text{W}] \cdot \text{total hours of tire use [h]} \qquad \text{(D.1)}$$

where

- B_d is the number of bits transferred per second, estimated as $B_d = \frac{1}{2}$* [transfers/minute] · 1/60 [minutes/second] · 4** [bytes/transfer] · 8 [bits/byte] = 0.267 [bits/s].
- D is number of downloads/uploads per hour, i.e., 30* [transfers/hour] based on.
- E_T is the cloud-side energy needed to transfer of 1 bit, estimated to 2.7**** [μJ/bit].
- $P_{st,SR}$ is the power consumption of a ‘content server’, estimated to 0.225**** [kW].
- $C_{st,SR}$ is the capacity of the content server, estimated to 800**** [Mbits/s].
- P_{SD} is the power consumption of the hard disk arrays, estimated to 4.9**** [kW].
- B_{SD} is the capacity of the hard disk arrays, estimated to 604.8**** [Tbits].

REFERENCES

S. Alongi Skenhall, L. Hallberg, and T. Rydberg (2012), *Livscykelanalys på återvinning av däck - Jämförelser mellan däckmaterial och alternativa material i konstgräsplaner , dräneringslager och ridbanor*, IVL Svenska Miljöinstitutet. Available from: https://www.sdab.se/media/1066/lca_livscykelanalys.pdf.

J. Baliga, R. W. A. Ayre, K. Hinton, and R. S. Tucker (2010). Green Cloud Computing: Balancing Energy in Processing, Storage and Transport. *Proceedings of the IEEE* **99**, 149.

Cementa (2018), *Färdplan cement för ett klimatneutralt betongbyggande*, Cementa AB. Available from: https://www.cementa.se/sv/fardplancement.

El-watch (2019), The Neuron Tyre Health System, https://www.el-watch.com/wp-content/uploads/2019/11/THS-Facts-EN-08.pdf [accessed 2020-08-19].

Energimyndigheten (2019), *ER 2019:14 Drivmedel 2018*, Energimyndigheten. Available from: http://www.energimyndigheten.se/statistik.

Eon (2011), *Med värme från Händelö kraftvärmeverk*, Eon.

L. Hallberg, T. Rydberg, L. Bolin, L. Dahllöf, H. Mikaelsson, E. Iverfeldt, and J. Tivander (2013), *Well-To-Wheel LCI Data for Fossil and Renewable Fuels on the Swedish market*, f3 the Swedish Knowledge center for renewable transport fuels. Available from: www.f3centre.se.

L. Hallberg, K. Stromberg, T. Rydberg, and E. Eriksson (2006), *Comparative life cycle assessment of the utilisation of used tyres*, CIT Ekologik AB & IVL Svenska Miljöinstitutet AB.

R. K. Kanth, P. Liljeberg, H. Tenhunen, H. Tenhunen, L. R. Zheng, Y. Amin, and H. Kumar (2015), Study on sustainability and life cycle assessment of RFID antenna, in *Environmental Engineering and Computer Application - Proceedings of the International Conference on Environmental Engineering and Computer Application, ICEECA 2014*, Hong Kong.

A.-C. Mellquist, C. Johansson, C. Jonasson, D. Diener, F. Norefjäll, M. Linder, P. Altmann, and T. Nyström (2020), *Circular economy in a business eco-system: Integrated sensors and new recycling technology for heavy vehicle tyres*, RISE AB, Gothenburg, Sweden. Available from: https://www.ri.se/en/what-we-do/projects/circular-business-ecosystem-sensors-and-recycling-heavy-vehicle-tyres.

H. Pihkola, M. Hongisto, O. Apilo, and M. Lasanen (2018). Evaluating the Energy Consumption of Mobile Data Transfer From Technology Development to Consumer Behaviour and Life Cycle Thinking. *Sustainability* **10**, 2494.

Ragnsells Däckåtervinning AB (2019), Ragn-Sells stänger produktionen av granulat på Heljestorp, https://www.mynewsdesk.com/se/ragnsells/pressreleases/ragn-sells-staenger-produktionen-av-granulat-paa-heljestorp-2908828 [accessed 2020-10-14].

Ragnsells Däckåtervinning AB (2019), Däckets väg i återvinningsprocessen, https://www.ragnsellstyrerecycling.com/article-startpage/dackets-vag-i-atervinningsprocessen/ [accessed 2020-10-14].

SDAB (2019), Uttjänta däck har mycket kvar att ge, https://www.sdab.se/newsletter/news-mars-2019/uttjaenta-daeck-har-mycket-kvar-att-ge/ [accessed 2020-04-24].

X. Sun, J. Liu, J. Hong, and B. Lu (2016). Comparative life cycle assessment of chinese radial passenger vehicle tire. *International Journal of Life Cycle Assessment* **21**, 1749

ACKNOWLEDGEMENTS

Thank you,

to Ella Jamsin and Ruud Balkenende, for guidance, encouragement, and countless hours spent reading my drafts,

to all my colleagues in Design for Sustainability, Sustainable Design Engineering, and beyond, for good company and support,

to everyone in the Circ€uit program for creating a fun and inspiring community,

to Marianna Lena Kambanou, Tomohiko Sakao, Gerd Kortuem, and Nancy Bocken, for fruitful collaboration and discussions,

to Diana Gonzalez, Helen Nieuweboer, Yihan Zhao, Julieta Bolaños Arriola, David de Witt, and Nilesh Nahar, for learning about this topic together with me through interesting graduation projects,

to the Sustainable Business group at RISE Sweden, for letting me take part in the tire project,

to the Industrial Ecology group at the CML institute in Leiden, for hosting me during my research secondment and for valuable advice on LCA methodology,

to all the participants in my studies, for sharing their time and experiences, and for teaching me the intricacies of lighting systems, heat pumps, forklifts, industrial robots, and truck tires,

to Vivian Tunn, Christoph Lofi, Maitê Freire de Medeiros, Mark Fiorentino, Claudia Szerakowski, Katja Obieglo, Monika Zajda, Rachel Greer, Rishab Ghotge, Susanne van Aardenne, and Vítor Pinheiro, for all the memories next to the PhD,

to Anastasia Wraa, for welcoming me when I arrived in Delft the very first time,

to Nils Grashorn, Yoanna Ohlson Yokoyama, Matthew Stogsdill, and Astrid Berghult for visiting me in Delft when it didn't really feel like home yet,

to Anneli Kamb, Daniel Böckin and Julia Sandén, for being part of this journey from the beginning and for continuing to be dear friends and inspiring sustainability champions,

to Maria Birck, Anna Martin, Ebba Söderström, Malin Faremo, Elsa Ramström, and Louise Hagblom, for perspective, good laughs, and lifelong friendship,

to my family, for love and constant support.

CURRICULUM VITÆ

Emilia Ingemarsdotter, born on the 14th of January 1990, in Partille, Sweden.

2009–2015	MSc in Engineering Physics & Industrial Ecology, Chalmers University of Technology, Gothenburg, Sweden. MSc thesis: D. Böckin & E. Ingemarsdotter (2015), *Foresight into emerging power system architectures, A scenario of maximised self-consumption in Sweden.* (supervised by Prof. Björn Sandén).
2014–2015	Project Assistant, Environmental Systems Analysis, Chalmers University of Technology, Gothenburg, Sweden. Publication: M. Ljunggren Söderman & E. Ingemarsdotter (2014) *Use and recycling of potentially critical materials. An overview.* (in Swedish)
2015–2016	Graduate Trainee, ABB, Västerås, Sweden.

LIST OF PUBLICATIONS

Manuscripts

- **E. Ingemarsdotter**, D. Diener, S. Andersson, C. Jonasson, A-C. Mellquist, T. Nyström, E. Jamsin, R. Balkenende (in review) Quantifying the Net Environmental Impact of Using IoT to Support Circular Strategies —The Case of Heavy-Duty Truck Tires in Sweden. *Circular Economy and Sustainability* **xx**, xx.
- **E. Ingemarsdotter**, M. L. Kambanou, E. Jamsin, T. Sakao, R. Balkenende (in review) Challenges and Solutions in Condition-Based Maintenance Implementation —A Multiple Case Study. *Journal of Cleaner Production* **xx**, xx.

Journal articles

- **E. Ingemarsdotter**, E. Jamsin, R. Balkenende (2020) Opportunities and Challenges in IoT-enabled Circular Business Model Implementation —A Case Study. *Resources, Conservation and Recycling* **162**, 105047.
- **E. Ingemarsdotter**, E. Jamsin, G. Kortuem, R. Balkenende (2019) Circular Strategies Enabled by the Internet of Things —A Framework and Analysis of Current Practice. *Sustainability* **11**, 5689.

Conference articles

- **E. Ingemarsdotter**, E. Jamsin, R. Balkenende (2018) How Can IoT Support Circular PSS Design and Implementation? A Case Study of LED Lighting Systems. in *R&D management Conference - R&Designing Innovation: Transformational Challenges for Organizations and Society* Milan, Italy.
- **E. Ingemarsdotter**, D. Diener, S. Andersson, C. Jonasson, A-C. Mellquist, T. Nyström, E. Jamsin, R. Balkenende (2020) Quantifying the Impacts and Benefits of Using IoT to Support Circular Strategies —The Case of Heavy-Duty Truck Tires in Sweden. in *Proceedings of the Inaugural Conference of the International Society for the Circular Economy (2020)* (online).

Book chapters

- N. Bocken, **E. Ingemarsdotter**, D. Gonzalez (2017) *Designing Sustainable Business Models: Exploring IoT-enabled Strategies to Drive Sustainable Consumption*, In: Aagaard A. (eds.) Sustainable Business Models. Palgrave Studies in Sustainable Business in association with Future Earth.