Towards the Smart Digital Circular Economy – Integrating Internet of Things and Digital Product Passports for Sustainability Innovation

Sorin-Daniel GHEORGHE[1]
Bucharest University of Economic Studies, Bucharest, Romania
gheorghesorin22@stud.ase.ro

This study explores the convergence of Internet of Things and Digital Product Passport technologies as a catalyst for achieving a Smart Digital Circular Economy. Anchored in a systematic literature review, the research identifies key IoT-driven use cases that enhance sustainability practices within Circular Economy context. The study also proposes a conceptual framework for integrating IoT data, interoperability standards, and circular metrics into DPP systems. By transforming static product information into dynamic, real-time data, the study demonstrates how IoT–DPP integration enables circular value creation, resource efficiency, and digital transparency across all stages of the product lifecycle. The findings offer both theoretical insights and practical guidance for industry stakeholders, policymakers, and researchers seeking to implement the digital transformation of circular economy practices and the circular transformation of the digital economy.

Keywords: *Circular economy, Digital Product Passports, Internet of Things, Sustainability*
DOI: 10.24818/issn14531305/29.3.2025.05

1 Introduction

The transition from a linear economic model to a Circular Economy (CE) paradigm has emerged as a pivotal sustainability strategy in addressing pressing environmental concerns, including resource depletion, excessive waste generation, and escalating carbon emissions [1]. The CE framework prioritizes resource efficiency, the waste reduction, the extension of product lifecycles, and the recovery and reintegration of materials into production processes, thereby fostering more sustainable patterns of consumption and production [2]. However, the effective operationalization of CE principles requires the deployment of advanced digital infrastructures capable of ensuring transparency, traceability, and continuous monitoring of product-related information across its entire lifecycle [3].

In this context, the Digital Product Passport (DPP) has gained significant traction as a key enabler of such digital capabilities [4]. A DPP constitutes a structured digital repository that aggregates critical data concerning a product's provenance, material composition, usage history, and end-of-life handling guidelines [5]. By enabling and improving the access to reliable and standardized product information among stakeholders throughout the value chain, DPPs support enhanced supply chain visibility, facilitate compliance with regulatory mandates, and enable the measurement and verification of sustainability and circular metrics [6]. Recognizing their strategic potential, the European Union (EU) has incorporated DPPs into its broader policy agenda – most notably within the European Green Deal and the Circular Economy Action Plan – as a means of promoting sustainable industrial transformation in key sectors, including electronics, textiles, and automotive manufacturing [7], [8].

At the same time, the Internet of Things (IoT) has emerged as a transformative technological paradigm with the potential to significantly augment the functionality of DPPs within the CE framework [9]. By leveraging interconnected sensors, intelligent identifiers (such as QR codes, RFID, and NFC), and Cloud-based analytical platforms, IoT enables the seamless acquisition, transmission, and interpretation of real-time data related to product status, location, usage, and condition [10].

When integrated with DPP systems, IoT

[1] This paper was co-financed by The Bucharest University of Economic Studies during the PhD program

technologies can support dynamic monitoring and tracking of product condition, automate lifecycle management processes, and facilitate predictive maintenance, thereby reinforcing sustainability-oriented operations across diverse industrial sectors [11].

This convergence of DPP and IoT technologies paves the way for the realization of a Smart Digital Circular Economy (SDCE), wherein data-driven decision-making and automation enhance resource circularity and environmental performance [12].

Despite the growing interest in the potential of DPPs and IoT synergy, there remains a notable gap in the development of comprehensive conceptual and technical frameworks that integrate these technologies [13]. Existing research and industrial implementations often address isolated applications or pilot initiatives, lacking a holistic and scalable approach that spans all stages of the product lifecycle [14], [15].

Furthermore, while DPPs offer static product information, their integration with IoT has the potential to transform them into dynamic, real-time sustainability tools [16], [17]. However, the specific use cases where IoT-enabled DPPs can provide the greatest impact remain underexplored, and a clear framework for their integration within CE practices is yet to be established [18]. Moreover, while traditional DPPs primarily function as repositories of static product information, their integration with IoT can catalyze a shift toward dynamic, real-time sustainability intelligence [17].

Nevertheless, the specific use cases in which IoT-enhanced DPPs can generate the most significant environmental, economic, and social value remain insufficiently investigated [15]. A coherent, cross-sectoral framework for embedding IoT-enabled DPPs into CE practices is yet to be established and urgently needed to guide both academic research and practical deployment.

This research is anchored in the central hypothesis that "*The integration of Internet of Things (IoT) technologies with Digital Product Passports (DPPs) enables the realization of a Smart Digital Circular Economy (SDCE) by enhancing sustainability practices across all stages of the product lifecycle*".

To investigate this hypothesis, the study is structured around two key research objectives:

(1) To identify and model IoT-driven use cases for DPPs across various stages of the product lifecycle;

(2) To develop a conceptual framework for IoT–DPP integration that enhances sustainability practices within the CE.

Through the attainment of these objectives, this research aims to generate both theoretical and practical contributions to the evolving discourse on IoT-enabled sustainability innovations.

The findings are expected to offer valuable insights for policymakers, industry stakeholders, and academic researchers, thereby fostering a deeper understanding of how the convergence of IoT and DPP technologies can support the digital transformation of circular economy and the circular transformation of the digital economy providing data-driven sustainability innovation.

Following the *Introduction* section, the remainder of the paper is organized as follows: the *Literature Review* section synthesizes the foundational concepts of the CE, DPPs, and the IoT, establishing a theoretical foundation for understanding their integration. The *Methodology* section details the research design, purpose, methods, and procedures for data collection and analysis employed in identifying relevant use cases and formulating the proposed conceptual framework. The *Research Results and Discussion* section presents the empirical findings, organized in accordance with the research objectives, and critically interprets their implications. Finally, the *Conclusion* section summarizes the key contributions of the study, outlines implications for industry and policy, acknowledges existing limitations, and proposes future research directions.

By adopting a structured and holistic approach to IoT–DPP convergence within the context of the CE, this study aims to bridge the gap between conceptual theory and practical application, thereby supporting the transition towards a SDCE.

2 Literature Review

2.1 Circular Economy

The Circular Economy represents a transformative economic model that prioritizes sustainability by minimizing waste, maximizing resource efficiency, and restoring natural systems [1]. In contrast to the traditional linear economy – characterized by the sequential "*take-make-dispose*" approach, CE model advocates for closed-loop systems in which products, components, and materials are continuously reused, repaired, remanufactured, and recycled,

This paradigm shift is driven by the imperative to mitigate environmental degradation, preserve finite natural resources, and enhance economic resilience in the face of global sustainability challenges, resulting in a holistic regenerative system as depicted in Figure 1 [1].

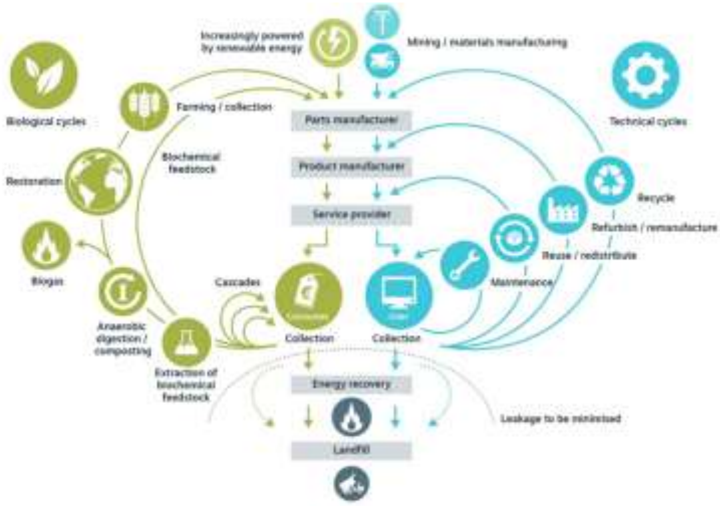

Fig. 1. Circular Economy – a holistic regenerative system *(source: [1])*

CE principles

As articulated by the Ellen MacArthur Foundation [1], the CE is grounded in three fundamental principles, each contributing to the creation of a sustainable, equitable, and resilient socio-economic system that benefits individuals, businesses, and the environment:

- **Design out waste and pollution** – This principle targets the *pre-use phase* of the product lifecycle and emphasizes the importance of eliminating waste and pollution at the design stage. It calls for a fundamental rethinking of product and process design through strategies such as *reducing*, *refusing*, *redesigning*, and *rethinking* innovation via circular strategies. The objective is to enhance production efficiency by reducing the consumption of natural resources and preventing the generation of waste and hazardous substances from the outset. This approach encourages advancements in materials science, sustainable product design, and cleaner production technologies. Furthermore, it may inspire entirely new modes of product-service delivery, potentially reshaping consumer behaviour to support circular consumption patterns.
- **Keep Products and Materials in Use** – This principle focuses on extending the functional lifespan of products and components to extract maximum value while in use. Circular strategies under this principle include designing for durability, modularity, and ease of repair, as well as promoting practices such as *repairing*, reusing, *refurbishment*, *remanufacturing*, and *repurposing*. Predominantly addressing the *use phase* of the lifecycle, this approach aims to maintain products, components, and materials at their highest utility for as long as possible. It also supports the development of closed-loop systems where products are intentionally designed for disassembly, reintegration, and regeneration.

- **Regenerate Natural Systems** – This principle addresses the *post-use phase* of the product lifecycle and goes beyond minimizing environmental impact to actively enhancing ecosystems. It emphasizes the regenerative capacity of biological (natural) and technical (socio-economic) systems by returning valuable nutrients and materials to these systems through *recovery*, *recycling*, *regenerating* and upcycling practices. This principle advocates for the creation of secondary raw materials (or feedstocks) from end-of-life products, which can be reintegrated into new production cycles. Such regenerative practices contribute to replenishing the natural resource base, thereby enabling economic systems to function within planetary boundaries while restoring the health and productivity of ecological systems.

Together, these principles form the conceptual foundation for designing economic systems that are circular by design—critical characteristics for achieving long-term sustainability.

The adoption of CE principles yields a range of multidimensional benefits across environmental, economic, and social domains [19]. Environmentally, CE contributes to the reduction of waste and greenhouse gas emissions, while promoting the conservation of biodiversity through more sustainable resource utilization. Economically, it enables the emergence of innovative business models, reduces production and operational costs through resource efficiency, and enhances supply chain resilience by fostering localized, regenerative value chains. Socially, the CE model supports the development of green jobs in sustainability-oriented industries and cultivates greater consumer awareness of responsible consumption practices [19].

However, despite these promising advantages, the widespread implementation of CE principles is hindered by several persistent challenges [1]. One major barrier is the *lack of standardization*: industries often operate without harmonized guidelines for sustainable product design, material selection, and end-of-life management, impeding interoperability and cross-sectoral scalability. Additionally, *data and transparency issues* present significant obstacles, as many organizations lack robust mechanisms for sharing, tracking, and verifying product and material information throughout their lifecycle. This fragmentation limits visibility and traceability—key enablers of circularity. Finally, *technological constraints* also impede CE adoption. The deployment of advanced digital technologies – such as the IoT, Blockchain, and Artificial Intelligence – is essential for enabling real-time monitoring, intelligent decision-making, and system-wide integration, yet remains limited by high implementation costs, technological complexity, and uneven digital readiness across sectors [2], [3], [12].

CE strategies

Within the CE context, a set of strategic best practices commonly referred to as the “R” strategies – or circular practices – has been widely adopted to guide actions aimed at preserving, enhancing, or restoring the value of products, components, and materials throughout their lifecycle [19]. These circular strategies serve as operational pillars of circularity by reducing environmental impact, improving resource efficiency, and supporting sustainable value creation. The most frequently cited “R” circular strategies in the literature [19], [20] include *rethink, reduce, redesign, refuse, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover, and regenerate*. Each of these practices addresses specific phases of the product lifecycle and contributes to circular value retention in distinct ways:

- **Rethink** – involves re-evaluating product needs, design assumptions, ownership models, usage patterns, and maintenance practices in order to prevent unnecessary waste generation and optimize utility.
- **Reduce** – focuses on minimizing the consumption of raw materials and energy in both products and production processes, thereby decreasing environmental burden.
- **Redesign** – entails reengineering products, systems, and processes to improve sustainability, durability, and efficiency across the value chain.
- **Refuse** – advocates for the deliberate

avoidance of products or materials that are unnecessary, environmentally harmful, or non-circular in design and function.
- **Reuse** – encourages the repeated use of products or components in their original or minimally altered forms to extend their functional life and defer end-of-life processing.
- **Repair** – involves restoring faulty or worn-out products to working condition, thereby extending their useful life and delaying disposal.
- **Refurbish** – entails restoring, upgrading and improving products to a near-original condition for continued use, often incorporating modernized features or components.
- **Remanufacture** – refers to the disassembly and reconstruction of products using original parts or components to create goods with equivalent functionality and performance standards.
- **Repurpose** – involves adapting products or discarded components for new applications beyond their original intended use, often requiring minimal transformation.
- **Recycle** – focuses on converting waste materials into new raw materials or products, thus preventing the loss of potentially valuable resources and reducing reliance on virgin inputs.
- **Recover** – pertains to the extraction of residual value from waste streams, such as the recovery of energy, heat, or secondary materials from non-recyclable waste.
- **Regenerate** – goes beyond resource efficiency by actively restoring and enhancing natural ecosystems through the use of renewable resources, regenerative agriculture, or restorative and sustainable production practices.

Collectively, these circular strategies provide a comprehensive toolkit for implementing CE principles across diverse industrial, commercial, and societal contexts. They enable organizations to design systemic interventions that prioritize longevity, circular resource flows, and environmental regeneration [20]

In addition to core principles and strategic circular practices, the transition to a CE model also relies heavily on the development of *circular business models* and the *integration of digital technologies*, both of which underpin the emerging paradigm of a SDCE [21]. These complementary elements enable the operationalization of CE principles through systemic innovation and the digitalization of circular processes.

Two prominent circular business models widely discussed in the literature [21] include:
- **Sharing Platforms** – This model facilitates shared access to products and services, thereby reducing the overall demand for new goods and optimizing resource use. Examples include car-sharing schemes, tool libraries, and other collaborative consumption mechanisms that emphasize access over ownership. By extending product utilization across multiple users, sharing platforms contribute to lowering material throughput and mitigating environmental impact.
- **Product-as-a-Service** – This model shifts the traditional notion of product ownership toward service-oriented delivery, wherein manufacturers retain ownership of their products and provide them as services. Under this approach, producers are incentivized to design products with durability, reparability, and recyclability in mind, as they remain responsible for maintenance, upgrades, and end-of-life management, thereby aligning business incentives with sustainability objectives.

Furthermore, the integration of digital technologies plays a critical role in enabling these business models and enhancing the efficiency of circular practices. Industry 4.0 technologies such as the IoT, Cloud Computing, Big Data Analytics, Artificial Intelligence, and the convergence of Information Technology (IT) and Operational Technology (OT) systems form the technological foundation of the SDCE model [22]. These digital technologies facilitate the tracking and tracing of products and materials throughout their lifecycle, optimize product usage through predictive analytics, and support the dissemination of essential digital product information to consumers with the goal of influencing sustainable behaviour

[23], [24].

In fact, digital transformation of the CE is enabled three key functions [24]:

- **Data collection and integration** – through connected sensors, digital identifiers, and automated systems;
- **Data processing and analysis** – using intelligent algorithms and cloud-based platforms to derive actionable insights;
- **Data communication and dissemination** – to inform stakeholders, optimize decision-making, and align actions with circularity and sustainability objectives.

Through the convergence of circular business models and integration of innovative digital technologies, the SDCE emerges as a data-driven, adaptive, and collaborative system capable of fostering long-term ecological and economic resilience [12].

2.2 Digital Product Passports

Digital Product Passports are increasingly recognized as essential enablers of traceability, transparency, and regulatory compliance within the CE [7]. By providing a structured, digitalized record of product-related information, DPPs support data-driven decision-making throughout a product's lifecycle, from design and production to end-of-life management [18]. A DPP comprises structured, machine and human readable data that captures key lifecycle parameters of a product, including its material composition, origin, manufacturing processes, environmental footprint, usage instructions, and end-of-life treatment pathways [13]. This comprehensive information architecture facilitates informed interventions by multiple stakeholders—manufacturers, consumers, recyclers, and regulators—who require reliable data to implement or support sustainable practices [15].

DPP objectives

According to [6], the core objectives of DPPs can be summarized as follows:

- **Enhancing sustainable production** by providing manufacturers with accurate data that supports eco-design and circular manufacturing strategies;
- **Extending product lifetimes** and optimizing product use, thereby enabling circular value retention and unlocking new business opportunities for economic actors;
- **Empowering consumers** to make sustainable purchasing and usage decisions through access to transparent and verifiable product information;
- **Facilitating the transition to CE** by improving materials and energy efficiency across value chains;
- **Supporting regulatory authorities** in monitoring compliance with environmental and CE regulations.

DPPs are thus closely aligned with the foundational principles of the CE, particularly those relating to resource efficiency, lifecycle thinking, and extended producer responsibility [13]. By ensuring the availability and interoperability of product-related data, DPPs enable the systematic tracking and tracing of resources, support efficient recycling processes, and foster responsible consumption. Moreover, the central aim of DPPs is to make high-quality product data *accessible*, *standardized*, and *actionable* across the entire ecosystem of stakeholders. As such, DPPs serve as a cornerstone of the digital infrastructure necessary to operationalize circular strategies at scale, supporting both industrial sustainability and policy-driven environmental objectives [5].

DPPs offer several key advantages that directly support the implementation of CE strategies and the development of a smart, data-driven sustainability infrastructure [8]. First, DPPs enhance *circularity* by enabling more effective reuse, refurbishment, and recycling of products and components through access to accurate material and lifecycle data. Second, they support *data-driven decision-making*, equipping manufacturers, consumers, and downstream actors with comprehensive information to inform product design, use, and end-of-life management. Third, DPPs contribute to *sustainability tracking*, allowing businesses to monitor environmental performance indicators and implement targeted improvements aligned with regulatory and corporate sustainability objectives [8].

Despite these promising benefits, several challenges must be addressed to enable the large-scale and cross-sectoral adoption of DPPs [11]. One major barrier is *interoperability*, as industries and manufacturers frequently operate with heterogeneous data standards, formats, and IT infrastructures, hindering seamless data exchange and cross-platform compatibility. Additionally, *data security and privacy* pose significant concerns: the dissemination of detailed product information across supply chains raises cybersecurity risks, intellectual property concerns, and compliance challenges related to data protection regulations. Finally, *technological integration* remains a critical issue. To realize their full potential, DPPs must be effectively integrated with emerging digital technologies – including the IoT, Blockchain, and AI – requiring scalable, interoperable, and secure digital ecosystems [11], [26].

DPP applications

DPPs have a wide range of practical applications that directly support the operationalization of CE principles, particularly in enhancing traceability, regulatory compliance, and material recovery [14]. One of the most significant applications lies in improving **product traceability**. When integrated with IoT technologies, DPPs enable real-time tracking of products and components across all stages of their lifecycle. This functionality facilitates a more nuanced understanding of product usage patterns and supports the development of optimized end-of-life management strategies. For example, manufacturers can leverage lifecycle data to design products that are more easily repaired, reused, or recycled, thereby minimizing waste generation and extending product longevity [26]. In addition, DPPs play a pivotal role in ensuring **regulatory compliance** by verifying that products conform to environmental and safety standards throughout their lifecycle. This is especially critical in the case of components containing hazardous materials, where proper handling, treatment, and disposal are essential to mitigating environmental and health risks. Compliance not only helps meet legal obligations but also enhances corporate reputation among environmentally conscious consumers and stakeholders [26]. Moreover, in the domain of **recycling**, DPPs provide recyclers with essential technical information needed to disassemble and process products safely and efficiently. This is particularly valuable in sectors such as electronics, where the recovery of critical raw materials depends on accurate identification of components and materials. For instance, having access to detailed specifications on the types of plastics, metals, or rare earth elements used in a product significantly improves the effectiveness and economic viability of recycling operations [26].

Through these applications and many others, DPPs function as a critical enabler of the CE model by ensuring that products and materials remain traceable, auditable, and responsibly managed throughout their entire lifecycle. Their ability to make product information transparent, actionable, and interoperable supports more sustainable decision-making across the entire value chain [16].

2.3 Internet of Things

The Internet of Things represents a global infrastructure that enables the seamless integration of physical and digital entities through the deployment of advanced, interoperable technologies and services [27]. By facilitating the connection of sensors, devices, and systems via the internet, IoT creates a dynamic ecosystem capable of collecting, transmitting, and processing real-time data across various sectors and applications [27].

IoT system model

According to [28], the IoT ecosystem comprises a wide range of use cases and stakeholders that interact within diverse application domains, including manufacturing, logistics, healthcare, and environmental monitoring. As illustrated in Figure 2, the general use case model of IoT includes four core functional categories that define the operations and value delivery mechanisms within IoT systems:

- **Sensing and Actuating** – This use case involves the deployment of smart sensors and actuators to monitor and control physical processes in real-time. Sensors collect data such as temperature, humidity, location, and motion, while actuators trigger physical actions based on data-driven insights.

- **Data Management** – Central to the IoT architecture, this layer encompasses the storage, integration, and preprocessing of collected data. It ensures that data from heterogeneous sources is transformed into meaningful and usable formats for further analysis.
- **Service Provision** – IoT systems deliver tailored services based on contextual data, supporting applications such as predictive maintenance, asset tracking, and smart resource allocation. These services often rely on cloud platforms and edge computing for scalability and responsiveness.
- **Privacy and Security Protection** – Given the vast volumes of data exchanged in IoT networks, ensuring data integrity, confidentiality, and access control is paramount. Security mechanisms are embedded throughout the IoT stack to protect against cyber threats and maintain user trust.

According to [28], the IoT involves a series of use cases and actors that interact within various application domains. The Figure 3 shows the general use case model of the IoT as per the [28], where four key use cases—sensing or actuating, data management, service provision, and privacy protection—outline the general functionality and operations within IoT systems.

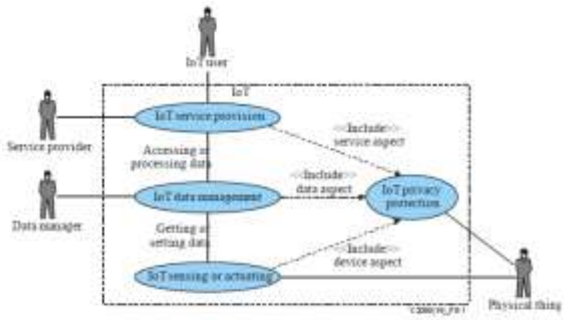

Fig. 2. The general use case model of the IoT (source: [29])

Each use case is composed of distinct activities associated with specific roles performed by various IoT actors, including the *Service Provider*, *Physical Thing*, *Data Manager*, and *IoT User*. These actors interact within the system to enable core IoT functions. Table 1 summarizes the generic use cases, their corresponding descriptions, and the roles of the associated actors, as adapted from [28].

Table 1. IoT generic use case description

IoT Use Case	Use Case Description	IoT Actors	Actor Description
Sensing or Actuating	Involves interaction with physical objects to collect data or trigger actions.	Physical Thing	Engages with the IoT system through sensing (data collection) or actuating (control).
Data Management	Encompasses the lifecycle of data from capture to processing.	Data Manager	Responsible for capturing, storing, transferring, and processing IoT-generated data.
Service Provision	Offers and utilizes services based on IoT-enabled data and functions	Service Provider, IoT User	Service Provider delivers IoT-enabled functionalities; IoT User consumes them.
Privacy Protection	Ensures confidentiality, integrity, and access control for sensitive data.	All Actors	Each actor plays a role in maintaining privacy and securing data within the system.

Source: Adapted from [28]

This IoT system model highlights the interdependent nature of IoT systems, where actors collectively contribute to the seamless operation, data governance, and service delivery of connected applications. In the context of DPPs, understanding the roles of these actors is essential for designing secure, scalable, and interoperable systems that support CE practices. Together, these elements form the foundational structure of the IoT, enabling a wide array of intelligent, automated, and connected solutions. Within the CE context, these capabilities are particularly valuable for monitoring product usage, optimizing resource flows, and supporting the implementation of DPPs with real-time, context-aware data streams [29].

IoT applications

Within the context of the CE and DPPs, IoT serves as a critical enabler for dynamic tracking, real-time monitoring, and data-driven decision-making throughout the product lifecycle [10]. By embedding intelligence into physical assets, IoT facilitates the digitalization of lifecycle processes, thereby supporting core CE principles such as resource efficiency, extended product use, and closed-loop material flows, as depicted in Figure 3.

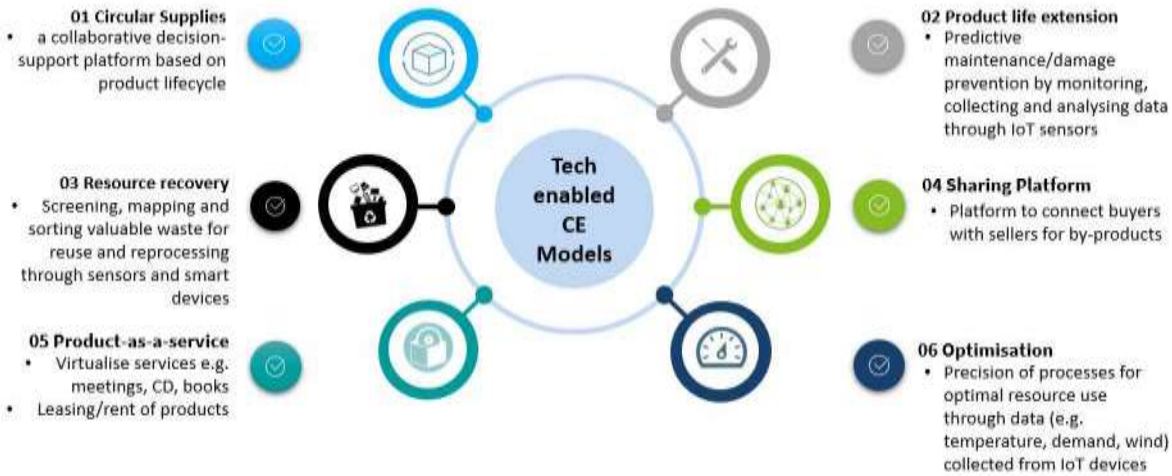

Fig. 3. Example of IoT-enabled CE business models (source: [33])

One of the most impactful applications of IoT in the SDCE is the **optimization of product lifecycles**. Through the deployment of advanced sensors and data analytics, IoT systems are capable of continuously monitoring the operational status and usage patterns of products. These insights can be used to predict failures and schedule *preventive maintenance*, reducing unplanned downtime and extending product longevity [29]. For instance, in the automotive sector, IoT-enabled devices can track component degradation and trigger maintenance alerts prior to breakdown, thereby improving vehicle durability and reducing material waste. In such contexts, maintenance, remanufacturing, or repair activities can be scheduled automatically in response to detected anomalies, sometimes using fully autonomous decision-making systems that contribute to *intelligent resource management*.

IoT also plays a key role in **enhancing material traceability** across supply chains, particularly within *product-service systems* – an essential feature of effective circularity and *industrial symbiosis*. By embedding *smart identifiers* such as Radio-Frequency Identification (RFID) tags into products and components, stakeholders can track the journey of materials from production to end-of-life. This level of *transparency* enables more accurate decisions related to reuse, refurbishment, and recycling. In the electronics industry, for example, IoT facilitates the tracking of specific components to ensure the responsible recovery of valuable materials such as gold, copper, and rare earth elements, thus improving the environmental and economic outcomes of recycling operations [30].

Beyond traceability, IoT significantly contributes to the management of **reverse logistics**, which involves the return of end-of-life products to the supply chain for reprocessing, recycling, or refurbishment [31]. IoT systems provide real-time data on the *location*, *condition*, and *status* of returned items, enabling optimized planning of logistics operations and resource recovery activities [32]. Such

integration not only increases operational efficiency but also supports more responsive and *circular supply chains* [30].
Furthermore, IoT is fostering the development of *new ownership and consumption models*, such as Product-as-a-Service (PaaS), wherein consumers gain access to products on a usage basis rather than through outright ownership [32]. This approach reduces the proliferation of single-use products and incentivizes manufacturers to design for durability, modularity, and lifecycle accountability – principles aligned with both CE and DPP implementation [29], [33].
IoT contributes to the implementation of CE principles and DPPs in multiple significant ways:

- **Real-time product tracking and monitoring**: IoT-enabled devices, such as sensors, RFID tags, and NFC chips, facilitate continuous monitoring of product conditions, including environmental parameters (e.g. temperature, humidity) and usage patterns. This functionality enables dynamic lifecycle management and proactive interventions [33]
- **Enhanced traceability and transparency**: By enabling end-to-end visibility across supply chains, IoT systems improve accountability in sourcing, production, distribution, and end-of-life management. This transparency is essential for supporting closed-loop systems and stakeholder collaboration [33].
- **Lifecycle optimization**: IoT-driven predictive analytics support optimized maintenance scheduling, reduce unplanned downtime, and extend product lifespans. These capabilities align with key CE objectives, such as waste minimization and value retention [33].
- **Automated data collection for regulatory compliance**: IoT facilitates the automatic generation and transmission of product lifecycle data, thereby supporting compliance with sustainability policies, environmental regulations, and extended producer responsibility frameworks [33].

Despite these advantages, the integration of IoT into CE and DPP systems faces several critical challenges [10], [11], [29]. First, *interoperability issues* arise due to the lack of standardized communication protocols and data formats across industries, limiting the seamless exchange and aggregation of IoT-enabled sustainability data [10]. Second, *data security and privacy concerns* persist, as managing and safeguarding large volumes of sensitive lifecycle data requires robust cybersecurity infrastructures and compliance with data protection regulations [11]. Third, *high implementation costs* remain a barrier, as the deployment of IoT infrastructure – encompassing smart sensors, connectivity platforms, and cloud-based analytics – demands substantial financial and technical investments [11]. Lastly, *scalability and infrastructure readiness* continue to pose challenges, particularly in global supply chains where heterogeneous technological maturity complicates the development of interoperable and scalable IoT solutions [29]. Nevertheless, the integration of IoT with DPPs presents a transformative opportunity for advancing a smart, connected, and sustainable economy. By enabling real-time, data-driven insights and automating key lifecycle processes, IoT-DPP systems can operationalize CE strategies at scale [3]. In summary, IoT acts as a foundational technology that enables the transition towards a SDCE by providing the infrastructure for transparency, responsiveness, and intelligent lifecycle management [2]. Its integration with DPPs strengthens product-level sustainability interventions and enhances systemic coordination across the value chain [9], [16].

3 Methodology

3.1 Research Design

This study employs a *Systematic Literature Review (SLR)* as its methodological approach to investigate the integration of IoT technologies with DPPs within the framework of the CE. The SLR methodology enables a rigorous, transparent, and replicable process for identifying, evaluating, and synthesizing existing knowledge from scholarly publications, industry white papers, and relevant policy and regulatory documents [34]. This structured approach ensures the reliability and comprehensiveness of the insights drawn, forming a robust foundation for theoretical development and practical analysis.

3.2 Research Purpose

The purpose of this research is *to identify and model key IoT-driven use cases for DPPs* and *to develop a conceptual framework* that supports the integration of IoT technologies into DPP systems for advancing sustainability within CE practices. The study aims to contribute both to the academic discourse on digital sustainability and to the practical implementation of IoT–DPP solutions across industrial sectors seeking to enhance circularity, transparency, and data-driven lifecycle management.

3.3 Research Questions

To guide the investigation, the study is structured around the following research questions:

- *[**RQ1**] What are the key IoT-driven use cases for DPPs that promote product sustainability practices within the CE?*
- *[**RQ2**] How can IoT be effectively integrated with DPPs to optimize CE practices and enable smart digital data-driven sustainability?*

3.4 Research Objectives

Aligned with the research questions, the study is organized around two primary objectives:

- *[**RO1**] To identify and model IoT-driven use cases for DPPs across various stages of the product lifecycle;*
- *[**RO2**] To develop a conceptual framework for IoT–DPP integration that enhances sustainability practices within the CE.*

3.5 Research Methodology

The research methodology employed in this study is grounded in a *Systematic Literature Review (SLR)*, a well-established method for aggregating, synthesizing, and critically analysing existing scholarly work [34]. This approach is particularly suited for examining the intersection of IoT technologies, DPPs applications, and CE principles. By employing an SLR, the study aims to extract state-of-the-art insights, identify prevailing research gaps, and understand current system design and modeling practices relevant to IoT–DPP integration in CE contexts.

To ensure methodological rigor and transparency, the SLR follows the *PRISMA* (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method. PRISMA provides a structured protocol for literature identification, screening, eligibility assessment, and inclusion, which supports the reproducibility and credibility of the review process [35].

Data Collection

The data collection phase focused on identifying high-quality, relevant literature related to IoT technologies, CE strategies, and DPPs applications. The objective was to obtain a comprehensive view of current knowledge and practices across academic, regulatory, and industrial domains.

- **Sources**: Peer-reviewed journal articles, conference proceedings, official policy and regulatory documents, and industry white papers.
- **Databases**: Literature was retrieved from major academic and technical repositories, including *Web of Science, Scopus, IEEE Xplore, ScienceDirect, SpringerLink, Emerald Insight*, and *Google Scholar*.
- **Search Queries**: Search strings were constructed using combinations of relevant keywords and Boolean operators ("*and*", "*or*", "*not*") to refine results. Example terms included: "*Internet of Things*", "*Circular Economy*", "*Digital Product Passports*", "*System Design*", "*Use Cases*", "*Sustainability*". This approach ensured that only literature directly aligned with the study's research objectives was considered.
- **Inclusion Criteria**: Publications in English from the last 15 years that explicitly address IoT, DPPs, CE concepts in relevant application domains.
- **Exclusion Criteria**: Studies not explicitly addressing IoT systems in the context of CE or DPPs, as well as non-scholarly sources such as editorials, opinion pieces,

or promotional content, were excluded from the review.

Data Analysis
The collected literature was analysed using *qualitative thematic analysis*, a method that facilitates the identification of recurring patterns, conceptual trends, and research gaps across the selected studies [36]. Themes were derived inductively and organized to inform the modeling of use cases and the development of the conceptual framework [37].
The systematic approach adopted in identifying and analysing IoT–DPP–CE use cases ensures that the resulting conceptual framework is evidence-based, technically coherent, and aligned with CE goals [36]. Particular emphasis was placed on the operationalization of DPPs, demonstrating how IoT technologies can support traceability, sustainability tracking, and lifecycle optimization within CE model [38].

4 Results and discussions

The research findings are presented in alignment with the research design and follow the structure defined by the research questions. This section addresses each question in detail, offering both conceptual and applied insights derived from the systematic literature review.

4.1 [RQ1] What are the key IoT-driven use cases for DPPs that promote product sustainability practices within the CE?

The study identified a set of critical IoT-driven use cases that support the implementation of DPPs across various phases of the product lifecycle, thereby reinforcing sustainability objectives within the CE context. These use cases are grounded in the literature and modeled through a system-level perspective that reflects interactions among key IoT actors and functional processes [37].

IoT Use Case Model
Building on the insights gathered from the literature review [2], [3], [8], [9], [25], [28], [38], the study proposes an IoT System Use Case Model tailored to DPP applications within the CE context. This model delineates the primary and secondary use cases supported by IoT technologies and highlights the key actors involved in each use case. It underscores how IoT systems enhance sustainability, regulatory compliance, traceability, and lifecycle efficiency through interconnected functions.

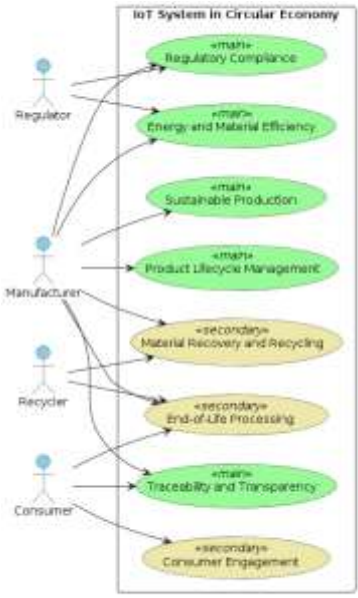

Fig. 4. IoT system use case model *(source: authors' own research)*

Figure 4 illustrates the proposed model, in which IoT infrastructure supports integrated CE-DPP activities across the product lifecycle. The corresponding use cases and actors are detailed in Table 2.

Table 2. IoT System Use Cases for DPP applications within CE domain

Use Case	Use Case Description	Actor	Actor Responsibilities
Product Lifecycle Management	Manages the entire lifecycle of a product by leveraging IoT data to enhance decision-making and operational efficiency.	Manufacturer	Oversees the full product lifecycle from design to end-of-life.
Traceability and Transparency	Ensures product traceability and status visibility across the value chain.	Manufacturer, Consumer	Manufacturer tracks and updates data; Consumers access product history.

Use Case	Use Case Description	Actor	Actor Responsibilities
Regulatory Compliance	Provides real-time compliance data to ensure adherence to legal and environmental regulations.	Manufacturer, Regulator	Manufacturer ensures product compliance; Regulator audits and verifies conformity.
Material Recovery and Recycling	Enables efficient material separation, recovery, and reintegration using IoT-linked product data.	Manufacturer, Recycler	Manufacturer designs for disassembly; Recycler processes recovered materials.
End-of-Life Processing	Optimizes decisions related to disposal, refurbishment, or reuse using real-time data.	Manufacturer, Consumer, Recycler	Involved actors coordinates return and processing of used products.
Sustainable Production	Enhances the sustainability of production by reducing resource inputs and emissions.	Manufacturer	Directly implements sustainable manufacturing practices using IoT insights.
Consumer Engagement	Supports informed consumer behaviour through access to DPP data and product status.	Consumer	Interacts with DPP systems to make environmentally responsible usage decisions.
Energy and Material Efficiency	Optimizes energy consumption and material usage in manufacturing and throughout product use.	Manufacturer, Regulator	Manufacturer adopts efficient processes; Regulator enforces sustainability standards.

Source: Authors' own research

Each of these use cases illustrates the potential for IoT–DPP integration to serve as a foundation for sustainability innovation in the CE. Through real-time data acquisition, system-wide visibility, and automated process optimization, IoT enables a level of lifecycle intelligence that is crucial for achieving CE goals. The following sub-section expands on these use cases by providing illustrative examples and functional activities associated with each, further contextualizing their role within practical implementations of IoT-based DPP systems in CE context.

Product Lifecycle Management use case

The Product Lifecycle Management (PLM) use case demonstrates a comprehensive and holistic approach to managing a product from design to end-of-life, leveraging IoT and DPP technologies to support sustainability goals in alignment with CE principles. Figure 5 illustrates the IoT-enabled PLM use case, which emphasizes how smart technologies contribute to enhanced resource efficiency, lifecycle transparency, and environmental stewardship at every stage of the product's journey.

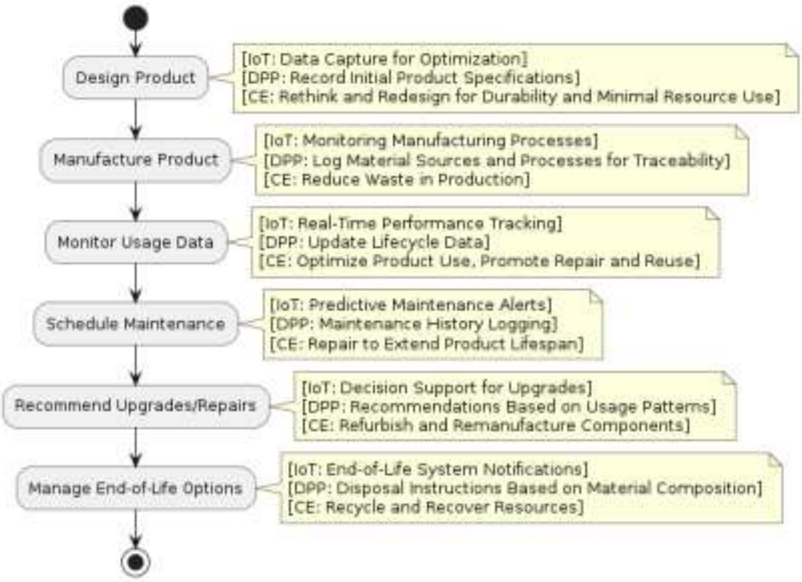

Fig. 5. IoT use case for Product Lifecycle Management (source: authors' own research)

This use case exemplifies the synergy between IoT infrastructure, DPP systems, and CE strategies, wherein data flows are continuously captured, updated, and utilized to support intelligent decision-making across the entire lifecycle. Each activity reinforces the vision of a SDCE by enhancing product durability, optimizing resource use, and facilitating sustainable end-of-life options.

A possible example of the lifecycle stages and their respective functions are described below:

- **Design Product**: IoT technologies are employed to collect real-time data on user behaviour, product usage environments, and material performance, which inform the design of next-generation products. DPPs document design specifications and component metadata to support traceability and facilitate future disassembly or recycling. CE principles guide product design toward resource minimization, modularity, and durability.
- **Manufacture Product**: During production, IoT devices monitor operational parameters such as energy consumption, machine efficiency, and material inputs. These data streams feed into DPPs, which log source materials, process steps, and compliance indicators. CE objectives focus on waste minimization, resource efficiency, and low-impact production.
- **Monitor Usage Data**: IoT sensors embedded in products track key performance indicators (e.g., temperature, vibration, energy use) to assess condition and usage patterns. This real-time data is continuously updated in the DPP, enabling manufacturers and users to monitor lifecycle progress. CE strategies promote maintenance, reuse, and optimized utilization during this phase.
- **Schedule Maintenance**: Predictive maintenance capabilities enabled by IoT algorithms identify potential failures before they occur. Maintenance events are logged in the DPP, creating a complete service history. CE encourages repair and restoration as a means to prolong the functional life of products and components.
- **Recommend Upgrades/Repairs**: Based on IoT-collected performance data, the system may recommend upgrades or component-level repairs. The DPP provides contextual information, such as part specifications and service provider options, facilitating informed decisions. CE supports refurbishment and remanufacturing as value-retention strategies.
- **Manage End-of-Life Options**: As the product nears obsolescence, IoT triggers notifications based on usage thresholds or failure conditions. DPPs offer disposal, return, or recycling instructions aligned with CE principles, ensuring that valuable materials are recovered and reintegrated into new production cycles, minimizing environmental impact.

Traceability and Transparency use case

The Traceability and Transparency use case illustrates how the integration of IoT technologies and DPPs supports comprehensive lifecycle documentation, ensuring that all stakeholders – manufacturers, consumers, recyclers, and regulators – have access to accurate and verifiable product information throughout the lifecycle. This visibility is essential for promoting accountability, informed decision-making, and alignment with CE principles. Figure 6 presents the IoT-enabled traceability and transparency use case, highlighting the continuous flow of data from raw material acquisition to end-of-life management.

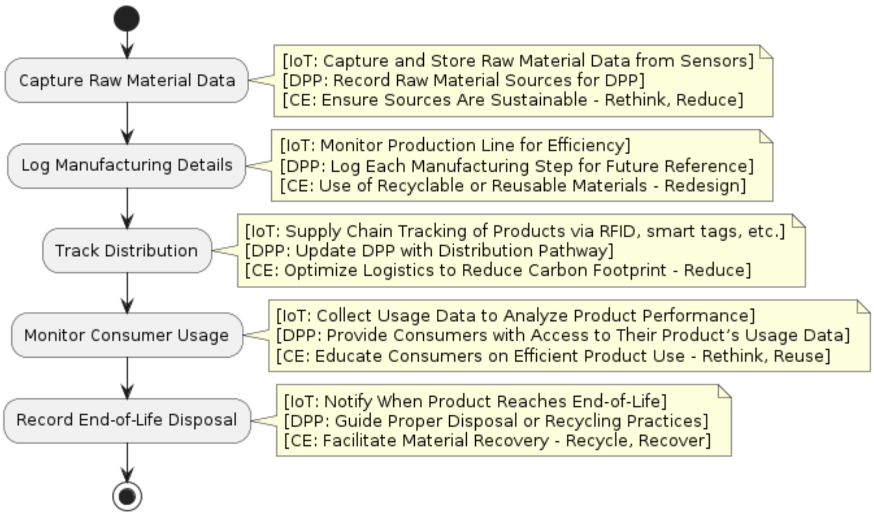

Fig. 6. IoT use case for Traceability and Transparency (source: authors' own research)

By ensuring that each lifecycle phase is transparently recorded and shared, this use case reinforces sustainable business models and supports the operationalization of CE strategies through data-driven collaboration.

A possible example of the lifecycle stages and their respective functions are described below:

- **Capture Raw Material Data**: IoT technologies are deployed at the extraction or sourcing stage to collect data on material type, origin, and sustainability credentials (e.g. carbon intensity, certification status). This information is recorded in the DPP, establishing material provenance. CE principles emphasize the responsible sourcing of raw materials to reduce upstream environmental impacts.
- **Log Manufacturing Details**: During production, IoT systems monitor manufacturing parameters such as energy use, emissions, and material efficiency. These data points are logged in the DPP to ensure process traceability and regulatory compliance. In accordance with CE strategies, manufacturers are encouraged to use recyclable, biodegradable, or modular materials, enabling easier disassembly and reuse.
- **Track Distribution**: IoT tools – including GPS, RFID, and geofencing technologies – enable real-time tracking of products during transportation and distribution. These updates are logged in the DPP, enabling supply chain stakeholders to monitor logistics performance. CE strategies focus on logistics optimization, seeking to minimize the carbon footprint of transportation networks through route efficiency and sustainable packaging.
- **Monitor Consumer Usage**: IoT sensors embedded in the product track usage behaviour, functional performance, and wear-and-tear patterns. This information is accessible to consumers via the DPP, fostering product stewardship and encouraging more sustainable usage habits. CE principles advocate for prolonging product life through informed use, maintenance, and behavioural change.
- **Record End-of-Life Disposal**: As the product reaches the end of its usable life, IoT systems detect lifecycle thresholds and trigger notifications. The DPP provides customized end-of-life instructions, such as return, repair, or recycling guidelines. These support CE goals by facilitating material recovery, closed-loop recycling, and waste minimization.

Regulatory Compliance Use Case

The Regulatory Compliance use case illustrates how the integration of IoT systems, DPPs applications, and CE strategies facilitates adherence to environmental, safety, and product-specific regulations. More than fulfilling legal obligations, this approach promotes sustainability as a core component of compliance, aligning corporate practices with broader ecological goals. Figure 7 presents the regulatory compliance use case, highlighting how IoT technologies and DPPs enable continuous monitoring, reporting, and verification of regulatory performance across the product lifecycle.

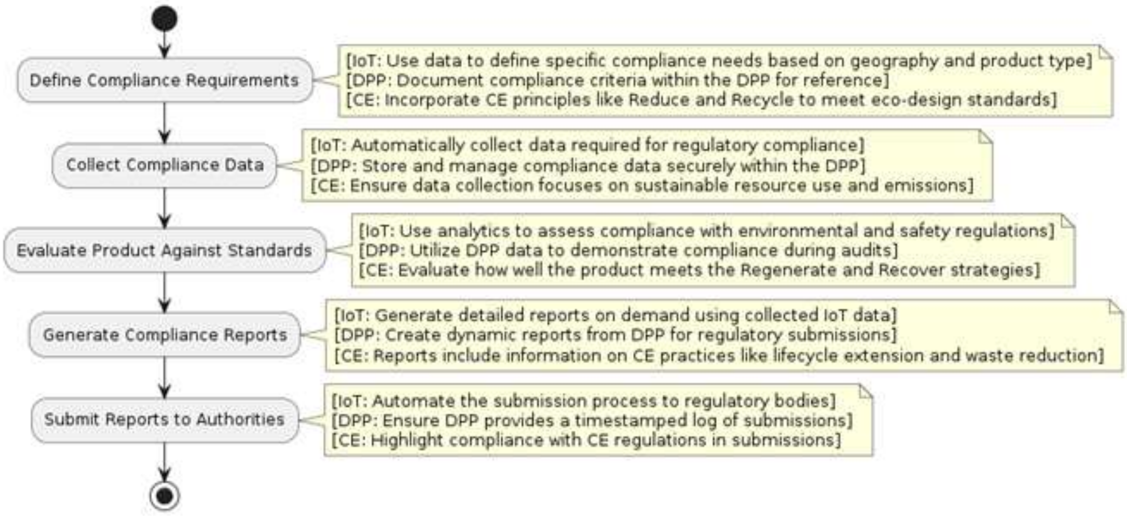

Fig. 7. IoT use case for Regulatory Compliance (source: authors' own research)

By automating compliance data collection, assessment, and reporting, this use case supports both regulatory accountability and environmental stewardship, fostering a data-driven and sustainable approach to product governance.

A possible example of the lifecycle stages and their respective functions are described below:

- **Define Compliance Requirements**: IoT systems assist in identifying and contextualizing specific regulatory requirements applicable to different markets, sectors, and product categories. These requirements – ranging from eco-design directives to material restrictions – are recorded in the DPP. CE principles, such as waste reduction and design for recyclability, are incorporated into compliance planning to ensure sustainable conformity from the outset.
- **Collect Compliance Data**: IoT sensors continuously gather relevant data during manufacturing, distribution, and product use (e.g. emissions, material composition, energy consumption). This data is securely stored in the DPP, establishing a verifiable digital audit trail. The collection process emphasizes sustainable resource utilization and the minimization of pollutants in alignment with CE objectives.
- **Evaluate Product Against Standards**: IoT-enabled analytics evaluate the product's performance against regulatory benchmarks using real-time and historical data housed in the DPP. This assessment includes compliance with environmental impact limits, safety certifications, and CE-aligned practices such as regenerate, recover, and reuse.
- **Generate Compliance Reports**: Detailed compliance reports are dynamically generated from the DPP also using IoT-collected product data. These reports include documentation of sustainability-oriented practices, such as lifecycle extension, material traceability, and waste minimization, reinforcing the organization's alignment with CE principles.
- **Submit Reports to Authorities**: IoT systems facilitate the automated submission of compliance reports to relevant regulatory authorities. The DPP ensures all submissions are timestamped, traceable, and securely archived, offering transparency and accountability. The documentation also serves as evidence of the company's commitment to environmental compliance and circular innovation.

Material Recovery and Recycling Use Case

The Material Recovery and Recycling use case demonstrates how IoT technologies, DPPs applications, and CE strategies work together to enable the efficient, sustainable, and traceable reintegration of materials into the production cycle. This use case supports the CE vision of closing material loops by ensuring that products, components, and materials are systematically recovered and redirected into productive use. Figure 8 illustrates the integration of IoT-enabled systems and DPP information throughout the recovery and recycling process, enabling data-driven decision-making and full lifecycle traceability.

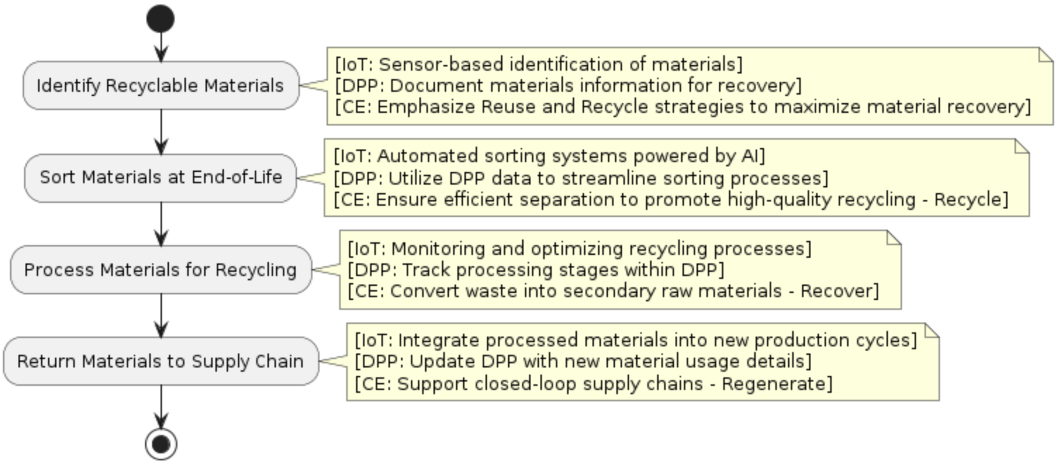

Fig. 8. IoT use case for Material Recovery and Recycling (source: authors' own research)

This use case exemplifies how intelligent sensing, automated sorting, and real-time data capture support circular practices such as reuse, recycling, recovery, and regeneration, contributing significantly to the reduction of waste and the preservation of natural resources.

A possible example of the lifecycle stages and their respective functions are described below:

- **Identify Recyclable Materials**: IoT sensors embedded in products or disassembly systems detect and classify recyclable materials based on type, purity, or contamination. The DPP provides precise information about material composition, origin, and recyclability, enabling informed decision-making at the recovery stage. CE strategies such as reuse and recycle guide this process, aiming to maximize the retention of material value.
- **Sort Materials at End-of-Life**: Automated IoT-driven sorting systems, often enhanced by AI and machine vision technologies, streamline the separation of materials into distinct categories (e.g. metals, plastics, glass). DPP data facilitates this by providing detailed tagging and material metadata. This stage is critical to achieving high-quality recycling and supports CE objectives related to efficient material disassembly, preservation, and optimization.
- **Process Materials for Recycling**: IoT systems monitor recycling operations in real time, capturing data on temperature, chemical treatments, and throughput rates. DPPs are continuously updated to log each step of the recycling process, ensuring traceability, compliance, and data integrity. The CE principle of recovery is operationalized here by transforming post-consumer waste into secondary raw materials suitable for reintegration.
- **Return Materials to Supply Chain**: Once recycled, the recovered materials are reintroduced into manufacturing workflows. IoT supports this reintegration by tracking the flow and quality of returned materials, while DPPs record the materials' new lifecycle phase. This step embodies the CE principle of regeneration, promoting closed-loop supply chains and reducing dependency on virgin resources.

End-of-Life Processing Use Case

The End-of-Life (EoL) Processing use case focuses on the final phase of a product's lifecycle, aiming to maximize resource recovery, extend product value, and minimize environmental impact. This process is enabled through the convergence of IoT technologies, DPPs, and CE strategies, forming a closed-loop system that ensures the responsible and efficient handling of products and materials at the end of their useful life. Figure 9 presents the IoT-enabled EoL processing use case, illustrating how data-driven tools and digital documentation facilitate sustainable waste management and material reintegration.

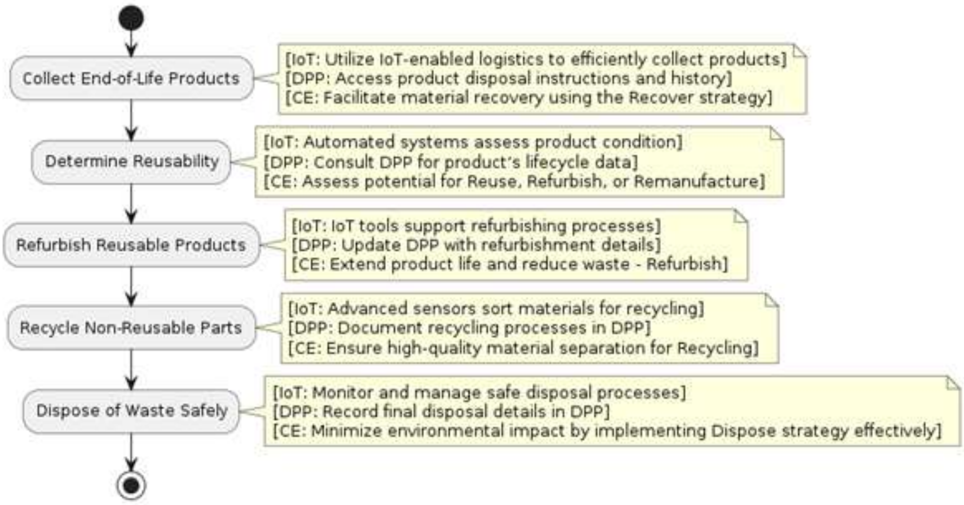

Fig. 9. IoT use case for End-of-Life Processing (source: authors' own research)

This use case exemplifies how technological systems, digital infrastructure, and circular design converge to create an intelligent, traceable, and sustainability-aligned approach to end-of-life product management.

A possible example of the lifecycle stages and their respective functions are described below:

- **Collect End-of-Life Products**: IoT-enabled logistics systems coordinate the identification, collection, and tracking of EoL products. Smart containers, geolocation, and scheduling tools improve collection efficiency, while DPPs provide detailed information regarding product composition, disassembly instructions, and return protocols. This aligns with CE principles focused on material retention and reverse logistics.
- **Determine Reusability**: Automated IoT diagnostic tools assess the physical and functional condition of returned products to determine their potential for reuse. The DPP supplies lifecycle data such as usage history, maintenance records, and repair logs, enabling informed decisions about whether to reuse, refurbish, or recycle. This supports CE strategies such as reuse, remanufacture, and value preservation.
- **Refurbish Reusable Products**: IoT technologies support the refurbishment process by guiding diagnostics, repair, and testing procedures. Refurbishment actions, parts replaced, and performance validation outcomes are recorded in the DPP, ensuring transparency. This step operationalizes CE principles aimed at extending product lifespan and reducing demand for new manufacturing inputs.
- **Recycle Non-Reusable Parts**: For components that cannot be reused or refurbished, IoT-powered sorting systems identify recyclable materials based on sensor analysis. The DPP ensures full traceability by documenting how each part was disassembled and where it was routed for recycling. This aligns with the CE focus on resource recovery and closed-loop material flows.
- **Dispose of Waste Safely**: Residual waste

that cannot be reintegrated into production cycles is handled through IoT-monitored disposal systems that enforce safe, compliant, and environmentally responsible practices. Final disposal details, including method, location, and environmental impact data, are stored in the DPP. This stage supports CE to minimize harmful emissions and landfill use, while maintaining regulatory accountability.

Sustainable Production Use Case

The Sustainable Production use case focuses on the integration of IoT technologies, DPPs, and CE strategies to promote resource efficiency, low-impact manufacturing, and eco-design principles from the earliest stages of product creation. By embedding sustainability into production workflows, this use case facilitates the shift from linear, resource-intensive manufacturing to smart, regenerative production systems. Figure 10 illustrates how IoT-enabled monitoring, automation, and data analytics – together with DPP-based documentation – enable manufacturers to implement CE-aligned strategies that reduce environmental impact while improving production transparency and performance.

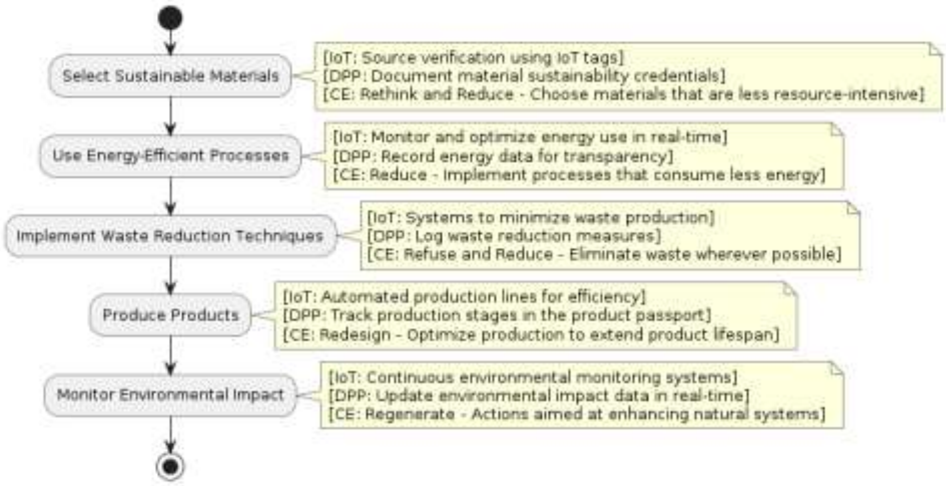

Fig. 10. IoT use case for Sustainable Production (source: authors' own research)

This use case demonstrates how sustainability can be proactively embedded into production processes, ensuring that products are not only efficient in use but also sustainably manufactured.

A possible example of the lifecycle stages and their respective functions are described below:

- **Select Sustainable Materials**: IoT-enabled verification systems assess the sustainability attributes of raw materials – such as recyclability, renewable sourcing, or low embodied carbon. These material details are documented in the DPP, enabling full traceability and reinforcing CE principles such as rethink, reduce, and refuse.
- **Use Energy-Efficient Processes**: IoT sensors monitor real-time energy usage across machinery and production lines. Collected data are analysed to optimize energy consumption and reduce waste. Energy performance metrics are recorded in the DPP, ensuring transparency, accountability, and alignment with CE goals to minimize resource inputs and reduce emissions.
- **Implement Waste Reduction Techniques**: IoT technologies support waste minimization through real-time monitoring, process control, and predictive analytics. For example, defect rates, offcuts, and excess materials are tracked and reduced through intelligent feedback systems. Each intervention is logged in the DPP to support CE principles such as refuse, reduce, and redesign out waste.
- **Produce Products**: IoT-integrated manufacturing systems enable automated, adaptive, and precise production, improving

both consistency and efficiency. The DPP maintains a digital record of the production process, including design versioning, quality control data, and material inputs. This ensures that production supports CE strategies like redesigning for durability and modular product architecture.

- **Monitor Environmental Impact**: Environmental parameters such as emissions, water usage, and air quality are continuously tracked through IoT-based environmental monitoring systems. These metrics are fed into the DPP, supporting continuous improvement and environmental performance benchmarking. This stage embodies CE principles of regeneration, helping to mitigate damage and restore natural systems.

Consumer Engagement Use Case

The Consumer Engagement use case highlights the critical role of consumers as active participants in the sustainable lifecycle of products. Through the integration of IoT technologies, DPPs, and CE strategies, this use case enables meaningful interaction between consumers and producers. By providing real-time feedback, sustainability education, and data-driven personalization, it promotes more responsible consumption and supports the long-term goals of circularity. Figure 11 illustrates how IoT systems and DPP applications facilitate a two-way flow of information, empowering consumers to make informed choices while enabling producers to adapt based on user behaviour and feedback.

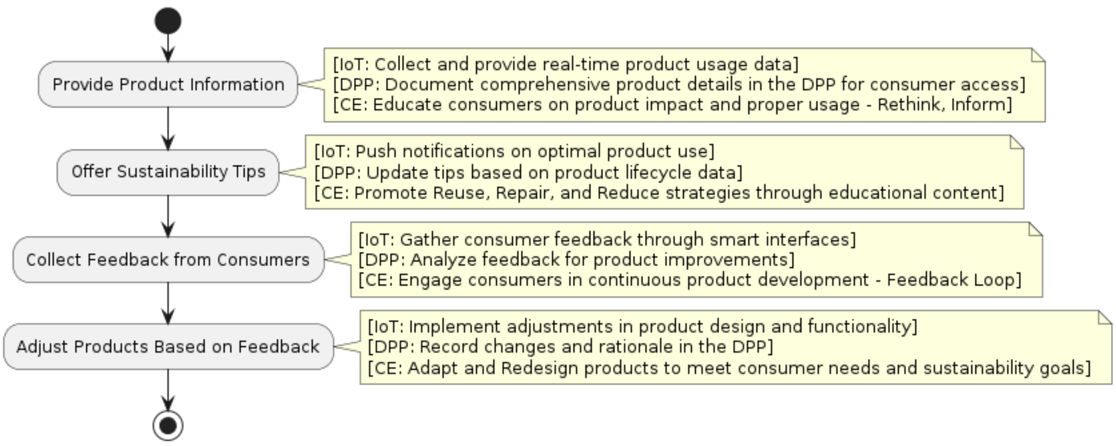

Fig. 11. IoT use case for Consumer Engagement (source: authors' own research)

This use case underscores the collaborative potential of digital technologies to enhance consumer awareness, product longevity, and sustainable decision-making, while improving consumer satisfaction.

A possible example of the lifecycle stages and their respective functions are described below:

- **Provide Product Information**: IoT sensors collect real-time usage data – such as energy consumption, maintenance status, and wear levels – which are recorded and visualized through the DPP. This transparency allows consumers to understand how their behaviours influence environmental performance. CE principles such as rethinking consumption and raising awareness are central to this function.
- **Offer Sustainability Tips**: IoT-enabled systems deliver personalized notifications and tips to encourage more sustainable use practices (e.g. avoiding overcharging, timely maintenance). These suggestions are dynamically updated in the DPP based on actual usage patterns. This approach supports CE strategies such as reuse, repair, and reduce, using behavioural nudges to foster sustainable habits.
- **Collect Feedback from Consumers**: Consumers interact with products via IoT user interfaces (e.g. mobile apps, dashboards) to provide feedback on product functionality, comfort, usability, and satisfaction. This feedback is analysed and

recorded in the DPP, establishing a feedback loop that allows manufacturers to improve products based on real-world usage. It supports the CE goal of co-creation and continuous improvement.

- **Adjust Products Based on Feedback**: Based on insights gained from consumer interaction, IoT systems support the real-time adjustment or future redesign of products to better meet user needs. These modifications are logged in the DPP to maintain full lifecycle transparency. This iterative process contributes to adaptive product development and supports CE strategies such as redesign, remanufacturing, and customer-centric circular innovation.

Energy and Material Efficiency Use Case

The Energy and Material Efficiency use case focuses on optimizing the use of resources throughout the entire product lifecycle, with the objective of minimizing environmental impact and enhancing sustainability performance. This use case demonstrates how the IoT technologies, DPPs, and CE strategies can drive measurable improvements in both energy performance and material utilization, contributing directly to the broader objectives of circular production and consumption. Figure 12 illustrates the IoT-enabled approach to achieving energy and material efficiency, emphasizing how real-time data, automation, and lifecycle documentation converge to support continuous optimization.

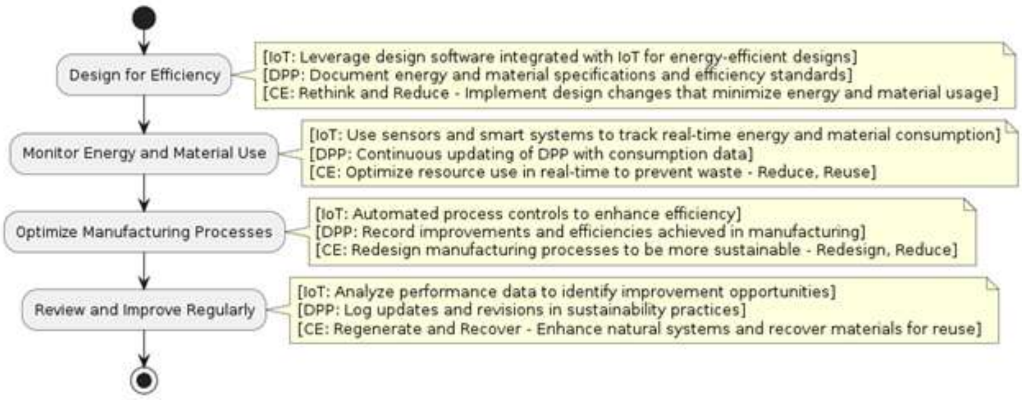

Fig. 12. IoT use case for Energy and Material Efficiency (source: authors' own research)

Through advanced monitoring, feedback loops, and lifecycle transparency, this use case provides a blueprint for resource-smart manufacturing and product design with significant improvements in energy and material efficiency.

A possible example of the lifecycle stages and their respective functions are described below:

- **Design for Efficiency**: IoT tools are integrated into product design software to model and simulate energy and material flows before physical production begins. This allows designers to select optimal materials and configurations that reduce waste and environmental impact. All specifications are recorded in the DPP to support traceability and lifecycle optimization. CE principles of rethinking and reducing are operationalized at this early stage to minimize inputs from the outset.
- **Monitor Energy and Material Use**: IoT-enabled sensors monitor the real-time consumption of energy (e.g. electricity, fuel) and materials (e.g. raw inputs, packaging) across various stages of the product lifecycle. These data streams are continuously updated in the DPP, allowing for transparent reporting and immediate adjustments to reduce inefficiencies. This aligns with CE strategies that promote resource conservation and dynamic process optimization.
- **Optimize Manufacturing Processes**: IoT-controlled automation and analytics

platforms are employed to enhance production efficiency, reduce material loss, and lower energy use. Each improvement – such as process redesign, waste reduction, or load balancing – is logged in the DPP, enabling full documentation of sustainability efforts. These practices reflect CE principles of redesign, reduce, and optimize.

- **Review and Improve Regularly**: IoT systems continuously analyse historical and real-time data to identify new opportunities for efficiency improvements. Updates to operational practices, materials, or technologies are captured in the DPP to maintain a living record of sustainability evolution. This supports CE goals related to regeneration, continuous improvement, and systemic circularity, where products and processes evolve to become more sustainable over time.

4.2 [RQ2] How can IoT be effectively integrated with DPPs to optimize CE practices and enable smart digital data-driven sustainability?

Drawing upon the insights derived from the identified IoT-driven use cases for the implementation of DPPs, this study proposes a conceptual framework for the integration of IoT with DPPs to operationalize CE practices and promote smart digital data-driven sustainability. This integrated conceptual model is visually represented in Figure 13.

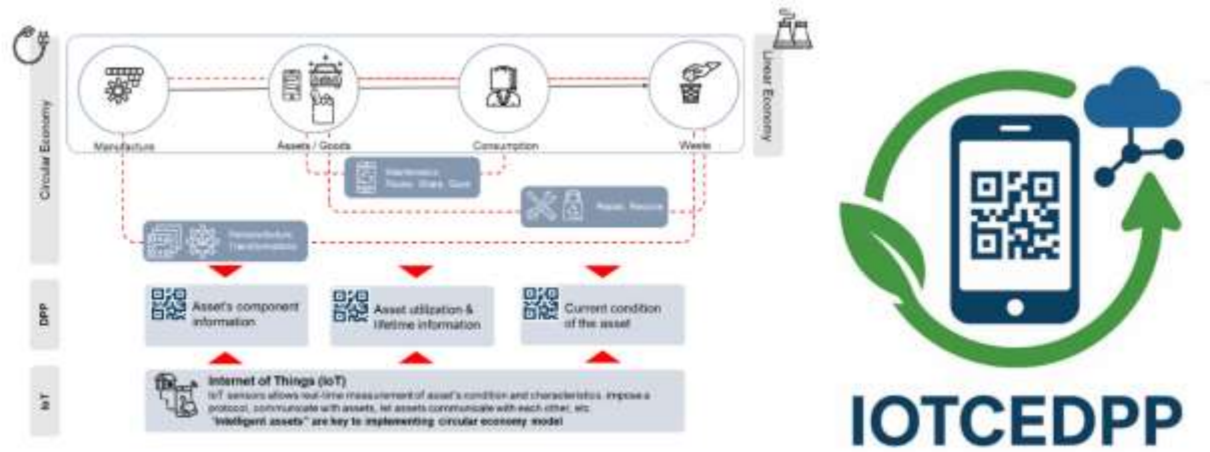

Fig. 13. IoT and DPP integration for a SDCE *(source: adapted from [33])*

This framework addresses the technological, structural, and regulatory elements necessary for enabling seamless data flows, interoperability, and real-time lifecycle intelligence across product systems [33]. It provides a unified model through which digital technologies can support sustainable product and resource management across pre-use, use, and post-use stages [1]. The conceptual framework consists of the following three foundational pillars aligned with [24]:

- **IoT-Enabled Data Collection**
  IoT technologies – including sensors, RFID tags, QR code data carriers, and smart labels – serve as primary mechanisms for capturing real-time product and environmental data throughout the lifecycle. This includes data on usage patterns, material conditions, location tracking, energy consumption, and performance metrics. These data streams are continuously logged and synchronized with the DPP, enabling dynamic lifecycle documentation and supporting decisions related to repair, reuse, recycling, and remanufacturing.
- **Data Interoperability Standards**
  A key enabler of IoT–DPP integration is the adoption of common data models and interoperability protocols that ensure seamless communication between systems across value chains. This includes alignment with emerging standards such as the Asset Administration Shell (AAS) standard and support for cross-sectoral machine-readable DPP schemas.

Interoperability facilitates the secure exchange of static (e.g. product design, material composition) and dynamic (e.g. condition, usage, maintenance) data across platforms and stakeholders, ensuring system compatibility and transparency.

- **Sustainability Metrics and Compliance Mechanisms**
  To translate data into actionable insights, the framework incorporates standardized circularity indicators and compliance reporting mechanisms. These include metrics such as product lifespan extension, material recovery rates, energy efficiency scores, and carbon footprint reductions. Embedded within DPPs, these metrics provide visibility into performance against CE goals and support compliance with environmental regulations (e.g. eco-design directives, extended producer responsibility). Real-time monitoring via IoT enables continuous performance assessment and adaptive optimization.

At the core of this framework lies the concept of a *Smart Digital Circular Economy* – a data-centric model that uses the integration of IoT and DPP technologies to enable resource efficiency, systemic traceability, product lifecycle optimization, and sustainable waste management [2]. By harnessing both static product data (e.g. design and materials) and dynamic operational data (e.g. usage and condition), this framework supports proactive, evidence-based interventions across the entire product lifecycle [12].

In summary, the analysis of key IoT-driven use cases, combined with the development of a conceptual framework for IoT-DPP-CE integration, confirms the central research hypothesis: "*Integrating IoT with Digital Product Passports (DPPs) enables a smart digital Circular Economy (SDCE) by enhancing sustainability practices across the product lifecycle*".

The findings demonstrate that IoT technologies, when systematically integrated with DPP systems, provide real-time data flows, traceability, and lifecycle transparency that are essential for operationalizing CE strategies. From product design and sustainable manufacturing to traceability, end-of-life recovery, and regulatory compliance, the synergy between IoT and DPPs facilitates data-driven sustainability across pre-use, use, and post-use phases. The conceptual framework presented in this study thus offers both theoretical validation and practical guidance for advancing smart, connected, and sustainable circular systems.

5 Conclusion

This research explored the integration of IoT technologies with DPPs systems within the context of the CE strategies, aiming to enhance sustainability practices across the product lifecycle. The study identified and modeled a comprehensive set of IoT-driven use cases for DPPs implementation, demonstrating their applicability in improving traceability, regulatory compliance, material recovery, and product lifecycle management. Furthermore, a conceptual framework was developed to guide the integration of IoT and DPPs in the CE context, emphasizing data interoperability, circular automation, and real-time decision-making.

This study contributes to both academic discourse and practical implementation by:

- Providing a structured taxonomy of IoT-enabled use cases for DPPs across different stages of the product lifecycle in CE context;
- Proposing a conceptual framework that offers guidance to policymakers, industry stakeholders, and researchers;
- Highlighting the role of IoT in DPP ecosystem for enabling SDCE.

While this research offers valuable theoretical insights, several limitations must be acknowledged:

- The reliance on a Systematic Literature Review method limits empirical validation and practical testing of the proposed framework;
- Persistent challenges related to data standardization, security, and implementation costs remain underexplored in this study;
- The proposed framework requires real-world validation through pilot

deployments and longitudinal assessments in industrial settings.

To advance this work, future studies should focus on:

- Empirical validation of the IoT–DPP integration through case studies and industry-led pilot projects;
- Exploring the integration of artificial intelligence and blockchain technologies to enhance circular data automation, data integrity, and decision support;
- Investigating the influence of regulatory policies, sector-specific constraints, and adoption dynamics across various industrial ecosystems.

In conclusion, the integration of IoT and DPPs represents a transformative opportunity for enabling a data-driven SDCE. By leveraging digital infrastructures to enhance transparency, traceability, and sustainability performance, IoT–DPP systems can significantly improve resource efficiency, support regulatory compliance, and promote responsible production and consumption. This research provides clarity for future interdisciplinary collaborations, encouraging academia, industry, and policymakers to collectively shape the next generation of sustainable digital innovation as well as digital transformation of circular economy practices and the circular transformation of the digital economy.

References

[1] E. MacArthur, "Towards the circular economy," *Journal of Industrial Ecology*, vol. 2, no. 1, pp. 23–44, 2013.

[2] A. Alcayaga, M. Wiener, and E. G. Hansen, "Towards a framework of smart-circular systems: An integrative literature review," *Journal of Cleaner Production*, vol. 221, pp. 622–634, 2019.

[3] Y. Han et al., "Exploring how digital technologies enable a circular economy of products," *Sustainability*, vol. 15, no. 3, p. 2067, 2023.

[4] A. Neligan, C. Schleicher, B. Engels, and T. Kroke, "Digital Product Passport – Enabler of the Circular Economy: Relevance and practicability for companies," *IW-Report*, no. 47/2023, 2023.

[5] S. F. Jensen, J. H. Kristensen, S. Adamsen, A. Christensen, and B. V. Waehrens, "Digital product passports for a circular economy: Data needs for product life cycle decision-making," *Sustainable Production and Consumption*, vol. 37, pp. 242–255, 2023.

[6] CIRPASS, "The Digital Product Passport as defined in the Proposal for Eco-design for Sustainable Product Regulation (ESPR)," 2024. [Online]. Available: https://cirpassproject.eu/dpp-in-anutshell/

[7] European Commission, "Proposal for a Regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC," COM/2022/142 final, 2022. [Online]. Available: https://eur-lex.europa.eu/legalcontent/EN/TXT/?uri=CELEX%3A52022PC0142

[8] A. Neligan, C. Schleicher, B. Engels, and T. Kroke, "Digital Product Passport – Enabler of the Circular Economy: Relevance and practicability for companies," *IW-Report*, no. 47/2023, 2023.

[9] I. Askoxylakis, "A framework for pairing circular economy and the Internet of Things," in *Proc. IEEE Int. Conf. on Communications (ICC)*, May 2018, pp. 1–6.

[10] N. Gligoric et al., "Smarttags: IoT product passport for circular economy based on printed sensors and unique item-level identifiers," *Sensors*, vol. 19, no. 3, p. 586, 2019.

[11] K. Voulgaridis et al., "Digital product passports as enablers of digital circular economy: a framework based on technological perspective," *Telecommunication Systems*, pp. 1–17, 2024.

[12] G. Bressanelli, F. Adrodegari, D. C. Pigosso, and V. Parida, "Towards the smart circular economy paradigm: A definition, conceptualization, and research agenda," *Sustainability*, vol. 14, no. 9, p. 4960, 2022.

[13] M. Jansen et al., "Stop guessing in the dark: Identified requirements for digital

product passport systems," *Systems*, vol. 11, no. 3, p. 123, 2023.
[14] M. Jansen et al., "Current approaches to the digital product passport for a circular economy: An overview of projects and initiatives," *Wuppertal Paper*, no. 198, Wuppertal Institute for Climate, Environment and Energy, 2022. [Online]. Available: https://epub.wupper-inst.org/files/8042/WP198.pdf
[15] E. Wagner et al., "D2.1 Mapping of legal and voluntary requirements and screening of emerging DPP-related pilots (2.0)," CIRPASS Consortium, 2023.
[16] M. Wiesner, J. Moreira, R. Guizzardi, and P. Scholz, "A reference architecture for digital product passports at batch level to support manufacturing supply chains," in *Proc. Int. Conf. on Research Challenges in Information Science*, Cham, Switzerland, May 2024, Springer, pp. 307–323.
[17] L. Stratmann, G. Hoeborn, C. Pahl, and G. Schuh, "Classification of product data for a digital product passport in the manufacturing industry," in *Proc. Conf. on Production Systems and Logistics (CPSL)*, Apr. 2023, pp. 448–458.
[18] CIRPASS, *Digital Product Passport*, 2024. [Online]. Available: https://cirpass-project.eu/dpp-in-anutshell/. [Accessed: May 21, 2025].
[19] P. Morseletto, "Targets for a circular economy," *Resources, Conservation and Recycling*, vol. 153, p. 104553, 2020.
[20] J. Mast, F. von Unruh, and W. Irrek, "R-strategies as guidelines for the Circular Economy," *RETHINK: Impulse zur zirklären Wertschöpfung – Enabling the Circular Economy*, vol. 3, 2022.
[21] One Planet Network, "Rethinking, Extending, Re-using. Harnessing Digital Technologies for the Circular Economy," 2023.
[22] S. D. Gheorghe, "A review of the Information Technology and Operational Technology convergence using Internet of Things within the Circular Economy," in *Proc. Int. Conf. on Business Excellence*, vol. 18, no. 1, pp. 829–845, 2024.
[23] E. Kristoffersen, F. Blomsma, P. Mikalef, and J. Li, "The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies," *Journal of Business Research*, vol. 120, pp. 241–261, 2020.
[24] E. Barteková and P. Börkey, "Digitalisation for the transition to a resource efficient and circular economy," *OECD Environment Working Papers*, no. 192, OECD Publishing, Paris, 2022. [Online]. Available: https://doi.org/10.1787/6f6d18e7-en
[25] M. L. Wiesner, "From component to product: Digital capabilities for the Digital Product Passport in the production sector," M.Sc. thesis, Univ. of Twente, Enschede, The Netherlands, 2023.
[26] C. Plociennik et al., "Requirements for a digital product passport to boost the circular economy," *INFORMATIK*, 2022.
[27] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2347–2376, 2015.
[28] ITU, *Recommendation ITU-T Y.2066: Common requirements of the Internet of Things*, 2014. [Online]. Available: https://handle.itu.int/11.1002/1000/12169
[29] K. Voulgaridis, T. Lagkas, C. M. Angelopoulos, and S. E. Nikoletseas, "IoT and digital circular economy: Principles, applications, and challenges," *Computer Networks*, vol. 219, p. 109456, 2022.
[30] L. Jum'a, M. Ikram, and C. J. C. Jabbour, "Towards circular economy: An IoT enabled framework for circular supply chain integration," *Computers & Industrial Engineering*, p. 110194, 2024.
[31] C. Garrido-Hidalgo, T. Olivares, F. J. Ramirez, and L. Roda-Sanchez, "An end-to-end Internet of Things solution for reverse supply chain management in Industry 4.0," *Computers in Industry*, vol. 112, p. 103127, 2019.
[32] CE-IOT, "A Framework for Pairing Circular Economy and IoT: IoT as an enabler of the Circular Economy & circularity-by-design as an enabler for IoT. D2.1: LCA

and CSPDI patterns," Horizon 2020 Program, Apr. 2020.

[33] CE-IOT, "A Framework for Pairing Circular Economy and IoT: IoT as an enabler of the Circular Economy & circularity-by-design as an enabler for IoT. D2.2: Business models for interplay of circular economy with IoT," Horizon 2020 Program, Apr. 2020.

[34] H. Snyder, "Literature review as a research methodology: An overview and guidelines," *Journal of Business Research*, vol. 104, pp. 333–339, 2019.

[35] A. A. Selçuk, "A guide for systematic reviews: PRISMA," *Turkish Archives of Otorhinolaryngology*, vol. 57, no. 1, p. 57, 2019.

[36] B. Kitchenham et al., "Systematic literature reviews in software engineering–a systematic literature review," *Information and Software Technology*, vol. 51, no. 1, pp. 7–15, 2009.

[37] M. Richards and N. Ford, *Fundamentals of Software Architecture: An Engineering Approach*. Sebastopol, CA, USA: O'Reilly Media, 2020.

[38] I. Compagnucci et al., "A systematic literature review on IoT-aware business process modeling views, requirements and notations," *Software and Systems Modeling*, vol. 22, no. 3, pp. 969–1004, 2023.

Sorin-Daniel GHEORGHE is a PhD student at the Doctoral School of Economic Informatics, The Bucharest University of Economic Studies. He holds an MBA degree in General Management from the University of Sheffield, International Faculty, CITY College. He also has a Master's degree in Management in Information Technology from the University POLITEHNICA of Bucharest, Faculty of Automatic Control and Computers and a Bachelor of Engineering degree in Information Technology and Computer Science from the University of Bucharest, Faculty of Mathematics and Computer Science. Currently, he works as an IT Project Officer Consultant for the European Commission. He is passionate about Information Technology, Enterprise Architecture, and IT Leadership, Management, and Governance consulting.