A Review of the Information Technology and Operational Technology Convergence Using Internet of Things within the Circular Economy

Sorin-Daniel GHEORGHE
Bucharest University of Economic Studies, Bucharest, Romania
gheorghesorin22@stud.ase.ro

Abstract. *The historical separation of Information Technology and Operational Technology in organizations, particularly in the industrial sector, is being challenged by the digital transformation. This shift towards a converged platform is driven by technological advancements, market pressures, and environmental and regulatory considerations. This paper explores the convergence of Information Technology and Operational Technology through the Internet of Things within the Circular Economy. A comprehensive overview of the current scientific literature is provided using a systematic review method. Initially, the evolving landscape of the Information Technology and Operational Technology integration is reviewed, then Internet of Things and Circular Economy are presented. The findings of this study include the challenges of the converged solution implementation, such as the technical integration complexities, cybersecurity risks, organizational and cultural barriers, and workforce skills gap. Furthermore, the role of the Internet of Things is demonstrated using novel smart circular loops, products, and applications showcasing innovative ideas such as product-as-a-service models, digital circular practices, products with embedded sensors, energy harvesting, and modular and upgrade capabilities as well as novel digital factory use cases such as smart manufacturing and industrial symbiosis networks. The key findings also outline the best practices and recommendations for a successful implementation of this converged infrastructure, highlighting the importance of a strategic implementation and cross-domain collaboration to achieve operational efficiency and environmental sustainability. The insights provided in this paper are valuable for academics, practitioners, and policymakers aimed to understand and harness the digital technologies for advancing sustainable practices towards a smart circular economy.*

Keywords: circular economy, internet of things, information technology/operational technology convergence, sustainable digital infrastructure, industry 4.0

Introduction

The Circular Economy (CE) has emerged as a promising concept for promoting sustainable development and resource efficiency in response to the growing challenges of resource depletion, environmental degradation, and climate change (MacArthur, 2013).

As seen in Bocken et al (2016), the new circular economy model aims to shift from the traditional linear economy model characterized by a take-make-dispose approach towards a more regenerative and restorative systems that reduces waste generation, optimizes resource use, and fosters closed-loop production systems.

To achieve these ambitious objectives, according to Stahel (2016), CE incorporates principles such as design for longevity, modularity, and recyclability, as well as strategies such as resource sharing, product life extension, and material recovery. However, according to Chauhan et al (2023), in order to realize its full potential, the CE paradigm requires not only the adoption of these principles and strategies, but also an effective and sustainable digital infrastructure.

DOI: 10.2478/picbe-2024-0073

The convergence between the Information Technology (IT) and Operational Technology (OT) systems using Internet of Things (IoT) technologies may prove to be the missing element for implementing a sustainable digital infrastructure towards a smart circular economy model.

This article is a systematic review that aims to provide an overview of the Information Technology and Operational Technology convergence using Internet of Things within the Circular Economy context and to identify what are the main challenges, the role, and the best practices and recommendations for implementing such a sustainable digital infrastructure solution as well as validating whether the research hypotheses are true or false.

The following research hypotheses are defined as part of this research:

(1) Hypothesis 1 – The IT and OT convergence using IoT technologies within the CE context is influenced by various challenges, such as technical complexities, cybersecurity risks, organizational behaviour, and workforce skill gaps, which can impact its effectiveness and widespread adoption.

(2) Hypothesis 2 – The integration of IT and OT through IoT technologies plays a pivotal role in enhancing the operational efficiency and environmental sustainability within the CE context, contributing to resource optimization and waste minimization.

(3) Hypothesis 3 – Effective implementation of the IT/OT convergence in the CE context through IoT technologies requires adherence to industry best practices such as embracing open standards, investing in advanced technical capabilities, addressing organizational and cultural barriers, and developing a diverse and skilled workforce.

The present paper is organized as following: the next section provides a brief literature review on the IT/OT convergence, the main IoT technologies, and the CE concepts. Furthermore, the research methodology section includes the research design, questions, methodology, data collection, and analysis used in this study. The research findings as well as their implications and relevance are presented in the results and discussions section. The conclusion section summarizes the main contributions of this study, the limitations and it recommends areas for future research.

Literature review

IT/OT convergence

The IT/OT convergence refers to the integration of traditional OT systems, which are used to monitor and control industrial processes and equipment such as industrial control systems (ICS) and supervisory control and data acquisition (SCADA) systems, with IT systems, which are used for data-centric computing tasks like enterprise resource planning (ERP) and customer relationship management (CRM) systems (Murray, 2017).

The Figure 1, depicted below, presents the continuous technology alignment over time between the IT and OT domains with the use of information technologies in industrial systems having the aim to establish a common technology platform.

IT systems typically deal with the processing, storage, and transmission of data, whereas OT systems focus on the monitoring and control of industrial processes, such as manufacturing, energy production, and transportation (Gharpure, 2021). As documented by Berardi et al (2023), an essential aspect of IT/OT convergence is the adoption of common protocols and standards to enable seamless communication between IT and OT systems.

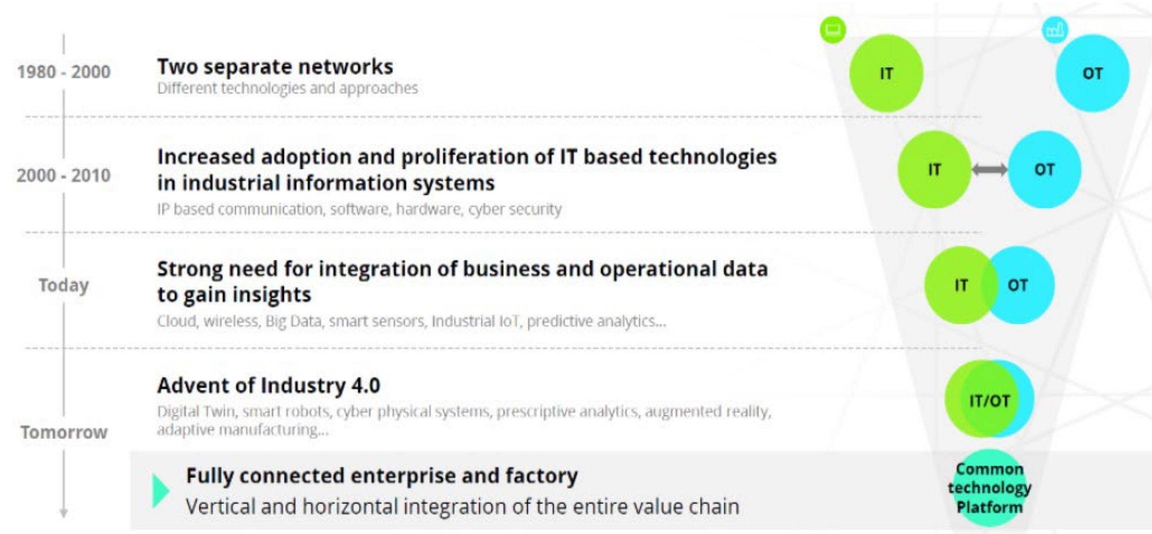

Figure 1. IT and OT convergence over time

Source: Cigref (2019).

Drivers of the IT/OT convergence

The main drivers of IT/OT convergence include technological advancements, market pressures, and regulatory and environmental concerns.

*Technological advancement*s are represented by the rapid developments in the IT domain, such as the emergence of the IoT, Big Data, and Cloud Computing technologies, which have facilitated the integration of IT and OT systems in industrial settings. According to Ashton (2009), these IoT technologies enable real-time monitoring, control, and optimization of the industrial processes, making the IT/OT convergence increasingly relevant and valuable for the industrial and commercial applications.

Market pressures are represented by the intense competition in global markets and the increasing demand for the customized products and services which, in turn, have forced the industrial organizations to improve their operational efficiency and agility. In Berardi et al (2023), the IT/OT convergence is seen as a way to achieve better operational objectives by leveraging the capabilities of IT systems to further enhance the performance of OT systems.

Regulatory and environmental concerns are represented by the growing awareness of the environmental issues and the introduction of stricter regulations which have led organizations to seek ways to reduce their environmental footprint. In Müller et al (2018), the IT/OT convergence is seen as sustainable digital infrastructure supporting various size organisations to achieve their sustainability and carbon neutral objectives with the optimization of resource use, energy efficiency, and waste reduction in industrial operations.

Benefits of the IT/OT convergence

The main benefits of IT/OT convergence include enhanced operational efficiency, improved decision-making, increased agility and flexibility, and environmental benefits.

Enhanced operational efficiency: the IT/OT convergence can improve the efficiency of industrial processes by enabling real-time monitoring, control, and optimization (Shilenge and Telukdarie, 2022; Ehie and Chilton, 2020). According to Müller et al (2018), this further allows organizations to reduce downtime, minimize waste, and optimize resource use, resulting in cost savings and increased productivity.

Improved decision-making: the integration of IT and OT systems facilitates data-driven decision-making, as IT systems can process and analyse large volumes of data generated by OT systems (Shilenge and Telukdarie, 2022). This supports more informed and timely decisions of the management and leading to better overall operational outcomes (Berardi et al, 2023).

Increased agility and flexibility: the IT/OT convergence enables organizations to respond more quickly to changing market conditions and customer demands (Ehie and Chilton, 2020). This increased agility and flexibility can help organizations to maintain their competitive edge and adapt to the evolving industrial landscape (Berardi et al, 2023).

Environmental benefits: the IT/OT convergence can contribute to the reduction of industrial waste and improve the resource use that can help the organizations to minimize their environmental impact and comply with the relevant regulations (Müller et al, 2018).

Challenges of the IT/OT convergence

Despite the potential benefits, the IT/OT convergence also comes with several challenges further detailed below.

Integration complexity: integrating IT and OT systems can be a complex and resource-intensive process, as it requires the alignment of different technologies, processes, and organizational structures (Ehie and Chilton, 2020). According to Givehchi et al (2017), many industrial organizations still rely on legacy OT systems that may not be easily integrated with newer IT systems and IoT technologies. Retrofitting or replacing these systems can be costly and time-consuming and, as mentioned by Felser et al (2019), developing strategies for integrating legacy OT systems with newer IT technologies is essential for successful IT/OT convergence which usually comes not without significant implementation costs and substantial organizational change management efforts.

Security and privacy concerns: the integration of IT and OT systems can introduce new security and privacy risks, as cyber-attacks on IT systems can potentially compromise the safety and performance of OT systems (Kuusk et al, 2013). Ensuring the security of industrial control systems (ICS) and other OT components is critical to maintaining the integrity and safety of industrial processes (Ehie and Chilton, 2020). Furthermore, the IT/OT convergence can raise data privacy concerns, particularly when sensitive information is exchanged between OT and IT systems (Kuusk et al, 2013). According to Azarmipour et al (2021), addressing these requires the implementation of robust security measures such as multi-layered defense strategies, continuous monitoring, data protection measures like encryption, access control, authentication, and authorizations mechanisms, and, last but not least, active intrusion detection systems.

Skill gaps: the successful implementation of the IT/OT convergence requires a workforce with a diverse range of skills, spanning both IT and OT domains (Shilenge and Telukdarie, 2022). According to Kuusk and Gao (2015), this skilled workforce can be challenging to achieve, as many organizations face a shortage of qualified professionals with the necessary expertise and, in fact, organizations must invest in training and reskilling programs to ensure a smooth transition to a converged IT/OT environment.

Interoperability and standardization: a lack of standardized protocols and communication technologies can hinder the seamless integration of IT and OT systems (Kuusk et al, 2013). According to Felser et al (2019), addressing this issue is not a standalone organizational activity, but it requires the development and adoption of industry-wide standards and guidelines, as well as the development of integration frameworks and middleware solutions, which can be a slow and complex process.

Internet of things (IoT) technologies
IoT refers to the interconnection of physical devices, vehicles, buildings, and other items embedded with sensors, software, and network connectivity, enabling these objects to collect and exchange data through Internet protocols (Ashton, 2009).

Furthermore, according to Lipnicki et al (2018) and Rejeb et al (2022), IoT technologies can be applied in various industrial settings to support the IT/OT convergence with the use of specialized industrial internet of things (IIoT).

Industrial internet of things (IIoT)
The IIoT is a subset of advanced IoT technologies that focuses specifically on industrial applications, such as manufacturing, energy, and transportation (Boyes et al, 2018).

As per Lipnicki et al (2018), IIoT can be considered a key component of industry 4.0, a term that refers to the ongoing transformation of industrial operations through the integration of advanced digital technologies, including cloud computing, big data, artificial intelligence, and robotics.

IIoT technologies enable the collection, processing, and analysis of data from various industrial processes, supporting real-time monitoring, control, and decision-making and are designed to improve the efficiency, productivity, and sustainability of industrial processes by integrating IT/OT systems (Boyes et al, 2018).

According to Al-Fuqaha et al (2015), the main IIoT technologies encompass a range of devices and systems, including: *sensors*, *actuators*, *communication networks*, and *data analytics platforms*, which facilitate seamless communication and data exchange.

Sensors enable the collection of data from various physical environment sources, such as temperature, pressure, and vibration (Al-Fuqaha et al, 2015). According to Boyes et al (2018), all the data collected by the sensors serves as the foundation for real-time monitoring, control, and decision-making in industrial processes.

Actuators: are devices that convert electrical, hydraulic, or pneumatic signals into physical or mechanical actions, enabling the control of industrial processes (Al-Fuqaha et al, 2015). According to Boyes et al (2018), the actuators play a crucial role in the automation and optimization of manufacturing operations and other industrial use cases or applications.

Communication networks: facilitate the exchange of data between sensors, actuators, edge computing nodes, and cloud-based data processing and analytics platforms (Al-Fuqaha et al, 2015). According to Boyes et al (2018), these networks must support the specific requirements of the industrial processes and applications in terms of latency, reliability, and scalability. Several communication protocols have been developed to support the specific requirements of IoT applications, such as low power consumption, long-range communication, and real-time data transmission. Some popular IoT communication protocols include MQTT, CoAP, and OPC-UA (Al-Fuqaha et al, 2015). MQTT is a lightweight messaging protocol designed for high latency and low bandwidth networks, while CoAP is a web-based protocol optimized for low-power devices. OPC-UA is an industrial communication protocol that enables secure and reliable data exchange between OT systems and IT systems.

Data analytics platforms: enable the processing, analysis, and visualization of data collected by IIoT systems (Al-Fuqaha et al, 2015). These data analytics platforms often leverage advanced data processing techniques, such as machine learning (ML) and artificial intelligence (AI) to support predictive maintenance, process optimization, and other industry 4.0 use cases.

IoT security and privacy

Securing IoT devices and networks is a critical aspect of IT/OT convergence, as security breaches can compromise the safety and performance of industrial processes (Ehie and Chilton, 2020).

As seen in specific IoT and IT/OT related research papers (Azarmipour et al, 2021; Kim et al, 2023), IoT systems security measures include device authentication, data encryption, and intrusion detection systems, among others. Furthermore, according to Murray et al (2017), privacy concerns related to the IoT data must also be addressed, particularly when sensitive information is involved such as with the data resulting from critical infrastructure systems.

Device authentication and access control mechanisms ensure that only authorized devices and users can access the IoT network and associated data (Azarmipour et al, 2021). These mechanisms can include password protection, digital certificates and cryptographic keys, and biometric authentication

Data encryption and secure communication techniques, such as symmetric and asymmetric cryptography, can be used to protect the confidentiality and integrity of IoT data with encryption during transmission between IoT devices and data processing and storage platforms (Azarmipour et al, 2021). Secure communication protocols, such as transport layer security (TLS), can also be implemented to protect data from unauthorized access and tampering.

Intrusion detection systems (IDS) monitor network traffic for signs of malicious activity, such as attempts to gain unauthorized access or disrupt the operation of IoT devices. IDS can be implemented at various levels of the IoT architecture, including the device, edge, fog, and cloud layers (Azarmipour et al, 2021).

Data privacy concerns related to IoT data must be addressed, particularly when sensitive information is involved (Murray et al, 2017). Techniques such as data anonymization, aggregation, and differential privacy can be employed to protect the privacy of individuals while still enabling the analysis of IoT data for industrial applications.

According to Kim et al (2023), other technologies such as *Blockchain* and *Distributed Ledger* technologies were proposed as potential solutions for enhancing the security and privacy of IoT data, enabling the secure and transparent sharing of information within multiple entities.

Circular economy (CE)

The circular economy (CE) is a systemic approach that counters the traditional linear economy development of "*take-make-dispose*" approach, where the raw materials are collected, transformed into products, and eventually disposed of as waste after their use (MacArthur, 2013).

In contrast, the CE aims to decouple resource consumption and environmental impacts from the economic growth by promoting a sustainable economic model and emphasizing the reduction, reuse, repair, and recycling of resources to minimize waste and optimize resource use (MacArthur, 2013).

CE Principles

According to MacArthur (2013), CE is based on three core principles: *designing out waste and pollution*, *keeping products and materials in use*, and *regenerating natural systems*.

Preserve and enhance natural capital (designing out waste and pollution) – this principle advocates for the efficient use of resources and the minimization of waste, pollution, and environmental degradation (MacArthur, 2013). According to Kirchherr et al (2017), the CE focuses on regenerative and restorative practices, such as recycling, remanufacturing, and the use of renewable energy sources.

Optimize resource yields (keeping products and materials in use) – this principle emphasizes the need to keep products, components, and materials at their highest utility and value throughout their lifecycle (MacArthur, 2013). As mentioned in Bocken et al (2016), strategies for this principle may include: product life extension, sharing, and product-as-a-service models, which can further help to reduce resource consumption and waste generation.

Foster system effectiveness (regenerating natural systems) – this principle involves minimizing negative externalities associated with economic activities, such as pollution and waste, while enhancing positive externalities, such as employment, innovation, and social welfare (MacArthur, 2013). According to Geissdoerfer et al (2017), this principle requires a systems-thinking approach that considers the interdependencies between various economic, social, and environmental factors.

CE Domains

As seen in the specific research literature (Bocken et al, 2016; Lieder and Rashid, 2016), CE can be applied across various industrial domains and at various stages of the product lifecycle, such as product design, manufacturing, consumption, and end-of-life management in order to create value and minimize negative environmental impacts.

Product design and development - integrating CE principles into the design and development of products can lead to the creation of more sustainable and resource-efficient products (Bocken et al, 2016). According to Bakker et al (2014), product design and development strategies can include designing for durability, repairability, upgradability, and recyclability, as well as the use of eco-friendly materials. Eco-design such as material selection, modularity, and design for disassembly, can also support circularity by facilitating the recycling, remanufacturing, or refurbishment of products at the end of their lifecycle (Bakker et al, 2014).

Manufacturing and production – CE principles can be applied to manufacturing processes to improve resource efficiency, minimize waste and pollution, and promote the use of renewable energy sources (Lieder and Rashid, 2016). This can involve the adoption of cleaner production technologies and sustainable materials and energy sources, the implementation of industrial symbiosis, lean manufacturing and process optimization, and, according to Uçar et al (2020), also the integration of digital technologies, such as IoT and AI, to optimize resource use and move from a "*take-make-dispose*" approach to a "*cradle-to-cradle*" approach.

Consumption – Encouraging sustainable consumption patterns, such as sharing, leasing, or subscribing to products and services, can support CE principles by reducing the demand for new resources and minimizing waste generation (MacArthur, 2013). Indeed, as shown also in Morone and Navia (2016), collaborative consumption models, such as car-sharing or tool libraries, can contribute to the circular economy by optimizing the use of existing assets and reducing the need for new products.

Supply chain and end-of-life management – CE principles can be integrated into supply chain management practices and in end-of-life management processes to enhance resource efficiency and reduce waste, while promoting the recovery, recycling, and remanufacturing of products and materials (Taddei et al, 2022). This can involve the implementation of closed-loop supply chains, reverse logistics systems, and the use of digital technologies to improve transparency and traceability and to facilitate take-back programs for the recovery and recycling of valuable materials (Pagoropoulos et al, 2017).

Waste management and recycling – CE strategies can be applied to waste management and recycling processes to recover valuable materials from waste streams and reintegrate them into the economy (Zhang et al, 2019). This can involve the development of innovative recycling technologies, the promotion of waste-to-energy solutions, and the implementation of extended producer responsibility (EPR) policies.

Business models and policy – CE principles can be incorporated into business models and policy frameworks to support the transition to a more sustainable and resource-efficient economy (Stahel, 2016). According to Geissdoerfer et al (2017), such business models examples include product-as-a-service models, sharing economy platforms, and the adoption of circular economy policies and regulations.

Methodology

Research Design

The research design for this study is a systematic literature review (SLR) that adheres to established academic research guidelines and methodologies (Kitchenham and Charters, 2007; Tranfield et al, 2003).

The SLR approach allows for the identification, evaluation, and synthesis of the existing body of knowledge on IT/OT convergence, IoT technologies, and their application within the CE. This design, depicted as a conceptual mode in Figure 2, ensures a rigorous and transparent process, minimizing bias and ensuring the validity and reliability of the findings in (1) identifying the challenges, (2) defining the role, and (3) recommending best practices for the implementation of the IT/OT convergence with IoT in the CE context.

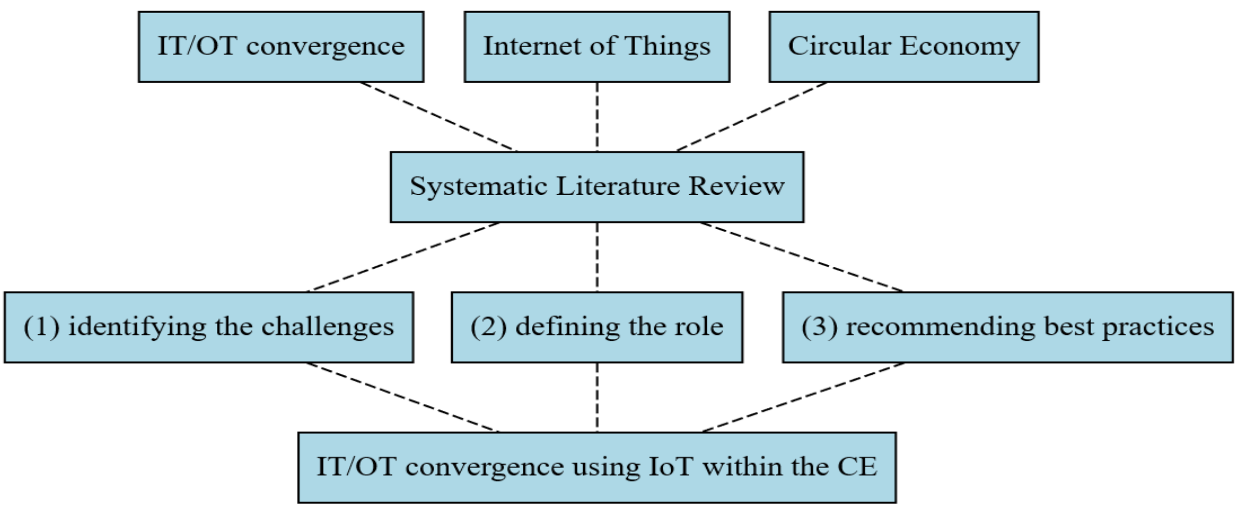

Figure 2. Research design conceptual model

Source: Authors' own contribution.

Furthermore, in order to test whether the research hypotheses are true or false, the following research questions are defined in this study.

Research Questions

The research questions guiding this study are the following:

*[**RQ1**] What are the main challenges associated with the implementation of the IT/OT convergence using IoT technologies within the CE?*

*[**RQ2**] What is the role of the IT/OT convergence using IoT technologies in the CE?*

*[**RQ3**] What are the best practices and recommendations to successfully implement the IT/OT convergence using IoT technologies within the CE?*

Research Methodology

The research methodology follows the systematic literature review (SLR) method respecting the guidelines outlined by Kitchenham and Charters (2007) and consists of six stages undertaken in the various sections of this article: (1) defining research questions, (2) identifying relevant sources of literature, (3) conducting a comprehensive search for primary studies, (4) selecting and appraising the quality of the studies, (5) extracting and synthesizing data, and (6) reporting the results and drawing conclusions.

Data Collection

Data collection begins with a comprehensive search for primary studies using multiple academic databases, such as: *Web of Science*, *Scopus*, *IEEE Xplore*, *ScienceDirect*, and *Google Scholar*.

The search strategy incorporates relevant keywords and phrases, including: "*information technology*," "*operational technology*," "*IT/OT convergence*," "*internet of things*," "*circular economy*," and "*sustainability*"; while Boolean operators (*and*, *or*, *not*) have been applied to combine and refine the search results.

Various results have been obtained in different academic databases and search engines, ranging from *4* results up to approximately *300* results depending on the Boolean operators and the other filters and combination of the keywords.

The inclusion and exclusion criteria are established to filter out irrelevant studies and ensure that only high-quality, relevant, and up-to-date articles are included in the review. The inclusion criteria are: (1) articles published in peer-reviewed journals or conference proceedings, (2) articles focusing on IT/OT convergence, IoT technologies, and CE, (3) articles presenting empirical, theoretical, or conceptual contributions, and (4) articles published in English. The exclusion criteria are: (1) articles not meeting the inclusion criteria, (2) duplicates, and (3) articles with insufficient data or unclear methodology.

From the initial search, a total of *300* articles were identified. After applying the inclusion and exclusion criteria and removing duplicates, *104* articles were selected for further analysis and understanding the context. Among these, *45* articles were directly cited in the present study.

Data Analysis

Data extraction and synthesis involve a qualitative content analysis approach (Elo and Kyngäs, 2008), in which the selected articles are read thoroughly, and relevant data are coded and organized into themes and sub-themes.

In the data synthesis process, a qualitative content analysis approach was employed to synthesize and categorize the information gathered from the initial 104 articles. The process involved the following steps: (1) familiarization with the data, (2) generating initial codes, (3) searching for themes, (4) reviewing and refining themes, (5) defining and naming themes, and (6) writing the report.

The data synthesis process was aimed to identify common patterns, trends, and relationships among the studies in order to address the research questions and validate the research hypotheses.

Results and discussions

The research findings are further presented following the structure of the research questions. The research hypotheses are also discussed given the results and a digital transformation roadmap is proposed.

[RQ1] What are the main challenges associated with the implementation of the IT/OT convergence using IoT technologies within the CE?

According to the insights found and analyzed from the literature review (Chauhan et al, 2022; Shilenge and Telukdarie, 2022; Pagoropoulos et al, 2017; Müller et al, 2018) and as further seen in the novel research of Hina et al (2022) and Ingemarsdotter et al (2020), there are several challenges that needs to be addressed for a successful implementation if the IT/OT convergence using IoT technologies within the CE context, as presented in Table 1.

Table 1. Main challenges for the IT/OT convergence using IoT technologies within the CE

# Challenges	***Relevant Examples***	***Brief Description***
Technological	Integration of legacy systems	Many organizations struggle with integrating existing IT/OT systems and IoT devices due to a lack of interoperability and compatibility
	Data management and processing	The large volume of data generated by IoT devices can be challenging to manage and process, requiring advanced analytics capabilities
	Scalability	The IoT technologies become more widely adopted and, as a result, organizations must address issues related to the scalability of IT/OT systems and IoT infrastructure
Security and privacy	Device authentication and access control	Ensuring the security of IoT devices and systems requires robust authentication and access control mechanisms
	Data encryption and secure communication	Protecting the privacy and integrity of data generated by IoT devices necessitates the use of encryption and secure communication protocols
	Intrusion detection systems	Implementing intrusion detection systems can help organizations to identify and respond to security threats targeting IoT devices and networks
Organizational and cultural	Resistance to change	Employees may resist the adoption of new technologies and processes due to the fear of job loss or a lack of understanding of the benefits
	Lack of awareness and understanding	Many organizations may not fully understand the potential of IT/OT convergence using IoT technologies within the CE, leading to a lack of investment and commitment.
	Siloed organizational structures	Traditional organizational structures may impede the integration of IT/OT systems and IoT technologies, hindering collaboration and the realization of CE benefits.
Skills Gap	IoT management and programming	Many organizations lack the technical expertise required to manage and program IoT devices effectively
	Data analytics and decision-making	Companies may not have the necessary skills to analyze the vast amounts of data generated by IoT devices and make informed decisions based on this information
	CE principles and strategies	A lack of understanding of CE principles and strategies can jeopardize the effective integration of IT/OT convergence using IoT technologies in support of the CE objectives

Source: Adapted from the literature review (Hina et al, 2022; Ingemarsdotter et al, 2020).

Research hypothesis 1 (Challenges in IT/OT convergence using IoT in the CE) – Considering the results presented in Table 1, this hypothesis is confirmed. The research identifies significant challenges such as technological integration complexities, cybersecurity and privacy concerns, organizational behaviour and cultural barriers, and lack of proper workforce and expertise in understanding the domains, which impact its effectiveness and widespread adoption.

[RQ2] What is the role of the IT/OT convergence using IoT technologies in the CE?

According to the insights found and analyzed from the literature review (Chauhan et al, 2022; Fraga-Lamas et al, 2021; Pagoropoulos et al, 2017), the IT/OT convergence using IoT technologies can be used to support and enhance the circular economy by developing smart: *circular loops*, *circular products*, and *circular applications*.

Smart circular loops

According to the novel research from Bressanelli et al (2022) and Alcayaga et al (2019), the *smart circular loop* is an approach that combines the principles of the circular economy with the industry 4.0 digital technologies, like IT/OT convergence through IoT infrastructure.

A smart circular loop optimizes resource use, reduce waste, and implement environmentally friendly strategies across the entire product or service lifecycle from design and production to consumption and end-of-life management supported by digital technologies (Lieder and Rashid, 2016; Laskurain-Iturbe et al, 2021).

Some of the most important smart circular loop's use cases found in the literature review (Chauhan et al, 2022; Uçar et al, 2020; Kristoffersen et al, 2020) are presented in Table 2.

Table 2. Smart circular loops

# Use case	***Description***
Product-as-a-Service (PaaS)	Products are provided as services, not goods, encouraging efficient resource use and longer product lifecycles. IoT enables real-time monitoring and maintenance during the entire lifecycle.
Predictive maintenance	IoT-enabled sensors and data analytics predict IT/OT equipment failures before they occur, extending their lifespan and minimizing waste. Predictive maintenance can also contribute to energy efficiency by optimizing equipment operation and reducing downtime.
Digital Twins	Virtual representations of IT and OT physical assets, processes, or systems, used for real-time monitoring and optimization. Digital Twins inform design decisions and support the development of circular business models by optimizing resource use and waste reduction.
Digital circular practices	IoT helps track product performance and maintenance data, supporting the extension of IT/OT (digital) product/service lifecycles and improving supply chain processes for end-of-life products/services and circularity practices. A digital sustainable infrastructure based on the IT/OT convergence using IoT technologies fully supports (digital) products/services circular practices such as: reduce, reuse, recycle, recover, refuse, rethink, repair, refurbish, remanufacture, repurpose.

Source: Adapted from the literature review (Chauhan et al, 2022; Kristoffersen et al, 2020).

Smart circular products

Smart circular products are developed with CE principles and make use of IT and OT integration through the IoT for the constant monitoring, controlling, and improving of how products perform and use resources (Bressanelli et al, 2022).

The smart circular products found in the literature review (Bressanelli et al, 2022; Alcayaga et al, 2019; Kristoffersen et al, 2020) are further presented in Table 3.

Table 3. Smart circular products

Categories	***Brief Description***
Modular and upgradable products	These are designed for easy disassembly, upgrades, or repairs, which helps extend their life and reduce waste. IoT technologies play a role by tracking how components perform and pinpointing opportunities for upgrades or repairs. IoT sensors also gather data on how the products are used, which is useful for future product improvements and promoting circularity.
Products with embedded sensors	Embedding sensors in products enables the continuous monitoring of how they perform, how they're used, and the environmental conditions they're exposed to. This information is crucial for making informed design choices, optimizing the use of resources, and supporting circular economy loops like Product as a Service (PaaS) and predictive maintenance. These sensors can also lead to the development of materials and systems that can self-repair, thus enhancing the product's longevity and circularity.
Products with energy harvesting capabilities	Integrating energy-harvesting technologies (like solar panels or piezoelectric materials) into products allows them to generate their own energy from the environment. This reduces dependence on non-renewable energy sources and adds to the product's lifecycle circularity.

Source: Adapted from the literature review (Alcayaga et al, 2019; Fraga-Lamas et al, 2021).

Smart circular applications

The IT/OT convergence using IoT technologies can lead to the development of smart circular applications in many CE domains for better resource efficiency, minimizing waste, and environmental performance (Alcayaga et al, 2019).

The domains for smart circular economy applications found in the literature review (Voulgaridis et al, 2022; Borgia, 2014; Rejeb et al, 2022) are presented in Table 4.

Table 4. Smart circular applications

Domains	***Brief Description***
Smart manufacturing	Combining IT/OT and IoT leads to smarter manufacturing methods like digital twins and additive manufacturing. These technologies help optimize resource use and cut down waste during production.
Smart waste management systems	IoT-enhanced waste management optimizes waste collection and recycling. It provides real-time data on waste levels and bin capacities, improving the routing of collection vehicles and lowering collection costs.
Smart energy management systems	IoT technologies in energy management monitor and control energy use in industrial settings. This optimizes energy consumption and reduces greenhouse gas emissions. These systems also support renewable energy and energy storage, aiding the shift to a low-carbon economy.
Smart supply chain management systems	IoT in supply chain management improves transparency and traceability, tracking products and materials through their lifecycle. This leads to more efficient closed-loop supply chains with less waste and resource consumption.
Smart product lifecycle management systems	IoT-enabled Product Lifecycle Management (PLM) systems provide data on product performance and maintenance needs. This helps in extending product life through predictive maintenance and remote services, reducing physical intervention and downtime.
Smart industrial symbiosis	The integration of IT/OT and IoT assists in identifying and exchanging by-products and waste between industrial facilities. This fosters industrial symbiosis networks, where resource sharing and collaboration lead to reduced resource consumption and improved environmental impact.

Source: Adapted from the literature review (Voulgaridis et al, 2022; Rejeb et al, 2022).

Research hypothesis 2 (Role of IT/OT convergence using IoT in the CE) – This hypothesis is also confirmed. The study highlights the critical role of IT/OT convergence in enhancing operational efficiency and environmental sustainability within CE, particularly through smart circular loops, products, and applications.

[RQ3] What are the best practices and recommendations to successfully implement the IT/OT convergence using IoT technologies within the CE?

To overcome various challenges associated with the implementation of the IT/OT convergence using IoT technologies within the CE context, according to the insights found and analyzed from the literature review (Kuusk et al, 2013; Kim et al, 2023; Hina et al, 2022; Ingemarsdotter et al, 2020) as well as seen in the novel research from Askoxylakis (2018) and Gräßler and Pottebaum (2021), organizations can address individual pain points at different levels by following some best practices and recommendations as presented in Table 5.

Table 5. Best practices and recommendations for the IT/OT Convergence using IoT within the CE

Best practices	*Recommendations*
Overcoming Technological Challenges	Adopt open standards and protocols, such as OPC UA, MQTT, and AMQP to facilitate interoperability and integration between IT/OT systems and IoT devices.
	Invest in advanced data analytics capabilities, including Machine Learning and AI, to manage and process the vast amounts of data generated by IT/OT systems and IoT devices.
	Use edge and fog computing architectures to enable efficient data processing, reduce latency, and improve scalability in the IT/OT integration and IoT deployments
Addressing Security and Privacy Concerns	Implement robust authentication and access control mechanisms, such as public key infrastructure (PKI) and role-based access control (RBAC), to secure IoT devices and systems
	Adopt lightweight cryptographic algorithms and secure communication protocols, such as TLS, to protect the privacy and integrity of IoT-generated data, especially in resource-constrained devices
	Use blockchain technology to enhance data integrity, security, and traceability in IoT ecosystems, particularly in supply chain management and product lifecycle management
Tackling Organizational and Cultural Barriers	Launch internal communication campaigns and workshops to educate employees on the benefits and potential of IT/OT convergence and IoT technologies within the CE
	Establish cross-functional teams, including members from IT, OT, and other departments, to promote collaboration and ensure the successful implementation of IT/OT convergence using IoT technologies
	Implement a IT service management framework, such as ITIL, to facilitate the transition to a circular economy mindset and the adoption of IT/OT convergence and IoT technologies
Bridging the Skills Gap	Offer hands-on training programs and certification courses in IoT device management, programming, data analytics, and CE principles and strategies
	Develop partnerships with universities, research institutions, and industry organizations to access cutting-edge research and expertise, as well as to create internship and co-op opportunities for students
	Encourage a culture of continuous learning and development through regular workshops, seminars, and webinars on the latest advancements in the IT/OT convergence, IoT, and CE domains

Source: Adapted from the literature review (Askoxylakis, 2018; Kuusk et al, 2013).

Research hypothesis 3 (Best practices for IT/OT convergence using IoT in the CE) – The hypothesis is validated by the research. It emphasizes the importance of best practices and digital transformation programs aligned to the business strategic objectives such as adopting industry open standards, investing in advanced technical capabilities, addressing organizational changes, and developing a skilled workforce for a successful implementation.

The IT/OT convergence using IoT technologies within the CE context is further depicted as a conceptual model in Figure 3 and based on the research results and the literature review, it is the authors opinion that this represents a sustainable digital infrastructure towards a smart circular economic model.

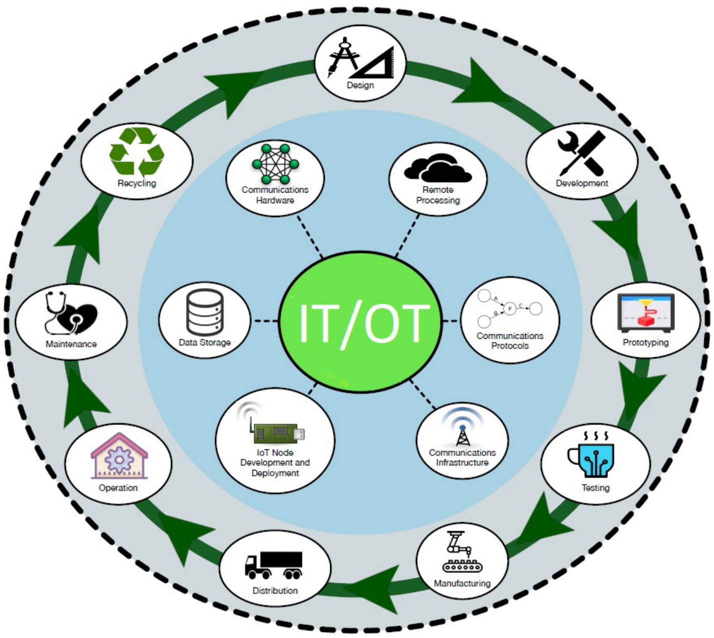

Figure 3. A conceptual model for IT/OT convergence using IoT within the CE.
Source: Authors' own contribution adapted from Fraga-Lamas et al (2021).

However, to build such a sustainable converged digital infrastructure and benefit from a successful implementation of this solution, the authors consider that organizations should undertake a series of steps and adopt industry best practices from the product and service management frameworks and development lifecycles such as ITIL, Agile, and DevSecOps methodologies, which should be further tailored under a digital transformation roadmap to align with the organization's business strategy and its internal and external environment and to promote cross-domain collaboration to achieve the circular economy and sustainable development goals.

Conclusion

In this paper, we have reviewed the IT/OT convergence using IoT technologies in the CE context. We have also identified the main challenges, the role, and the best practices and recommendations for implementing such a sustainable digital infrastructure solution.

While our systematic review has provided valuable insights for the academics and practitioners alike, there are some **research limitations**:

- The literature review may not have covered all relevant studies, as the field is rapidly evolving, and new research is continuously emerging.

- Our recommendations and best practices may not be universally applicable, as different organizations and industries may face unique challenges and constraints.

Future **research directions** could address these limitations by conducting more in-depth case studies such as:

- To explore case studies of successful IT/OT convergence using IoT technologies within the CE context in different industry sectors.
- To investigate the long-term economic, social, and governance impact of this implementation on businesses and the environment.
- To assess the role of government policies and regulations in facilitating this convergence.

Our research has revealed that IT/OT convergence using IoT technologies hold significant promise for transforming traditional linear economic models into more sustainable, digital, smart, circular economic models.

References

Alcayaga, A., Wiener, M., & Hansen, E.G. (2019). Towards a framework of smart-circular systems: An integrative literature review. *Journal of Cleaner Production*, 221, 622-634.

Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash, M. (2015). Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. *IEEE Communications Surveys & Tutorials*, 17(4), 2347-2376.

Ashton, K. (2009). That 'internet of things' thing. *RFID Journal*, 22(7), 97-114.

Askoxylakis, I. (2018). A Framework for Pairing Circular Economy and the Internet of Things. In *2018 IEEE International Conference on Communications (ICC)*. Kansas City, MO, USA.

Azarmipour, M., Hana, R., Ansar, Z., & Kleinert, T. (2021). Secure Communication between Information Technology and Operational Technology. In *47th Annual Conference of the IEEE Industrial Electronics Society (IECON 2021)* (pp. 1-6). Toronto, ON, Canada.

Bakker, C., Wang, F., Huisman, J., & Den Hollander, M. (2014). Products that go round: exploring product life extension through design. *Journal of Cleaner Production*, 69, 10-16.

Berardi, D., Callegati, F., Giovine, A., Melis, A., Prandini, M., & Rinieri, L. (2023). When Operation Technology Meets Information Technology: Challenges and Opportunities. *Future Internet*, 15(3), 95.

Bocken, N. M., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, 33(5), 308-320.

Borgia, E. (2014). The Internet of Things vision: Key features, applications and open issues. *Computer Communications*, 54, 1-31.

Boyes, H., Hallaq, B., Cunningham, J., & Watson, T. (2018). The industrial internet of things (IIoT): An analysis framework. *Computers in Industry*, 101, 1-12.

Bressanelli, G., Adrodegari, F., Pigosso, D.C.A., & Parida, V. (2022). Towards the Smart Circular Economy Paradigm: A Definition, Conceptualization, and Research Agenda. *Sustainability*, 14(9), 4960.

Chauhan, C., Parida, V., & Dhir, A. (2022). Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technological Forecasting and Social Change*, 177, 121508.

Cigref. (2019). *IT/OT convergence*. Retrieved January 18, 2024 from: https://www.cigref.fr/wp/wp-content/uploads/2020/02/Cigref-IT-OT-Convergence-Fruitful-integration-information-operational-systems-December-2019-EN.pdf

Ehie, I. C., & Chilton, M. A. (2020). Understanding the influence of IT/OT Convergence on the adoption of Internet of Things (IoT) in manufacturing organizations: An empirical investigation. *Computers in Industry*, 115, 103166.

Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing*, 62(1), 107-115.

Felser, M., Rentschler, M., & Kleineberg, O. (2019). Coexistence standardization of operation technology and information technology. *Proceedings of the IEEE*, 107(6), 962-976.

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(17), 5745.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757-768.

Gharpure, R., Kardekar, A., & Vyas, R. (2021). Industry 4.0 Digital Transformation: Information Technology (IT)–Operations Technology (OT) Convergence Model and its Implementation in Asset-Heavy Manufacturing Industry. *IEEE Transactions on Industrial Informatics*, 17(5), 3235-3244.

Givehchi, O., Landsdorf, K., Simoens, P., & Colombo, A. W. (2017). Interoperability for industrial cyber-physical systems: An approach for legacy systems. *IEEE Transactions on Industrial Informatics*, 13(6), 3370-3378.

Gräßler, I., & Pottebaum, J. (2021). Generic product lifecycle model: a holistic and adaptable approach for multi-disciplinary product–service systems. *Applied Sciences*, 11(10), 4516.

Hina, M., Chauhan, C., Kaur, P., Kraus, S., & Dhir, A. (2022). Drivers and barriers of circular economy business models: Where we are now, and where we are heading. *Journal of Cleaner Production*, 333, 130049.

Ingemarsdotter, E., Jamsin, E., & Balkenende, R. (2020). Opportunities and challenges in IoT-enabled circular business model implementation–A case study. *Resources, Conservation and Recycling*, 162, 105047.

Kim, J., Park, J., & Lee, J.-H. (2023). Analysis of Recent IIoT Security Technology Trends in a Smart Factory Environment. In *2023 International Conference on Artificial Intelligence in Information and Communication (ICAIIC)* (pp. 840-845).

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221-232.

Kitchenham, B., & Charters, S. (2007). Guidelines for performing systematic literature reviews in software engineering. *Keele University and Durham University Joint Report*. Retrieved January 18, 2024 from: http://www.cs.ecu.edu/gudivada/research/papers/guidelines-for-se-literature-reviews-full.pdf

Kristoffersen, E., Blomsma, F., Mikalef, P., & Li, J. (2020). The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *Journal of Business Research*, 120, 241-261.

Kuusk, A. G., & Gao, J. (2015). Consolidating people, process and technology to bridge the great wall of operational and information technologies. In *Engineering Asset Management-Systems, Professional Practices and Certification: Proceedings of the 8th World Congress on Engineering Asset Management (WCEAM 2013) & the 3rd International Conference on*

Utility Management & Safety (ICUMAS) (pp. 1715-1726). Springer International Publishing.

Kuusk, A., Koronios, A., & Gao, J. (2013). Overcoming integration challenges in organisations with operational technology. In *24th Australasian Conference on Information Systems (ACIS 2013)* (pp. 1-15). RMIT University.

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. *Journal of Cleaner Production*, 321, 128944.

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, 115, 36-51.

Lipnicki, P., Lewandowski, D., Pareschi, D., Pakos, W., & Ragaini, E. (2018). Future of IoTSP – IT and OT Integration. In *IEEE 6th International Conference on Future Internet of Things and Cloud (FiCloud)* (pp. 203-207). Barcelona.

MacArthur, E. (2013). Towards the circular economy. Journal of Industrial Ecology, 2(1), 23-44.

Morone, P., & Navia, R. (2016). New consumption and production models for a circular economy. *Waste Management & Research*, 34(6), 489-490.

Müller, J. M., Kiel, D., & Voigt, K.-I. (2018). What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. *Sustainability*, 10(1), 247.

Murray, G., Johnstone, M. N., & Valli, C. (2017). The Convergence of IT and OT in Critical Infrastructure. In *15th Australian Information Security Management Conference (AISM)* (pp. 149-155). Perth, WA.

Pagoropoulos, A., Pigosso, D. C. A., & McAloone, T. C. (2017). The emergent role of digital technologies in the Circular Economy: A review. *Procedia CIRP*, 64, 19-24.

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. *Journal of Cleaner Production*, 331, 131439.

Shilenge, M. C., & Telukdarie, A. (2022). Optimization of Operational and Information Technology Integration Towards Industry 4.0. In *IEEE 31st International Symposium on Industrial Electronics (ISIE)* (pp. 1076-1081). Anchorage, AK, USA.

Stahel, W. R. (2016). The circular economy. *Nature*, 531(7595), 435-438.

Taddei, E., Sassanelli, C., Rosa, P., & Terzi, S. (2022). Circular supply chains in the era of Industry 4.0: A systematic literature review. *Computers & Industrial Engineering*, 108268.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, 14(3), 207-222.

Uçar, E., Le Dain, M.-A., & Joly, I. (2020). Digital technologies in circular economy transition: evidence from case studies. *Procedia CIRP*, 90, 133-136.

Voulgaridis, K., Lagkas, T., Angelopoulos, C. M., & Nikoletseas, S. E. (2022). IoT and digital circular economy: Principles, applications, and challenges. *Computer Networks*, 208, 109456.

Zhang, A., Venkatesh, V. G., Liu, Y., Wan, M., Qu, T., & Huisingh, D. (2019). Barriers to smart waste management for a circular economy in China. *Journal of Cleaner Production*, 240, 118198.