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Review

Opportunities and risks of internet of things (IoT) technologies for circular business models: A literature review

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ABSTRACT

In recent years, circular business models (CBM) have become an inevitable requirement to foster improvements in environmental performance. However, the current literature rarely discusses the link between Internet of Things (IoT) and CBM. This paper first identifies four IoT capabilities including monitoring, tracking, optimization and design evolution for improving CBM performance based on the ReSOLVE framework. In a second step, a systematic literature review using the PRISMA approach analyzes how these capabilities contribute to 6 R and CBM through the CBM-6R and CBM-IoT cross-section heatmaps and relationship frameworks, followed by assessing the quantitative impacts of IoT on potential energy saving in CBM. Finally, challenges are analyzed for the realization of IoT-enabled CBM. The results show that the assessments of *Loop* and *Optimize* business models dominate current studies. IoT plays a significant role in these business models respectively through tracking, monitoring and optimization capabilities. While (quantitative) case studies for *Virtualize*, *Exchange* and *Regenerate* CBM are substantially needed. IoT holds the potential to reduce energy consumption by around 20–30% for referenced applications in the literature. However, the IoT hardware, software and protocol energy consumption, interoperability, security and financial investment might become main obstacles for the wider use of IoT in CBM.

1. Introduction

1.1. Key concepts and a brief history of the IoT

Since the birth of the internet in the early 1980s, attempts have been made to connect “Things” with the internet. In 1990, John Romkey created the first Internet ‘device’, a toaster that could be turned on and off via the Internet (Romkey, 2017). Paul Saffo gave the first brief description of sensors and how they could be used in connection with the internet in 1997 (Saffo, 1997). To describe this growing connection of sensors and similar devices providing real-time information via the internet, in 1999 the term “Internet of Things” was coined by Kevin Ashton, who was working in supply chain optimization and invented a new technology called Radio-frequency identification (RFID)-based item identification in the same year (Suresh et al., 2014). In 2003, Walmart deployed RFID in all its shops across the globe to measure product stocks and sales and support supply chain management (Harold, 2007). In 2005, International Telecommunication Union (ITU, 2005) regarded the IoT as a third wave of the world’s information industry transformation. In 2008, the Federal Communications Commission approved the usage of the “white space spectrum” (Suresh et al., 2014). Later, IT giants like Cisco, IBM and Ericsson took a lot of educational and commercial initiatives with IoT. Some countries, like China, listed the IoT as a strategic emerging technology in their long-term plans (MIIT, 2012).

The IoT technology can be simply explained as a connection between humans - computers - things. It uses RFID, infrared sensors, global positioning systems, laser scanners and other information-sensing equipment to connect any item under internet protocol (IP) with a unique IP address for information exchange and communication, which can achieve intelligent positioning, tracking, monitoring and management of items. The systems architecture can, for instance, be based on the context of operations and processes in real-time scenarios. For instance, in a smart home, every electrical switch box could be connected with a smart phone so that it could be operated remotely. The HarmonyOS system recently created by Huawei uses full stack

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decoupling architecture that could even solve constraints issues on the boundary of software and hardware, thus making it possible for other collaborators to join the system (Chen and Matt, 2021). Altogether, the application boundary of the IoT has been expanded considerably. Such a scenario does not need a processor and a storage device installed in every switch box. It just needs a sensor to capture signals and process them (mostly switching ON/OFF).

1.2. *Potentials by IoT technologies in CE in a finite world*

Avoiding overshooting of planetary boundaries for climate change (Rockström et al., 2009) and switching to more sustainable practices are among the greatest challenges of the 21st century. Any approach to reduce pressures requires simultaneous consideration of economic, social, and especially environmental aspects of industrial processes, as well as respective interactions along cradle-to-grave value chains of products and services (Ren et al., 2013). Important strategies to reduce critical raw material use are sustainable supply chain management (SSCM) and circular usage of products and materials (Manavalan and Jayakrishna, 2019). Seuring and Müller (2008) defined SSCM as “the management of material, information and capital flows as well as cooperation among companies along the supply chain, while taking goals from all three dimensions – environmental, economic and social into account which are derived from customer and stakeholder requirements.”

Circularity adds a different perspective to SSCM as it tries to keep substances in closed loops. Unlike a linear economy that is based on a “take-make-dispose” model, CE promotes longevity, reparability, durability and recyclability of products with the aim of a full re-use of resources (Elisha, 2020). It therefore symbolizes a linear to loop transition for supply chains in sustainability (Schröder et al., 2019). In the industry 4.0 (I4.0) era, the IoT offers opportunities to foster CE in value chains through real-time monitoring of the resources inventory (Mohammadian, 2019). It can support the minimization of waste flows through product lifetime detection. As consequence material reuse and recycling processes can be optimized. In summary, IoT promotes a highly accurate, efficient and sound use of resources aimed at the shift from disposable to renewable resources paradigm, and facilitates the born and development of CBM (Ghisellini et al., 2016; Nižetić et al., 2020). Therefore, progress of IoT-enabled CBM has attracted academic researches, which have recently assessed the impact of I4.0 technologies such as IoT on CBM with different conclusions (Rosa et al., 2019, 2020). They discussed CBM and IoT from economic, social and environmental perspectives (Govindan and Hasanagic, 2018; Ding et al., 2023). Rejeb et al. (2022) reviewed how the IoT provides contributions and challenges in the CBM domain. They identified important drivers and provided a structured framework that exploring business and management-focused CE strategies based on IoT technologies.

However, there is still a large gap between theory and practice (Gorissen et al., 2016). In particular, most small and medium enterprises (SMEs) are encountering unprecedented pressure to improve environmental performance. Since the adoption cost of the IoT could be tremendous, they might hesitate to seize IoT-enabled emission reduction opportunities based on their specific status (Ding et al., 2023; Awan et al., 2022a). This requires an in-depth understanding of the IoT capabilities and the characteristics of different CBMs to find their best intersection point. Besides, the circularity of IoT devices themselves should also be considered (Beier et al., 2018). Given these research gaps this paper addresses the following research questions.

i) What are the (synergy) contributions of IoT capabilities under different CBM?
ii) What are the carbon emission reduction potentials of the IoT in different CBM?
iii) What are the obstacles for SMEs to adopt IoT in promoting circular strategies?

The contributions of this paper are as follows: We used a pre-defined circular business framework (ReSOLVE) developed by Ellen MacArthur Foundation (EMF, 2015) to analyze the CBM-IoT context and linked it to 6 R principles to specifically map the IoT capabilities into each business practices. This visualizes how IoT contributes differently in each business model and provides information for us to describe the relationship between IoT capabilities, 6 R and CBM. Additionally, we quantitatively review the literature on how IoT can contribute to reducing environmental impacts under CBM and identify their obstacles.

This paper proceeds as follows. Section 2 introduces the Prisma methodology we used as the method for the literature review, and the reasoning of paper selection. Section 3 reviews IoT’s role in CE, introduces the capabilities of IoT correlated with CBM and identifies its environmental opportunities. Section 4 reflects on potential obstacles for IoT adjustment in CBM. Section 5 comprehensively summarizes our findings and concludes. Finally, section 6 outlines limitations and gives recommendations for future research.

2. Review approach: Prisma

2.1. *Introduction of Prisma*

In June 2022, we conducted a literature search based on the checklist framework provided by the PRISMA-P guidelines (Moher et al., 2015). PRISMA was initially used in the medical field. Although other methods for conducting literature reviews and meta-analyses are available (Horvathova, 2012; Luederitz et al., 2016), PRISMA guidelines have become widely accepted as an approach to conduct transparent literature reviews. Recently they have been applied in the field of sustainability and CE research (Blanco et al., 2020; Jin et al., 2019; Zalk and Behrens, 2018; Aguilar-Hernandez et al., 2021). The latest PRISMA Abstract 2020 (Page et al., 2021a,b) suggests discussing 5 main items in relation to 10 subcategories in a review. We refer to the checklist items listed in Table 1.

2.2. *Classification of papers*

We use the 6 R concept (Joshi et al., 2006) to initially classify circularity strategies and related business models, as shown in Fig. 1. The 6 R concept discerns Reuse, Recycle, Reduce, Repair, Remanufacture and Redesign. Sihvonen and Ritola (2015) regarded the 6 R framework as the operational approaches and core principles of CE. Report of Ellen MacArthur Foundation (EMF, 2013) pointed out that discovering new paths to support CE under 6 R guidance – “an industrial system that is restorative or regenerative by intention and design” is becoming more and more vital against the background of Industrial 4.0 era. From a systems perspective, the combination of six operational approaches (6 R) enables new business models of CE at the macro level (Kirchherr et al., 2017).

Based on these characteristics, the ReSOLVE framework further explains CE – Preserve and enhance natural capital, optimize resource yields and foster system effectiveness, and classifies circular models based on the economic and resource impacts of major sectors (EMF, 2015). It offers a tool for generating circular strategies and growth initiatives. Jabbour et al. (2018) then connected Industry 4.0 technologies to six CBM proposed by the ReSOLVE framework, namely Regenerating, *Share*, *Optimize*, *Loop*, *Virtualize* and *Exchange*, to guide organizations

Table 1
Major steps in Prisma Abstract 2020 (Page et al., 2021a,b).

Section and Topic	Item #	Checklist item
TITLE		
Title	1	Identify the report as a systematic review.
BACKGROUND		
Objectives	2	Provide an explicit statement of the main objectives or questions.
METHODS		
Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review.
Information sources	4	Specify the information sources (e.g., databases, search terms) used to identify studies.
Risk of bias	5	Specify the methods used to assess risk of bias in the studies included.
Synthesis of results	6	Specify the methods used to present and synthesize results.
RESULTS		
Included studies	7	Give the total number of studies included and participants and summarize relevant characteristics of the studies.
Synthesis of results	8	Present results for main outcomes, preferably indicating the number of studies included and participants for each. If a meta-analysis was carried out, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e., which group is favoured).
DISCUSSION		
Limitations of evidence	9	Provide a brief summary of the limitations of the evidence included in the review (e.g., study risk of bias, inconsistency and imprecision).
Interpretation	10	Provide a general interpretation of the results and important implications.

These categories explain the search objectives and eligibility criteria, including the methods and reasons for including and excluding certain records (i.e. some papers do not contain the keywords checked for but have keywords with similar meanings, some papers contain the keywords but do not explain them in detail). Second, it describes the steps of the quantitative analysis, which includes collecting data from selected publications and harmonizing their values. Based on this framework, this literature review was conducted.

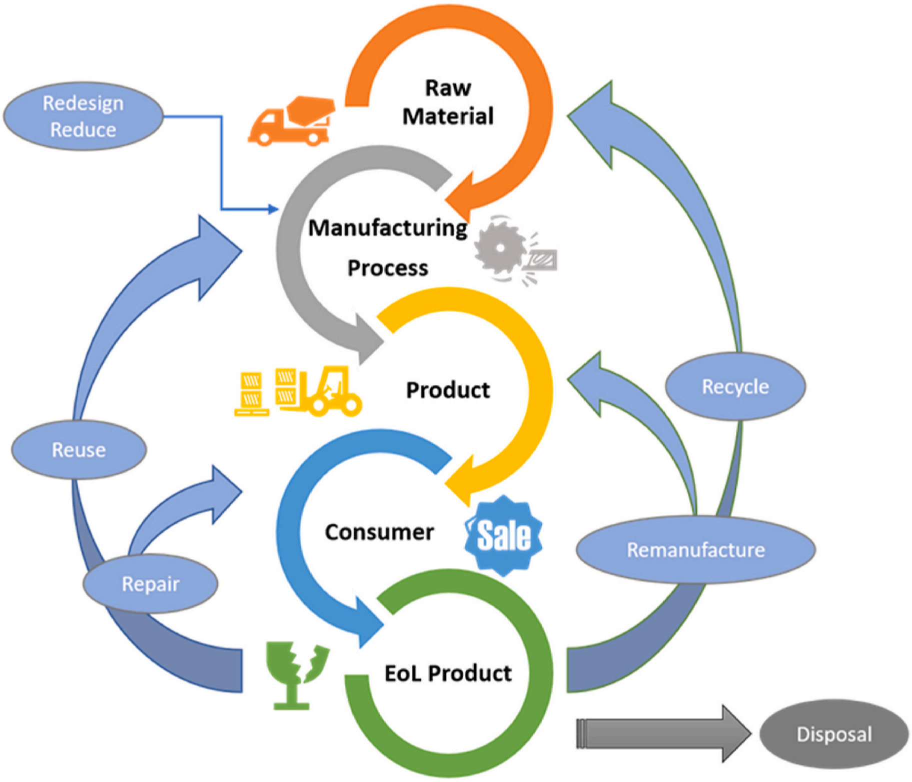

Fig. 1. 6 R to achieve CE goals (Chau et al., 2021).

through implementing the principles of the CE (EMF, 2015), as shown in Table 2. Most technologies own opportunities in specific areas, while the IoT can play a significant role to make such business models viable (Jabbour et al., 2018).

While the exact terminology to describe IoT-related capabilities varies under different scenarios, we synthesized core capabilities of the technology as found in literature. Ingemarsdotter et al. (2019) suggests that IoT's can support the development of circular business models via capabilities such as tracking, monitoring, control, optimization and design evolution, and stated that optimization often relies on the use of control capability. Therefore, we incorporated the control capability into optimization to reduce the list of relevant IoT capabilities to four, as shown in Table 3.

Table 2

Explanation of six business models in ReSOLVE framework.

Business models	Explanation
Regenerate	This business model is based on a shift to renewable energy and materials. Biological cycles are used to enable the circulation of energy and materials, and to convert organic waste into sources of energy and raw material for other chains.
Share	Assets are shared between individuals (peer-to-peer sharing of privately owned products or public sharing of a pool of products). As a consequence, products should be designed to last longer by the producers, and maintenance should be available to allow the re-use and extension of product life.
Optimize	This business model requires organizations to use digital manufacturing technologies, such as IoT, automation, and big data to reduce waste in production systems across supply chains. As a result, organizations will benefit from increased performance.
Loop	This business model aims to promote the circularity of raw materials and energy. The design, production, and supply chain therefore have to be adjusted from the perspective of the entire life cycle.
Virtualize	This business model is service-focused which replaces physical with virtual and dematerialized products.
Exchange	It involves substituting old and non-renewable goods for advanced and renewable ones.

Table 3

IoT capabilities that can support implementation of the ReSOLVE framework.

IoT capabilities	Definition of functions
Tracking	Available information for products' identity, location, or unique composition.
Monitoring	Available information for products' real-time condition, or environment. This includes alerts and notifications.
Optimization	Goal-based improvements of operations are controlled and optimized by using advanced algorithms.
Design Evolution	The design of a product can be upgraded based on data feedback from other lifecycle phases. This includes functional or routing upgrades.

2.2.1. *Selection of papers*

On the basis of the discussion above, in order to systematically review the contribution of the IoT to circular economy business models, we used the following terms as a basis for the literature search in a Boolean operation – Title, Abstract, Keyword = ["internet of things" AND ("circular economy" OR "circular business model" OR "sustainable supply chain")]. In total, there were 432 papers available on Scopus and 142 papers available on Web of Science (WoS). We excluded duplicate records and papers that have no relation to any elements of the 6 R through browsing abstracts. Then, we further excluded papers with non-

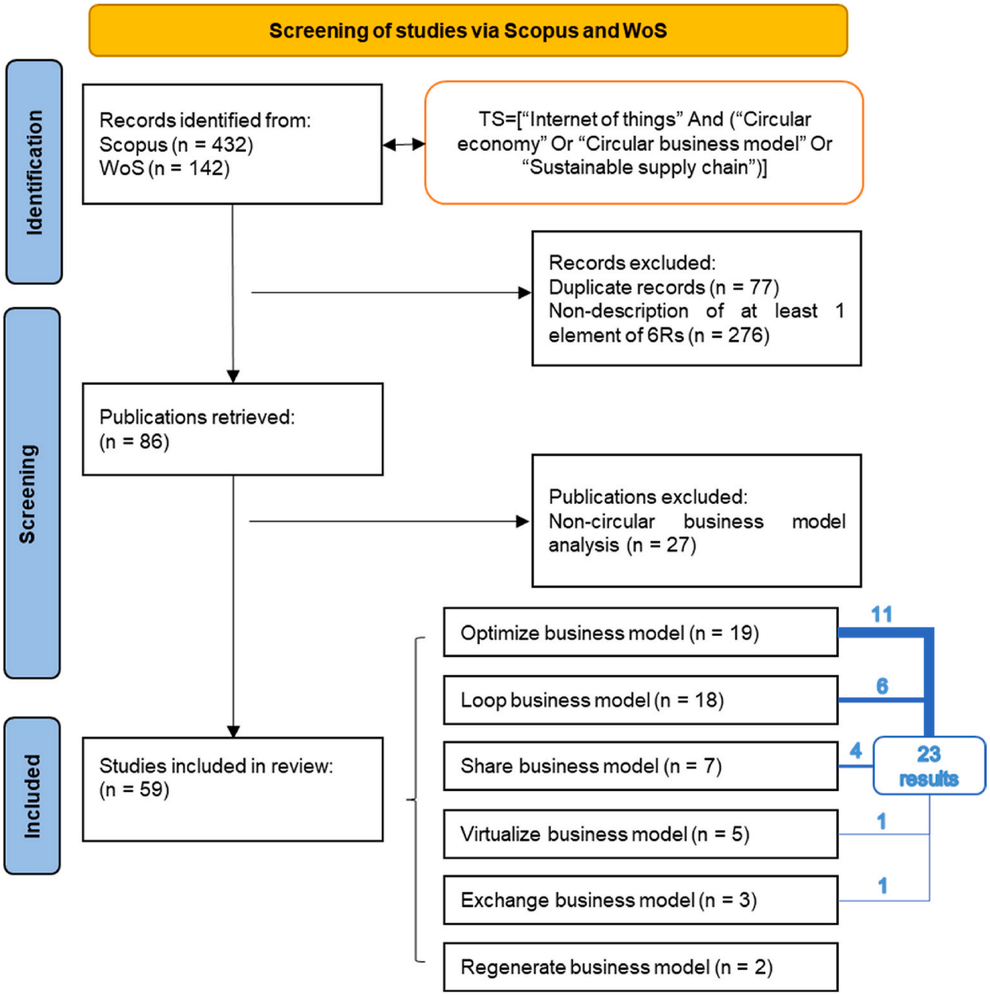

Fig. 2. Flowchart of selected publications in the review (status in June 2022).

CBM descriptions discerned in the RESOLVE framework after browsing the full texts. In this way, 59 papers were retained to explore the contribution of the IoT to CBM, see Fig. 2.

Then, a quantitative analysis of how the IoT reduces environmental impacts in CBM was conducted. For this, from the included papers we acquired 23 results that a) quantified impacts on energy-related indicators in circular economy (e.g., energy use or CO2 emissions) and b) compared these impacts before and after using IoT technology.

3. Review: impacts of the IoT on CBM

3.1. Descriptive results

The retrieved 59 papers used for describing the contribution of the IoT to CBM can be categorized by journal, year of publication, and sector/application.

Fig. 3 shows the number of articles published in different journals under the given search term and constraints. The number of papers published in the *Journal of Cleaner Production*, *Sustainability* and *Computers in Industry* appears to dominate. These journals make up 25.5% of the total share, which is much higher than that of other journals. The core fields covered by these journals include computer science, engineering and environmental science. The number of papers has increased significantly over time. Publications in the last 3 years occupy exceed 2/3 of the total share, which indicates a growing interest on this topic.

Next, we use the framework developed by Maroli et al. (2021) to classify 59 papers into 4 major categories: reviews, theory studies, new designs and case studies. Reviews include pure review articles that classify and summarize previous studies. Theory studies generally analyze and discuss the proposed new framework for specific issues mainly based on surveying experts (Delphi) or questionnaires. New designs imply the development of a new mathematical model or a new protocol design for an IoT solution but without a real case to verify factual feasibility. Case studies further calculate or simulate the case and obtain reference results based on real or defined cases compared with the new design. A brief supplementary description of each article is also attached to this table to provide an overview of each research division.

These classified papers are then categorized into six business models suggested by ReSOLVE framework (EMF, 2015). As shown in Fig. 4.

Over 60% of the papers describe the contribution of IoT to *Loop* and *Optimize* models. Both of these two models have higher potential impacts on manufacturing, transportation and storage, and IoT could thus promote significant business transformation within these sectors (EMF, 2015).

As for *Optimize*, IoT helps to realize smart manufacturing and SSCM through improving decision-making plans to reduce the consumption of energy and resources. Most of the theoretical studies here explored and developed frameworks for low carbon footprints in different industries based on IoT capabilities of collecting, processing information more efficiently (Gružauskas et al., 2018; Chit et al., 2021; Ghoreishi and

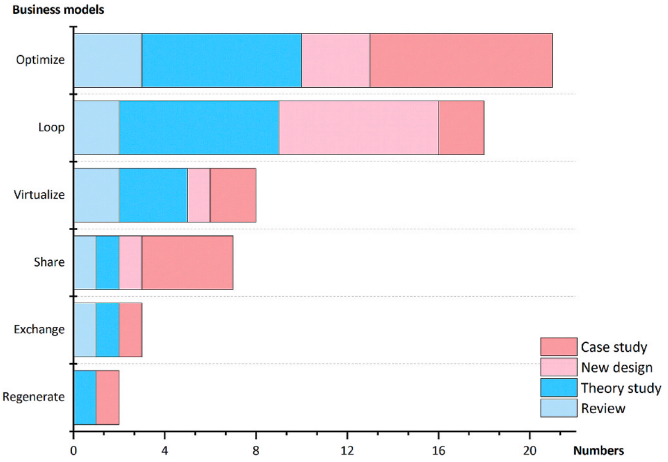

Fig. 4. Division of publications into the 6 ReSOLVE categories of CE business models.

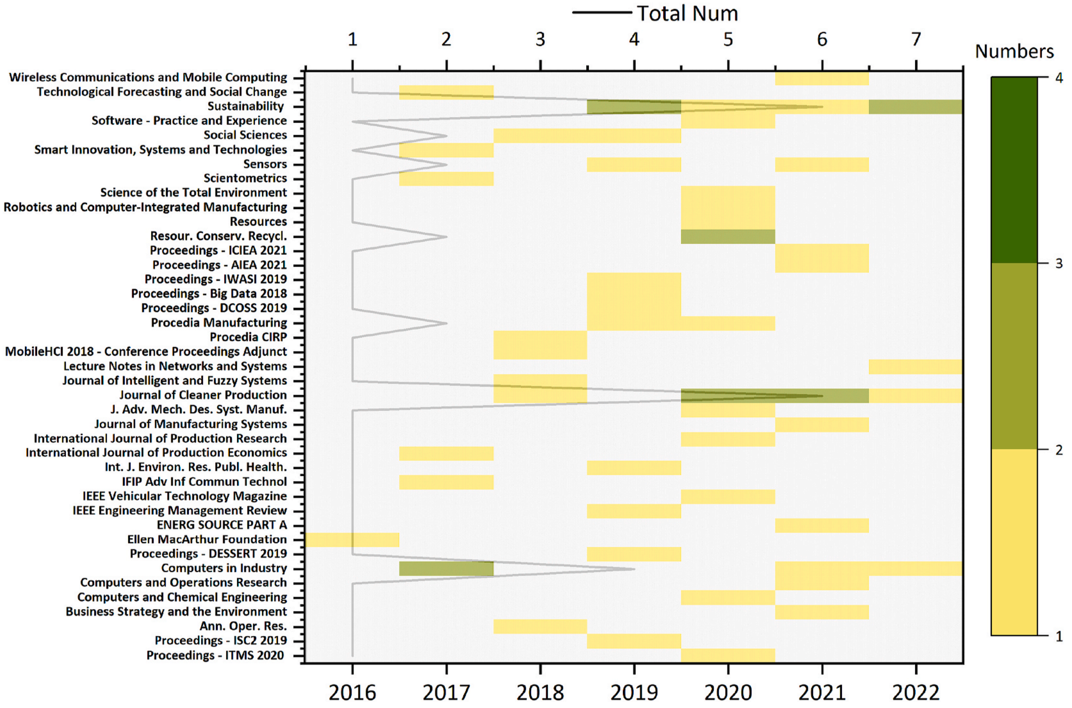

Fig. 3. Numbers of IoT publications in different types of journals.

Happonen, 2022; Jagtap et al., 2021). The limited number of cases and new designs are usually process optimizations in enterprises, where IoT is used to develop intelligent production scheduling and logistics delivery models to promote green and sustainable development of intelligent manufacturing (Liao and Wang, 2019).

In the *Loop* business model, most studies focused on waste management. Here, IoT is mainly used to realize waste collection optimization and more accuracy of decision support system for end-life products recycling (Bányai et al., 2019; Velvizhi et al., 2020; Al-Masri et al., 2018). Some theoretical studies designed CE–IoT-enabled ecosystems based on key enabling IoT technologies (Miaoudakis et al., 2020). Others combined it with LCA model to aid their processes of designing new products with low environmental impact (Zhang et al., 2020; de Oliveira and Soares, 2017). New designs and case studies validated IoT-enabled solutions based on products with different technical route characteristics, such as plastic waste and scrapped cars (Plakas et al., 2020; Zhou et al., 2018), etc. Though the proportion of case studies is relatively low, only 11%.

The remaining four business models account for only a small part of the articles. Among them, the sharing model generally relies on online platforms or apps supported by IoT, which brings the channel for products or information sharing between different stakeholders (Mastos et al., 2020). *Virtualize* and *Exchange* models usually demands extra technologies such as virtual world tools, digital twin (DT) and 3D printers to realize (Gustafson-Pearce and Grant, 2017; Despeisse et al., 2017; Rocca et al., 2020).

3.2. Connection of ReSOLVE framework with 6 R and IoT capabilities

We further classified the papers in a number of matrices, considering the 6 R, IoT capabilities and Circular Business Model (CBM) categories discussed in section 2. This results in a ‘heat map’ of the occurrences of CBM-IoT and CBM-6R cross-sections within the sample of 59 papers, see Fig. 5. Many papers describe multiple CBM-IoT and CBM-6R cross-sections. It should further be noted that while the categories are uniquely defined, they are not mutually exclusive. Below, we explored patterns for each of the CBM.

1. *Loop* business model

The findings show that IoT-enabled ‘Recycle’ dominates, followed by ‘Remanufacture’ and ‘Repair’. Papers displaying *Loop* usually rely on tracking or monitoring capabilities, while optimization and design evolution are relatively unexplored.

In terms of recycling, remanufacturing, and repairing, the adoption of novel Internet-based transactions can exploit information for faster and more sustainable collection of post-consumption products, they can be tracked using sensors, RFID tags, and barcodes (Al-Masri et al., 2018). As a consequence, organizations are able to remanufacture, or recycle components of products and packaging (Vanderroost et al., 2017; Gligoric et al., 2019).

In line with the Redesign prospect, product designers need to incorporate environmental criteria into their design decisions. They can obtain data from an IoT-based product life cycle management system to aid their processes of sustainable design and development (Zhang et al., 2020; Chit et al., 2021; de Oliveira and Soares, 2017). Typical cases are listed in Table 4.

Table 4
Illustration of the use of IoT capabilities in the *Loop* model.

IoT capabilities	Representative examples
Tracking	A research project called POIROT, which exploits IoT technologies, aiming to realize a platform for the traceability of organic waste and transform it into inert, odorless and sanitized material (De Fazio et al., 2019).
Monitoring	An IoT-enabled decision support system for a CE model that addresses the uncertainty of a product's residual value based on the life cycle monitored from the IoT sensors (Mboli et al., 2020).
Optimization	A system that combines intelligent transportation systems (RFIDs, sensors, cameras, actuators and surveillance systems) and an advanced decision system (incorporating data sharing between truck drivers in real time to perform dynamic route optimization) for efficient waste collection (Velvizhi et al., 2020).

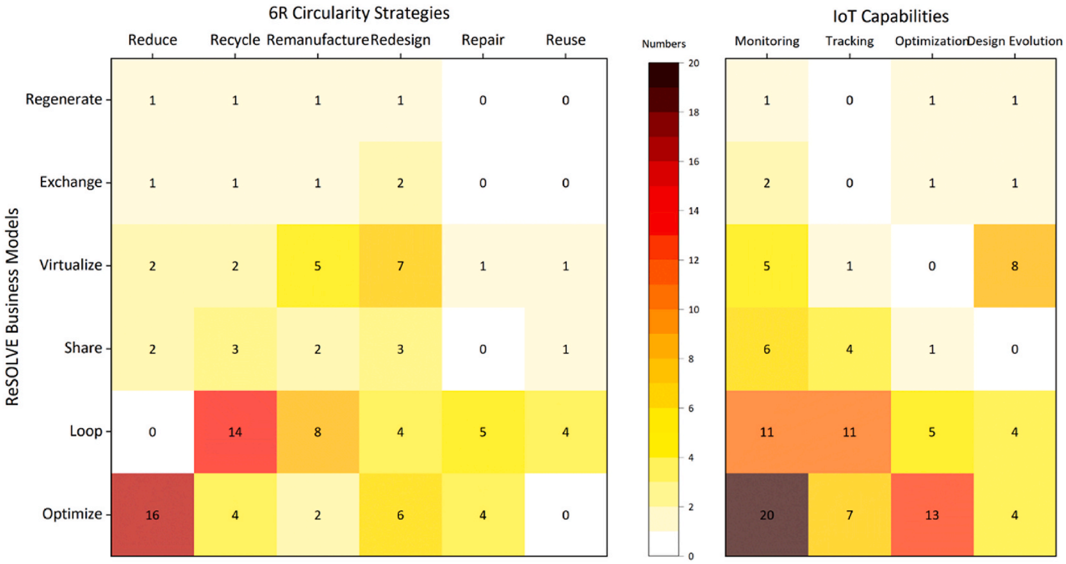

Fig. 5. Heat map of the CBM-6R and CBM-IoT cross-section occurrences.

Table 5
Illustration of the use of IoT capabilities in the *Optimize* model.

IoT capabilities	Representative examples
Tracking	RFID technology to tag and track fresh milk could reduce the amount of product shrinkage (Bottani et al., 2014).
Monitoring	Based on IoT sensors, energy and cost savings will be achieved as long as the state of the ideal ball mill is specifically analyzed and extended to the other ball mills. (Ma et al., 2020).
Optimization	Each node (including suppliers, wholesalers and retailers) could be involved in managing and optimizing its own performance in terms of production, deliveries and environmental compliance by using RFID tags and wireless sensor networks (Hofmann and Rüsch, 2017; Hasanova and Romanovs, 2020).

2. *Optimize* business model

Most of the papers exploring *Optimize* models are highly related to IoT-enabled 'Reduce', which is mainly realized by monitoring and optimization capabilities, as shown in Appendix figure A1. Through data monitoring from processes and agents such as machines, the IoT increases the possibility of identifying potential failures, and predictive maintenance can reduce the waste of non-performing products (Venkatesh et al., 2020; Laskurain-Iturbe et al., 2021). Additionally, based on the demands of the production and consumption of resources, managers could monitor and Optimize production rates and the use of sensors as well as algorithms would enable them to automatically intervene in processes to reduce intermediate inventory (Ghoreishi and Happonen, 2022; Roy and Roy 2019; Awan et al., 2022b). The IoT with the combination of cloud computing and machine learning provides potential for complex and integrated data-driven process manufacturing models in terms of robustness and accuracy (Fisher et al., 2020). Typical cases are listed in Table 5.

3. *Share* business model

Monitoring and tracking are main capabilities of IoT that contribute to sharing business model, they help in the product 'Resign' and 'Recycle' in order to achieve product lifetime extension, as shown in Appendix figure A2. Information on consumers' behavior is collected through websites and apps, organizations can therefore both improve product design and provide a digital service for better utilization or replacement of equipment, and increase customer satisfaction (Rymaszewska et al., 2017; Ingemarsdotter et al., 2020). Moreover, the use of sensors in products allows performance monitoring - for instance, monitoring maintenance requirements - thereby allowing organizations to proactively provide a high quality of service to customers. As a consequence of monitoring products during consumer use, organizations can invest in extending product life spans by applying the 3Rs strategy (repair, reuse, and recycle). Typical cases are listed in Table 6.

4. Virtualize business model

Since service is a core focus of *Virtualize*, using real-time data to monitor supply activities is important to enhance the customer experience. It also triggers the potential of IoT-enabled "Redesign" of the product or service with the help of design evolution capability. Through virtually designing, simulating, and optimizing the system and converting it on the real world, it is possible to achieve system reconfigurability through a change of both specific hardware (i.e., change of robot tools for disassembly activities), and software resources (i.e., robot program coding) (Sassanelli et al., 2021). The IoT enables connections between organizations, suppliers, and customers in order to offer services rather than physical products (Jabbour et al., 2018). In addition, the IoT is able to collect information on consumers' behavior and features of past designs, which designers can use to improve service quality. Typical cases are listed in Table 7.

5. Exchange business model

This model could acquire strength by adopting additive manufacturing and IoT systems with monitoring capability (Despeisse et al., 2017). 3D printers are able to process renewable and sustainable production. Based on interaction between organizations and customers, some companies are able to manufacture customized products by using databases incorporating 3D printers, where IoT helps to save time and material use in additive manufacturing. These kinds of functions make IoT easier to achieve CE principles. Typical cases are listed in Table 8.

Table 7
Illustration of the use of IoT capabilities in the *Virtualize* model.

IoT capabilities	Representative examples
Monitoring	Gustafson-Pearce and Grant (2017) tested 3D Virtual World tools with multiple sources of 'streamed' data generated by IoT, to discover whether knowledge sharing and learning within a horizontal supply chain was effective and reduced greenhouse gas emissions related to business travel.
Design evolution	A platform that combines hybrid IoT and blockchain to provide interactive innovation in prefabricated housing construction among shareholders, who were involved in life-cycle value co-design via online channels (e.g., mobile apps) (Li et al., 2021). A platform installing IoT devices in a smart building to measure energy consumption and provide energy optimization consulting services for end-users and building managers (Sharma et al., 2021). IoT could provide a scenario of experience shopping from a mirror image, aiming to solve the distortion of consumer's experience in traditional online shopping (Gao and Han, 2021). IoT integrates the manufacturing execution system (MES) to the DT by using a communication protocol, which is able to give commands to the MES from external sources and digitalize the CE practices (Rocca et al., 2020).

Table 6
Illustration of the use of IoT capabilities in the *Share* model.

IoT capabilities	Representative examples
Tracking	Cranfield University launched a shoe recycling project: it includes the design of an intelligent component (IoT) that tracks the condition of the shoes and identifies the need for replacement/upgrading. The modular design of the shoes allows them to be easily disassembled for refurbishing or recycling (Nobre and Tavares, 2017).
Monitoring	A cross-company IoT communication protocol has the potential to offer an automated negotiation ecosystem between scrap metal producers and waste collecting companies based on cost, demand etc. (Mastos et al., 2020).
Optimization	IoT helps to achieve a mutual visible inventory under business-to-business e-commerce models in real time, where average food inventory, amount of food waste, frequency of lateral inventory share and ordering from the main depot; customer service level in the network is optimized (Ekren et al., 2021).

Table 8
Illustration of the use of IoT capabilities in the *Exchange* model.

IoT capabilities	Representative examples
Monitoring	The additive manufacturing leads to reduced use of material, IoT-enabled 3D printers enable the recycling of small quantities of waste (Despeisse et al., 2017).
Optimization	IoTs are used for the identification of engineered disassemblers as well as the real-time status of reproducible resources to build efficient multi-target production planning in real-time by the seed swarm optimization algorithm (Chau et al., 2021).

6. *Regenerate* business model

The model could benefit from IoT in the form of sensors and networks. The design, production and supply decisions of CE could be adjusted based on data provided by IoT (EMF, 2016). This would make it possible to reduce unnecessary resource consumption to improve the productivity of harvests, and to extend the life cycle of the land use. Typical cases are listed in Table 9.

In all, the concept of 6 R is gradually supported by IoT technology. It promotes the combination of 6 R in different circular business practices (Kirchherr et al., 2017; Spaltini et al., 2021), and each business model represents a major circularity opportunity enabled by the IoT technology that is quite different from growth in the linear economy. Therefore, we selected main contributors of 6 R and CBM from the 'heat map' results, and then constructed a relationship framework that containing the conceptualization of 4 IoT capabilities, 6 R and ReSOLVE framework, as shown in Fig. 6.

As for IoT capabilities, the monitoring plays a significant role, which promotes most circular business models by jointly facilitating all 6Rs, followed by the optimization capability. And for the intermediate nodes of 6 R actions, Recycle and Redesign are the core CE principles linking upstream IoT capabilities and downstream circular strategies. In different ways, these actions all increase the utilization of physical assets, prolong their life, and shift resource use from finite to renewable sources. They potentially reinforce and accelerate the performance of the other actions, creating a compounding effect.

Table 9
Illustration of the use of IoT capabilities in the *Regenerate* model.

IoT capabilities	Representative examples
Monitoring	To monitor, and control factors related to land management between crop rotation, to automate irrigation systems based on weather conditions in real time, and to manage the use of pesticides according to the health of plantations (EMF Report of Ellen MacArthur Foundation, 2016).
Optimization	IoT allows real-time measurement of ceramic tile production, providing the capability to modify the composition of the ceramic bodies and the transport mix to maximize the use of local raw materials, reducing the distances between mines and the factory and by favoring rail transport (Garcia-Muiña et al., 2019).

3.3. *Quantitative analysis of how the use of IoT in CBMs reduces energy-related environmental impacts*

Within the collected papers, 20 papers provide quantitative data on how the use of IoT in CBMs can reduce environmental impacts. These papers provide 23 cases. We included them in our quantitative analysis for they mainly use energy savings as the primary measurement. Fig. 7 depicts how much energy is saved by using IoT in the six ReSOLVE business model categories (*Virtualize* is missing due to lack of data). The X-axis shows the ReSOLVE business model categories and their number of samples in each. The Y-axis represents the relative energy savings compared to a baseline scenario without IoT enhancement (i.e., the energy use in the baseline is set on 100%). Supplementary Table 2 contains a list of cases and their references.

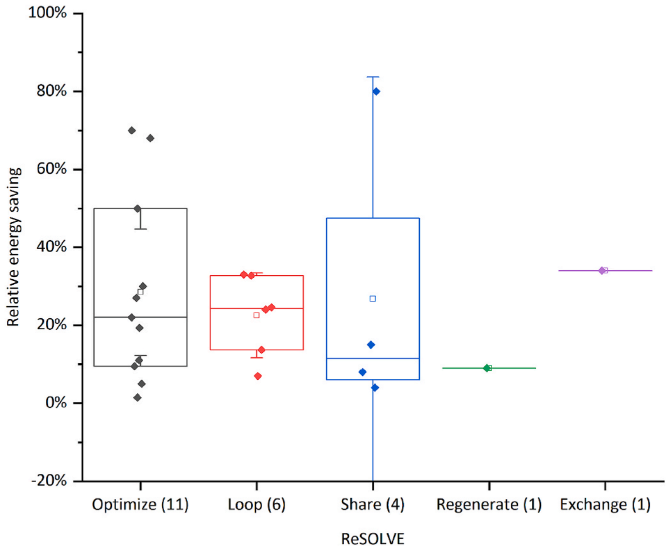

Fig. 7. Relative energy saving under different IoT-enabled CBM (CI = 95%).

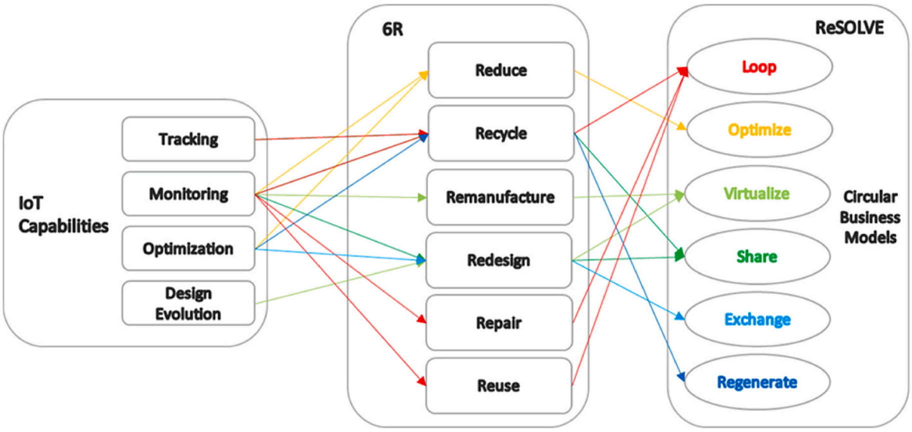

Fig. 6. Relationship framework for IoT enabled 6 R and CBM.

1. *Optimize* business model

Most results show quantitative data from the *Optimize* business model (11 results). Here, big data of related resource objects is collected using IoT sensors. The resource allocation framework is then optimized using heuristic algorithms for specific consumption habits to prevent any unwanted negative environmental impact in scheduling issues (Liao and Wang, 2019).

2. *Loop* business model

6 results consider the *Loop* business model. IoT solutions enable the transition to a cyber-physical[1] waste management system, and provide real-time information on waste generation, treatment, transportation, and material handling capacity in big random systems. Carbon emissions from collected and transported waste have been significantly reduced due to enhanced recycling (Velvizhi et al., 2020).

3. *Share* business model

4 results discuss the *Share* business model, where IoT lowers energy and resource waste in corporate processes by sharing information, products or services (Ekren et al., 2021). For instance, IoT facilitates the recording of food expiration dates and facilitates communal food sharing (Phiri and Trevorrow, 2019).

4. *Regenerate* and *Exchange* business model

The *Regenerate* and *Exchange* models each have a single case. In *Regenerate* model, IoT is utilized for the identification of engineered disassemblers and the real-time status of regenerable resources in order to construct effective multi-target production planning (Garcia-Muiña et al., 2019). While in *Exchange* model, IoT assists in modifying the composition of the ceramic bodies and the transport mix to maximize the utilization of local raw materials (Chau et al., 2021).

The effects of relative energy savings in the *Optimize* and *Loop* business models are evident and comparable, with corresponding mean value of 30% and 25%. It may be attributed to the parallels of the two models in leveraging IoT capabilities. With the difference that *Optimize* model utilizes more on the optimization capabilities, which may provide it with higher energy saving potential. Some measures in the *Optimize* model could even achieve energy savings of up to 70%. But the effect of the *Share* business model is highly variable, ranging from less than 20%–80%, with the majority of results falling closer to the lower end. The results of the remaining three models are limited. Nevertheless, they present oppotunities for further investigation.

4. Environmental drawbacks and other obstacles to the use of IoT in CBMs

While reviewing the literature, as described above we found many ways of how IoT could support the implementation of circular CBMs. However, some of these references also highlighted environmental risks of IoT, or other obstacles to implementing and using IoT. These findings including related references are discussed below, and Table 10 summarizes them.

4.1. Environmental drawbacks

One of the drawbacks of IoT-enabled business models includes the energy use of IoT and related carbon emissions, such as IoT hardware, node software and protocol energy consumption (Fraga-Lamas et al., 2021). Hardware is the basis for the IoT network, and both hardware and software needs to be optimized together to re duce environmental burdens. Such optimizations are particularly important for certain digital signal processing tasks, including compression, feature extraction, or machine learning training. The IoT is also dependent on protocols that enable communicating between the various nodes and routing devices involved in an IoT network. In terms of software implementation, these protocols must be energy-efficient and should minimize the use of communication interfaces.

Table 10
Environmental drawbacks and other obstacles to the implementation of IoT.

Type	Drawbacks and obstacles
Environmental	Use of harmful substances and non-degradable resources Hardware power consumption IoT node software energy consumption IoT protocol energy efficiency
Other	Lack of standardization and technological knowledge among partners Data availability High financial investment Security of virtual platform Inadequate internet connectivity

Next to this, IoT equipment may result in difficult to process electronic waste. An example consists of RFID tags that are hazardous to the environment and are difficult to recycle (Yu et al., 2022). Another concern is that IoT enables mass customization. Customization makes it more difficult for another user to reuse or recycle an item (Birkel et al., 2019).

A key observation is that many studies do not take into account such environmental drawbacks of implementing IoT technology (i.e., the impact of producing or using IoT devices, etc.). Some preliminary analyses have been presented in the literature. For instance, Mataloto et al. (2019) discovered that IoT devices (LoRa) for energy management systems require an annual energy usage of 5.2 kWh if applied in small buildings (16–40 m2). Bottani et al. (2014) assessed the environmental performance and burdens of the use of RFID tags in a fresh milk supply chain based on life cycle assessment (LCA) and found that the environmental costs of 1 million RFID tags are 32,900 kg CO2-eq in climate change potential, 23.9 kg P-eq in freshwater eutrophication, and 156 molc H + -eq in acidification potential. Comparatively to the existing studies, there is a dearth of papers that examine the positive and negative contributions of IoT to CBM via case studies or simulations. This involves not only a full examination of its production, transportation, disposal, and reuse synergies, but also an evaluation of the LCA of IoT components.

4.2. Other obstacles

Next to environmental drawbacks the literature we reviewed gave some more general implementation obstacles with regard to the use of IoT in CBMs. Firstly, there is often a lack of structured data management processes to ensure the acquisition of high-quality data for industrial analysis (Ingemarsdotter et al., 2020). Due to the limited availability and variety of industrial data, evaluating and validating representative models of real-world systems can be difficult, i.e., determining when sufficient data has been acquired to ensure the representativeness of a simulation framework. (Fisher et al., 2020).

Secondly, the absence of standardization and guidance in implementing IoT across various businesses poses a concern. There can be a lack of regulations addressing data ownership among stakeholders (Astill et al., 2019). The wide implementation of CE strategies is contingent upon solving such data ownership issues.

Thirdly, ensuring privacy and data security poses a challenge (Roy and Roy, 2019). End-users as intermediate nodes in the manufacturing and remanufacturing cycle and vulnerable firewall nodes can be

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[1] In cyber-physical systems, physical and software components are deeply intertwined, able to operate on different spatial.

susceptible to botnet assaults (Tuptuk and Hailes, 2018). One typical case is the IoT botnet Mirai, a malware that could target consumer electronics and home routers, turning them into a zombie remotely controlled bots that can be used in large-scale network attacks (Antonakakis et al., 2017). Such challenges may be solved by IoT projects funded by the European Union's Horizon 2020 research program, it includes the European Cloud Initiative, the GAIA-X initiative, as well as public-private partnerships such as the Smart Networks and Services JU and the AI, Big Data and Robotics (Calisti, 2020). These projects are expected to use distributed AI, address security, privacy and trust requirements by design and allow for new de-centralized topologies and governance.

In addition, it is challenging to rapidly design IoT-enabled products for interoperability, adaptability, and upgradability (Ingemarsdotter et al., 2020). Currently, potential solutions tend to point at blockchain technology. However, integrating blockchain within the IoT framework will also pose technical, infrastructure, energy consumption, interoperability and social regulatory issues (Feng et al., 2020; Zhang et al., 2020; Venkatesh et al., 2020).

The last impediment are the limited resources small-scale enterprises can invest systematically in IoT technologies throughout their entire supply chains (Tan et al., 2020).

5. Conclusion and outlook

This review has assessed the state-of-the-art relation of IoT and CBM from several perspectives. Based on the Prisma approach, this article reviews the literature on the IoT and CBMs that has been expanding significantly in recent years. Through the classification of their methods and contents, this paper constructed a mapping framework connecting the ReSOLVE concept with four IoT capabilities and the 6 R framework. It depicts the current research status of IoT supported CBMs and explains their contribution for enterprises from the perspective of 6 R with representative cases.

IoT by its support of joint interoperability for system optimization, timely monitoring and tracking, has contributed to the enhancement of industrial efficiency, recycling, and the reduction of unnecessary material and energy use. These characteristics of IoT support the implementation and success of CBMs, particularly the *Loop* and *Optimize* CBMs. These conclusions are similar to those of previously published studies. However, the dynamic feedback potential of the IoT also proves to be vital for the "Redesign" of product or service concepts, especially for *Virtualize*, *Share* and *Exchange* models which have not been fully explored before. Therefore, we revealed potential directions based on these preliminary studies: For instance, in the *Share* approach, IoT helps to provide a sharing platform that enables consumers to share products, essentially providing the same amount of final services with a smaller product pool. The IoT also provides virtual and dematerialized options as service solutions rather than physical products with similar functions to achieve design evolution capability, supporting the "Redesign" CE strategy through the combination of other I4.0 technologies such as DT.

The review of quantitative assessments suggests that IoT has the potential to reduce the energy consumption of the *Optimize* and *Loop* business model by about 20–30%. By redesigning and integrating IoT and IoT-based algorithms into business operations, the energy efficiency of the system can be greatly increased. In addition, IoT can help to minimize waste generation and enhance efficiency of resource use. However, the widespread usage of IoT and related data processing activities in itself can lead to higher energy use and generation of e-waste, which often is difficult to recycle. IoT also poses a number of obstacles for its cross-business applications, including the difficulties of establishing universal standards for data processing, cybersecurity liability issues, and relatively high investment costs. These assessments of strengths and challenges of IoT can provide more intuitive information for SMEs investors who are interested in innovative technologies and circular development.

6. Limitations and recommendations

This research has limitations as well. Firstly, given the fact that the research on the interaction between the IoT and CE is still in its infancy, most of the references discuss conceptual frameworks, models and theoretical evaluations, and just a few case studies. Most case studies only explore one or a few technical applications of IoT, these limits the value of meta-analyses as attempted in this paper. Particularly for the *Virtualize*, *Exchange* and *Regenerate* CBMs the number of available cases was low. We hence recommend a more systematic, quantitative analysis of case studies on how IoT can contribute to CBMs and environmental improvements.

Secondly, the literature gives just limited information on the environmental drawbacks of IoT. Some studies on e.g., RFID suggest that their production and use generate just limited environmental damage (Jia et al., 2012). However, to analyze the environmental benefits and drawbacks of IoT comprehensively, further research is needed that should consider specific IoT application scenarios, material choices and future improvement potentials that may be available due to scale and learning effects. These could become the focal points of the future phase of IoT research.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Suiting Ding reports financial support was provided by China Scholarship Council.

Data availability

Data will be made available on request.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117662.

Appendix A

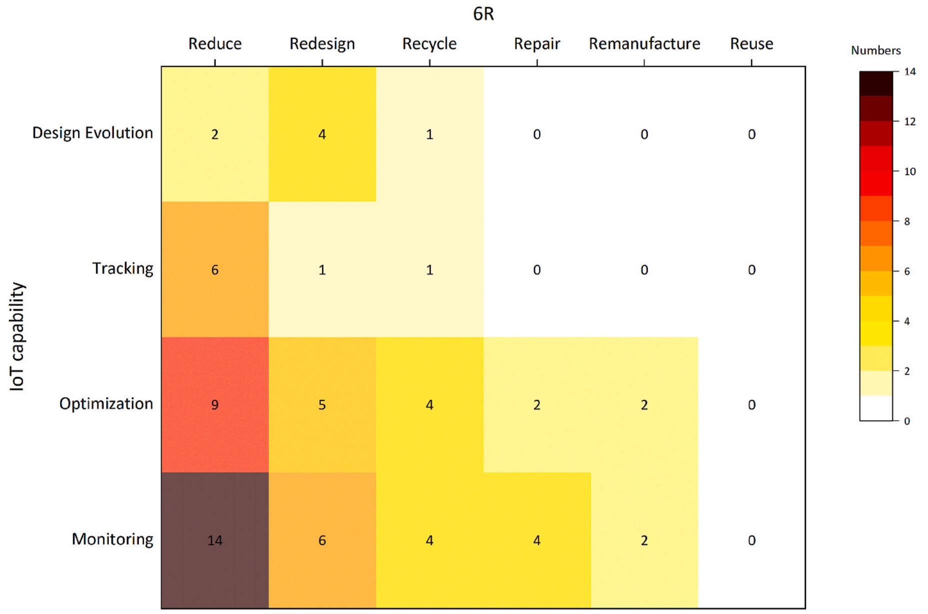

Fig. A1. IoT-6R cross-section occurrences in Optimize business model

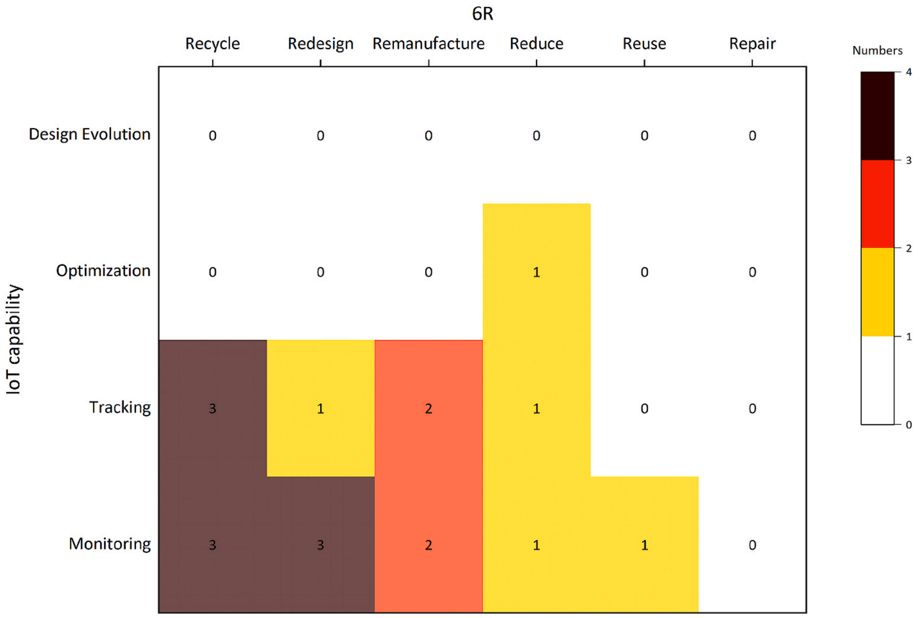

Fig. A2. IoT-6R cross-section occurrences in Share business model

References

Aguilar-Hernandez, G., Rodrigues, J., Tukker, A., 2021. Macroeconomic, social and environmental impacts of a circular economy up to 2050: a meta-analysis of prospective studies. J. Clean. Prod. 278, 123421. https://doi.org/10.1016/j.jclepro.2020.123421.

Al-Masri, E., Diabate, I., Jain, R., Lam, M.H., Nathala, S.R., 2018. Recycle.io: an IoT-enabled framework for urban waste management. In: 2018 IEEE International Conference on Big Data. IEEE, pp. 5285–5287. https://doi.org/10.1109/BigData.2018.8622117.

Antonakakis, M., April, T., Bailey, M., Bernhard, M., Bursztein, E., Cochran, J., et al., 2017. Understanding the Mirai botnet. In: 26th USENIX Security Symposium (USENIX Security, 17. USENIX Association, Vancouver, BC, pp. 1093–1110.

Astill, J., Dara, R.A., Campbell, M., et al., 2019. Transparency in food supply chains: a review of enabling technology solutions. Trends Food Sci. Technol. 91, 240–247. https://doi.org/10.1016/j.tifs.2019.07.024.

Awan, U., Gölgeci, I., Makhmadshoev, D., Mishra, N., 2022a. Industry 4.0 and circular economy in an era of global value chains: what have we learned and what is still to be explored? J. Clean. Prod. 371, 13362. https://doi.org/10.1016/j.jclepro.2022.133621.

Awan, U., Sroufe, R., Bozan, K., 2022b. Designing value chains for industry 4.0 and a circular economy: a review of the literature. Sustainability 14 (7084). https://doi.org/10.3390/su14127084.

Bányai, T., Tamás, P., Illés, B., Stankevičiūtė, Ž., Bányai, Á., 2019. Optimization of municipal waste collection routing: impact of industry 4.0 technologies on environmental awareness and sustainability. Int. J. Environ. Res. Publ. Health 16 (634). https://doi.org/10.3390/ijerph16040634.

Beier, G., Niehoff, S., Xue, B., 2018. More sustainability in industry through industrial internet of things? Applied Sciences 219 (2). https://doi.org/10.3390/app8020219, 8.

Birkel, H.S., Veile, J.W., Müller, J.M., 2019. Hartmann E, voigt K-I. Development of a risk framework for industry 4.0 in the context of sustainability for established manufacturers. Sustainability 384 (2). https://doi.org/10.3390/su11020384, 11.

Blanco, C.F., Cucurachi, S., Peijnenburg, W.J.G.M., Beames, A., Vijver, M.G., 2020. Are technological developments improving the environmental sustainability of photovoltaic electricity? Energy Technol. 1901064 https://doi.org/10.1002/ente.201901064.

Bottani, E., Manfredi, M., Vignali, G., Volpi, A., 2014. Life cycle assessment of RFID implementation in the fresh food supply chain. Int. J. Real. Ther. 6, 51–71. https://doi.org/10.3233/RFT-140060.

Calisti, M., 2020. EU-IoT project kicks off. Next generation IoT, 4 november. Retrieved from. https://www.ngiot.eu/eu-iot-project-kicks-off. (Accessed 27 October 2021).

Chau, M.Q., Nguyen, X.P., Huynh, T.T., Chu, V.D., Le, T.H., Nguyen, T.P., Nguyen, D.T., 2021. Prospects of application of IoT-based advanced technologies in remanufacturing process towards sustainable development and energy-efficient use, Energy Sources, Part A: recovery, Utilization, and Environmental Effects. https://doi.org/10.1080/15567036.2021.1994057.

Chen, C., Matt, H., 2021. Will Huawei's Harmony operating system end the global duopoly of Google's Android and Apple's iOS? South. China Morning Post, 4 June. Retrieved from. https://www.scmp.com/tech/big-tech/article/3136017/will-huaweis-harmony-operating-system-end-global-duopoly-googles. (Accessed 1 September 2021).

Chit, T.W., Ning, L., Paliath, N.A., Long, Y.M., Akhtar, H., Shanshan, Y., 2021. IIoT-enabled and data-driven sustainability evaluation framework for textile supply chain. 2021 IEEE 16th Conference on Industrial Electronics and Applications (ICIEA 297–304. https://doi.org/10.1109/ICIEA51954.2021.9516314.

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S.J., Garmulewicz, A., et al., 2017. Unlocking value for a circular economy through 3D printing: a research agenda. Technol. Forecast. Soc. Change 115, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021.

Ding, S., Ward, H., Tukker, A., 2023. How Internet of Things can influence the sustainability performance of logistics industries – a Chinese case study. Cleaner Logistics and Supply Chain 6, 100094. https://doi.org/10.1016/j.clscn.2023.100094.

Ekren, B.Y., Mangla, S.K., Turhanlar, E.E., Kazancoglu, Y., Li, G., 2021. Lateral inventory share-based models for IoT-enabled E-commerce sustainable food supply networks. Comput. Oper. Res. 130, 105237. https://doi.org/10.1016/j.cor.2021.105237.

Elisha, O.D., 2020. Moving beyond take-make-dispose to take-make-use for sustainable economy. International Journal of Scientific Research in Education 13 (3), 497–516.

EMF (Report of Ellen MacArthur Foundation), 2013. Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. pp. 24-25.

EMF (Report of Ellen MacArthur Foundation), 2015. Growth within: A Circular Economy Vision for a Competitive Europe, pp. 25–26.

EMF (Report of Ellen MacArthur Foundation), 2016. Intelligent assets:Unlocking the circular economy potential, pp. 13–14.

Fazio, De, et al., 2019. Sensors-based treatment system of the organic waste with RFID identification and on-cloud traceability. 2019 IEEE 8th International Workshop on Advances in Sensors and Interfaces (IWASI 245–250. https://doi.org/10.1109/IWASI.2019.8791339.

Feng, H.H., Wang, X., Duan, Y.Q., Zhang, J., Zhang, X.S., 2020. Applying blockchain technology to improve agri-food traceability: a review of development methods, benefits and challenges. J. Clean. Prod. 260, 121031. https://doi.org/10.1016/j.jclepro.2020.121031.

Fisher, O.J., Watson, N.J., Escrig, J.E., et al., 2020. Considerations, challenges and opportunities when developing data-driven models for process manufacturing systems. Comput. Chem. Eng. 140, 106881. https://doi.org/10.1016/j.compchemeng.2020.106881.

Fraga-Lamas, P., Lopes, S.I., Fernández-Caramés, T.M., 2021. Green IoT and edge AI as key technological enablers for a sustainable digital transition towards a smart circular economy: an industry 5.0 Use case. Sensors 21 (5745). https://doi.org/10.3390/s21175745.

Gao, X., Han, H., 2021. Five senses' experience model for mirroring online shopping in IoT. International Conference on Artificial Intelligence and Electromechanical Automation (AIEA 286–289. https://doi.org/10.1109/AIEA53260.2021.00067.

Garcia-Muiña, F.E., González-Sánchez, R., Ferrari, A.M., Volpi, L., Pini, M., Siligardi, C., Settembre-Blundo, D., 2019. Identifying the equilibrium point between sustainability goals and circular economy practices in an industry 4.0 manufacturing context using eco-design. Social Sciences 241 (8). https://doi.org/10.3390/socsci8080241, 8.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Ghoreishi, M., Happonen, A., 2022. The case of fabric and textile industry: the emerging role of digitalization, internet-of-things and industry 4.0 for circularity. Proceedings of Sixth International Congress on Information and Communication Technology 216, 189–200. https://doi.org/10.1007/978-981-16-1781-2_18.

Gligoric, N., Krco, S., Hakola, L., Vehmas, K., De, S., Moessner, K., Jansson, K., Polenz, I., Van Kranenburg, R., 2019. Smarttags: IoT product passport for circular economy based on printed sensors and unique item-level identifiers. Sensors 586 (3). https://doi.org/10.3390/s19030586, 19.

Gorissen, L., Vrancken, K., Manshoven, S., 2016. Transition thinking and business model innovation–towards a transformative business model and new role for the reuse centers of limburg, Belgium. Sustainability 112 (2). https://doi.org/10.3390/su8020112, 8.

Govindan, K., Hasanagic, M., 2018. A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. Int. J. Prod. Res. 56 (1–2), 278–311. https://doi.org/10.1080/00207543.2017.1402141.

Gružauskas, V., Baskutis, S., Navickas, V., 2018. Minimizing the trade-off between sustainability and cost-effective performance by using autonomous vehicles. J. Clean. Prod. 184, 709–717. https://doi.org/10.1016/j.jclepro.2018.02.302.

Gustafson-Pearce, O., Grant, S.B., 2017. Supply chain learning using a 3D virtual world environment. Smart innovation. Systems and Technologies 68, 386–397. https://doi.org/10.1007/978-3-319-57078-5_37.

Harold, G.C., 2007. The RFID Certification Textbook, third ed. Copyright.

Hasanova, H., Romanovs, A., 2020. Best practices of technology management for sustainable digital supply chain. 2020 61st International Scientific Conference on Information Technology and Management Science of Riga Technical University (ITMS 1–6. https://doi.org/10.1109/ITMS51158.2020.9259319.

Hofmann, E., Rüsch, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. Comput. Ind. 89, 23–34. https://doi.org/10.1016/j.compind.2017.04.002.

Horvathova, E., 2012. The impact of environmental performance on firm performance: short-term costs and long-term benefits? Ecol. Econ. Times 84, 91–97. https://doi.org/10.1016/j.ecolecon.2012.10.001.

Ingemarsdotter, E., Jamsin, E., Kortuem, G., Balkenende, R., 2019. Circular strategies enabled by the internet of things—a framework and analysis of current practice. Sustainability 11 (5689). https://doi.org/10.3390/su11205689.

Ingemarsdotter, E., Jamsin, E., Balkenende, R., 2020. Opportunities and challenges in IoT-enabled circular business model implementation – a case study. Resources. Conserv. Recycl. 162, 105047. https://doi.org/10.1016/j.resconrec.2020.105047.

ITU (International Telecommunication Union), 2005. ITU internets reports 2005: The Internet of Things. pp. 4-5.

Jabbour, A.B., Jabbour, C.J.C., Godinho Filho, M., et al., 2018. Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. Ann. Oper. Res. 270, 273–286. https://doi.org/10.1007/s10479-018-2772-8.

Jagtap, S., Garcia-Garcia, G., Rahimifard, S., 2021. Optimisation of the resource efficiency of food manufacturing via the Internet of Things. Comput. Ind. 127, 103397. https://doi.org/10.1016/j.compind.2021.103397.

Jia, X., Feng, Q., Fan, T., Lei, Q., 2012. RFID technology and its applications in internet of things (IoT). 2012 2nd International Conference on Consumer Electronics, Communications and Networks (CECNet) 1282–1285. https://doi.org/10.1109/CECNet.2012.6201508.

Jin, Y., Behrens, P., Tukker, A., Scherer, L., 2019. Water use of electricity technologies: a global meta-analysis. Renew. Sustain. Energy Rev. 115, 109391. https://doi.org/10.1016/j.rser.2019.109391.

Joshi, K., Venkatachalam, A., Jawahir, I.S., 2006. A New Methodology for Transforming 3R Concept into 6R Concept for Improved Product Sustainability. in: Proceedings of the IV Global Conference on Sustainable Product Development and Life Cycle Engineering, Sao Carlos.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resources. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Laskurain-Iturbe, I., Arana-Landín, G., Landeta-Manzano, B., Uriarte-Gallastegi, N., 2021. Exploring the influence of industry 4.0 technologies on the circular economy. J. Clean. Prod. 321, 128944. https://doi.org/10.1016/j.jclepro.2021.128944.

Li, C.Z., Chen, Z., Xue, F., et al., 2021. A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction. J. Clean. Prod. 286, 125391. https://doi.org/10.1016/j.jclepro.2020.125391.

Liao, W., Wang, T., 2019. A novel collaborative optimization model for job shop production–delivery considering time window and carbon emission. Sustainability 11(10) 2781. https://doi.org/10.3390/su11102781.

Luederitz, C., Meyer, M., Abson, D.J., Gralla, F., Lang, D.J., Rau, A.L., Von Wehrden, H., 2016. Systematic student-driven literature reviews in sustainability science – an effective way to merge research and teaching. J. Clean. Prod. 119, 229–235. https://doi.org/10.1016/j.jclepro.2016.02.005.

Ma, S., Zhang, Y.F., Liu, Y., Yang, H.D., Lv, J.X., Ren, S., 2020. Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries. J. Clean. Prod. 274, 123155. https://doi.org/10.1016/j.jclepro.2020.123155.

Manavalan, E., Jayakrishna, K., 2019. An analysis on sustainable supply chain for circular economy. Procedia Manuf. 33, 477–484. https://doi.org/10.1016/j.promfg.2019.04.059.

Maroli, A., Narwane, S.V., Gardas, B.B., 2021. Applications of IoT for achieving sustainability in agricultural sector: a comprehensive review. J. Environ. Manag. 298, 113488. https://doi.org/10.1016/j.jenvman.2021.113488.

Mastos, T.D., Nizamis, A., Vafeiadis, T., Alexopoulos, N., Ntinas, C., Gkortzis, D., Papadopoulos, A., Ioannidis, D., Tzovaras, D., 2020. Industry 4.0 sustainable supply chains: an application of an IoT enabled scrap metal management solution. J. Clean. Prod. 269, 122377. https://doi.org/10.1016/j.jclepro.2020.122377.

Mataloto, B., Ferreira, J.C., Cruz, N., 2019. Lobems—IoT for building and energy management systems. Electronics 8(7) 763. https://doi.org/10.3390/electronics8070763.

Mboli, J.S., Thakker, D., Mishra, J.L., 2020. An Internet of Things-enabled decision support system for circular economy business model. Software Pract. Ex. 1–16. https://doi.org/10.1002/spe.2825.

Miaoudakis, A., et al., 2020. Pairing a circular economy and the 5G-enabled internet of things: creating a class of looping smart assets? IEEE Veh. Technol. Mag. 15 (3), 20–31. https://doi.org/10.1109/MVT.2020.2991788.

MIIT (Ministry of Industry and Information Technology), 2012. Internet of things "twelfth five-year" development plan. http://www.gov.cn/zwgk/2012-02/14/content_2065999.htm.

Mohammadian, H.D., 2019. IoE – a Solution for Energy Management Challenges. 2019 IEEE Global Engineering Education Conference (EDUCON).

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L.A., Group, P., 2015. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst. Rev. 4, 1–9. https://doi.org/10.1186/2046-4053-4-1.

Nižetić, S., Šolić, P., López-de-Ipiña González-de-Artaza, D., Patrono, L., 2020. Internet of Things (IoT): opportunities, issues and challenges towards a smart and sustainable future. J. Clean. Prod. 274, 122877. https://doi.org/10.1016/j.jclepro.2020.122877.

Nobre, G.C., Tavares, E., 2017. Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study. Scientometrics 111, 463–492. https://doi.org/10.1007/s11192-017-2281-6.

Oliveira, De, S, F., Soares, A.L., 2017. A PLM vision for circular economy. IFIP Adv. Inf. Commun. Technol. 506, 591–602. https://doi.org/10.1007/978-3-319-65151-4_52.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., et al., 2021a. Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. J. Clin. Epidemiol. 134, 103–112. https://doi.org/10.1016/j.jclinepi.2021.02.003.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., et al., 2021b. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372. https://doi.org/10.1136/bmj.n71 n71.

Phiri, G., Trevorrow, P., 2019. Sustainable household food management using smart technology. 2019 10th international conference on dependable systems. Services and Technologies (DESSERT) 112–119. https://doi.org/10.1109/DESSERT.2019.8770023.

Plakas, G., Ponis, S.T., Agalianos, K., Aretoulaki, E., 2020. Reverse logistics of end-of-life plastics using industrial IoT and LPWAN technologies – a proposed solution for the bottled water industry. Procedia Manuf. 51, 1680–1687. https://doi.org/10.1016/j.promfg.2020.10.234.

Rejeb, A., Suhaiza, Z., Rejeb, K., Seuring, S., Treiblmaier, H., 2022. The Internet of Things and the circular economy: a systematic literature review and research agenda. J. Clean. Prod. 350, 131439. https://doi.org/10.1016/j.jclepro.2022.131439.

Ren, J., Manzardo, A., Toniolo, S., Scipioni, A., 2013. Sustainability of hydrogen supply chain. Part I: identification of critical criteria and cause-effect analysis for enhancing the sustainability using DEMATEL. Int. J. Hydrogen Energy 38, 14159–14171. https://doi.org/10.1016/j.ijhydene.2013.08.126.

Rocca, R., Rosa, P., Sassanelli, C., Fumagalli, L., Terzi, S., 2020. Integrating virtual reality and digital twin in circular economy practices: a laboratory application case. Sustainability 12 (2286). https://doi.org/10.3390/su12062286.

Rockström, J., Steffen, W., Noone, K., et al., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecology and Society 32 (2), 14. http://www.ecologyandsociety.org/vol14/iss2/art32/.

Romkey, j., 2017. Toast of the IoT: the 1990 interop internet toaster. IEEE Consum. Electron. Mag. 6 (1), 116–119. https://doi.org/10.1109/MCE.2016.2614740.

Rosa, P., Sassanelli, C., Terzi, S., 2019. Towards Circular Business Models: a systematic literature review on classification frameworks and archetypes. J. Clean. Prod. 236, 117696. https://doi.org/10.1016/j.jclepro.2019.117696.

Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., Terzi, S., 2020. Assessing relations between Circular Economy and Industry 4.0: a systematic literature review. Int. J. Prod. Res. 58 (6), 1662–1687. https://doi.org/10.1080/00207543.2019.1680896.

Roy, M., Roy, A., 2019. Nexus of internet of things (IoT) and big data: roadmap for smart management systems (SMgS). IEEE Eng. Manag. Rev. 47 (2), 53–65. https://doi.org/10.1109/EMR.2019.2915961.

Rymaszewska, A., Helo, P., Gunasekaran, A., 2017. IoT powered servitization of manufacturing: an exploratory case study. Int. J. Prod. Econ. 192, 92–105. https://doi.org/10.1016/j.ijpe.2017.02.016.

Saffo, P., 1997. Sensors: the next wave of innovation. Commun. ACM 40 (2), 92–97. https://doi.org/10.1145/253671.253734.

Sassanelli, C., Rosa, P., Terzi, S., 2021. Supporting disassembly processes through simulation tools: a systematic literature review with a focus on printed circuit boards. J. Manuf. Syst. 60, 429–448. https://doi.org/10.1016/j.jmsy.2021.07.009.

Schröder, P., Bengtsson, M., Cohen, M., Dewick, P., Hofstetter, J., Sarkis, J., 2019. Degrowth within—aligning circular economy and strong sustainability narratives. Resour. Conserv. Recycl. 146, 190–191. https://doi.org/10.1016/j.resconrec.2019.03.038.

Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. J. Clean. Prod. 16 (15), 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020.

Sharma, M., Singla, M.K., Nijhawan, P., Dhingra, A., 2021. Sensor-based optimization of energy efficiency in internet of things: a review. Sustainable Development Through Engineering Innovations 113, 153–161. https://doi.org/10.1007/978-981-15-9554-7_14.

Sihvonen, S., Ritola, T., 2015. Conceptualizing ReX for aggregating end-of-life strategies in product development. Procedia CIRP 29, 639–644. https://doi.org/10.1016/j.procir.2015.01.026.

Spaltini, M., Poletti, A., Acerbi, F., Taisch, M., 2021. A quantitative framework for Industry 4.0 enabled Circular Economy. Procedia CIRP 98, 115–120. https://doi.org/10.1016/j.procir.2021.01.015.

Suresh, P., Daniel, J.V., Parthasarathy, V., Aswathy, R.H., 2014. A state of the art review on the Internet of Things (IoT) history, technology and fields of deployment. 2014 International Conference on Science Engineering and Management Research (ICSEMR 1–8. https://doi.org/10.1109/ICSEMR.2014.7043637.

Tan, B.Q., Wang, F.F., Liu, J., Kang, K., Costa, F., 2020. A blockchain-based framework for green logistics in supply chains. Sustainability 12 (4656). https://doi.org/10.3390/su12114656.

Tuptuk, N., Hailes, S., 2018. Security of smart manufacturing systems. J. Manuf. Syst. 47, 93–106. https://doi.org/10.1016/j.jmsy.2018.04.007.

Vanderroost, M., Ragaert, P., Verwaeren, J., De Meulenaer, B., De Baets, B., Devlieghere, F., 2017. The digitization of a food package's life cycle: existing and emerging computer systems in the pre-logistics phase. Comput. Ind. 87, 15–30. https://doi.org/10.1016/j.compind.2017.01.004.

Velvizhi, G., Shanthakumar, S., Bhaskar, D., Pugazhendhi, A., Priya, T.S., Ashok, B., Nanthagopal, K., Vignesh, R., Karthick, C., 2020. Biodegradable and non-biodegradable fraction of municipal solid waste for multifaceted applications through a closed loop integrated refinery platform: paving a path towards circular economy. Sci. Total Environ. 731, 138049. https://doi.org/10.1016/j.scitotenv.2020.138049.

Venkatesh, V.G., Kang, K., Wang, B., Zhong, R.Y., Zhang, A., 2020. System architecture for blockchain based transparency of supply chain social sustainability. Robot. Comput. Integrated Manuf. 63, 101896. https://doi.org/10.1016/j.rcim.2019.101896.

Yu, Z., Khan, S., Mathew, M., Umar, M., Hassan, M., Sajid, M.J., 2022. Identifying and analyzing the barriers of Internet-of-Things in sustainable supply chain through newly proposed spherical fuzzy geometric mean. Comput. Ind. Eng. 169, 108227. https://doi.org/10.1016/j.cie.2022.108227.

Zalk, J., Behrens, P., 2018. The spatial extent of renewable and non-renewable power generation: a review and meta-analysis of power densities and their application in the U.S. Energy Pol. 123, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023.

Zhang, A., Zhong, R.Y., Farooque, M., Kang, K., Venkatesh, V.G., 2020. Blockchain-based life cycle assessment: an implementation framework and system architecture. Resources. Conserv. Recycl. 152, 104512. https://doi.org/10.1016/j.resconrec.2019.104512.

Zhou, Z., Cai, Y., Xiao, Y., Chen, X., Zeng, H., 2018. The optimization of reverse logistics cost based on value flow analysis - a case study on automobile recycling company in China. J. Intell. Fuzzy Syst. 34, 807–818. https://doi.org/10.3233/JIFS-169374.