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Opportunities and challenges in IoT-enabled circular business model implementation – A case study

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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.

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 utilisation 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

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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, organisations 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 organisation that has popularised and spread the CE concept, has published two reports on the topic (Ellen MacArthur Foundation, 2016; Ellen MacArthur Foundation et al., 2019).

However, the opportunities of IoT for CE as presented in literature (summarised in Section 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 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.

2. Background

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 utilisation, 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 Table 1. In this paper, we use this framework to represent the 'theoretical opportunities' of using IoT for CE.

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 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) summarised 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

Table 1
Framework categorizing 'IoT-enabled circular strategies', from Ingemarsdotter et al. (2019).

	Circular strategies					
	In-use strategies			Looping strategies		
IoT capabilities	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.*
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.*						

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. 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.

3.1. 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 additonal criterion used for selecting the particular case was that it provided sufficient access to data. In Section 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.

3.2. 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 A1 in the Appendix 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 A2 in the Appendix. 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 Table 1.

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 summarise 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 analysed 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 A3 and A4 in the Appendix. We also mapped the opportunities mentioned by the interviewees in relation to the ‘theoretical opportunities’. To assess the validity of the conclusions drawn from analysing the interviews, representatives from the company read and commented on a draft of this paper.

4. The case and its context

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

Table 2
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 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 redesign to reduce faults.

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 analysed 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.

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 5.

5. Results

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 summarised in Table 2 and explained below. Table 3 displays the already implemented IoT-enabled circular strategies in the food retail segment (as presented in Section 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 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.

Table 3
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).

	Circular strategies					
	In-use strategies			Looping strategies		
IoT capabilities	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			

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.

5.2. Challenges associated with implementing IoT-enabled circular strategies

The challenges found are explained below, and summarized in Table 4. Although the focus of this study was preliminary 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 4, 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

Table 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 interviewees
IoT-specific challenges	Data quality and 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.

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.

6. Discussion

In this section, we relate our findings to previous literature about IoT as an enabler for CE (Section 2.1) and barriers to circular business model implementation (Section 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.

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-orientated 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 categorisation 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 categorisation 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 Table 5, the following four categories of theoretical opportunities were not considered in the case: (1) optimisation and design evolution for efficiency in use, (2) IoT-enabled increased utilisation, (3) control, optimisation, 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 utilisation was not seen as relevant in the studied context, because no utilisation 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.

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

Table 5
The four types of theoretical opportunities not considered in the studied case are shown in grey:
(1) optimisation and design evolution for efficiency in use, (2) IoT-enabled increased utilisation, (3) control, optimisation, and design evolution for reuse and remanufacturing, and (4) IoT-enabled recycling. Framework based on Ingemarsdotter et al. (2019).

<table>
<tr><th rowspan="3" colspan="2"></th><th colspan="6">Circular strategies</th></tr>
<tr><th colspan="3">In-use strategies</th><th colspan="3">Looping strategies</th></tr>
<tr><th>Efficiency</th><th>Increased utilisation</th><th>Product lifetime extension</th><th>Reuse</th><th>Remanufacturing</th><th>Recycling</th></tr>
<tr><th rowspan="5">IoT capabilities</th><th>Tracking</th><td>X</td><td rowspan="5">2</td><td>X</td><td>O</td><td>O</td><td rowspan="5">4</td></tr>
<tr><th>Monitoring</th><td>X</td><td>O</td><td>O</td><td>O</td></tr>
<tr><th>Control</th><td>X</td><td>O</td><td rowspan="3" colspan="2">3</td></tr>
<tr><th>Optimisation</th><td rowspan="2">1</td><td>O</td></tr>
<tr><th>Design Evolution</th><td>O</td></tr>
</table>

cannot be directly transferred to different contexts. A discussion about the generalisability 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 2.2, 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.

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 servitised 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 analysing the data, and lead the writing process. E.J. and R.B. supervised the research and contributed to writing and reviewing the paper internally.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix

Tables A1–A4

Table A1
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		2017–09–29	60 min	Int-3
Circular Economy		5			
	Sustainability strategy manager		2017–09–29	50 min	Int-4
	Marketing manager		2017–09–14 (video link)	50 min	Int-5
	Product manager		2017–09–29	40 min	Int-6
	R&D manager		2017–10–05	70 min	Int-7
	Product designer		2017–09–15	50 min	Int-8
Internet of Things		4			
	Business developer		2017–09–29	50 min	Int-9
	Data-enabled services manager		2017–09–13 (video link)	70 min	Int-10
	Research manager		2017–09–29	60 min	Int-11
	Data scientist		2017–09–15	50 min	Int-12

Table A2
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? • What are challenges/focus areas from your perspective for development in food retail?
	Current level of implementation of CE and IoT	• 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 A3
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 interviewees	Example quotes
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.	*"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 supports maintenance	• IoT enables detailed record keeping of installed products and parts, facilitating maintenance and adaptations. • IoT enables condition-based and predictive maintenance.	*"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)*
	IoT supports reuse and/or remanufacturing	• IoT enables tracking of used products, parts and materials. • IoT enables better estimations of remaining lifetime.	*"One of the key elements in CE is residual value … Currently, it is very difficult to determine residual value. We do not know what the product has done, how much it has been used, how has it been used, how it performs currently. But with IoT I believe that we could measure in real time what is happening to our products. Then we could calculate residual value fairly easily and thereby close a lot of risk if we want to reuse certain elements of that product." (Int-I5)*
	IoT supports design for durability	• Data about products' condition in the field can inform product redesign to reduce faults.	*"You can also use it* [the data] *internally. It tells you something about your design or the quality of your product internally. If you see that a certain part breaks sooner or more often than others, then you might improve that one."(Int-12)*

Table A4
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 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. • Not always clear which data set originated from which product. • Lack of data about which luminaires actually failed in the field (labelled data).	*"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)* *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)*
	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 lifecycles 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)*
	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)*

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