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Designing Internet of Things Systems for Circular Economy and Digital Product Passports – A Requirements Engineering Perspective

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Abstract. *The proliferation of Internet of Things technologies presents unprecedented opportunities for enhancing sustainability through the principles of the Circular Economy. This research explores the integration of Digital Product Passports within Internet of Things systems to support Circular Economy goals, focusing on the Requirements Engineering perspective. Key objectives include identifying essential requirements for Internet of Things systems, developing a design blueprint, and establishing validation techniques to ensure system compliance with Circular Economy principles and Digital Product Passports integration. The methodology involves a systematic literature review with thematic analysis adapted to the Requirements Engineering process, and the use of FURPS+ and MoSCoW frameworks for categorizing and prioritizing requirements. Findings highlight the critical functional, non-functional, domain-specific, and application-specific requirements necessary for Internet of Things systems to support Circular Economy and Digital Product Passports. The research findings indicate that properly engineered Internet of Things systems facilitate the transition from a linear to a smart digital circular economy by enhancing resource efficiency, minimizing waste, and promoting sustainability.*

Keywords: circular economy, internet of things, digital product passports, requirements engineering, green digital infrastructure, smart digital circular economy.

Introduction

The Internet of Things (IoT) represents a paradigm shift in the technological landscape, marked by its capability to connect a vast network of smart devices with sensors, actuators, and/or identification tags, enabling them to communicate and exchange data with minimal human intervention (Al-Fuqaha et al, 2015).

This interconnectivity facilitates unprecedented levels of data collection and analysis, driving efficiency and innovation across various industries including manufacturing, healthcare, and transportation (Voulgaridis, 2022).

In the realm of environmental sustainability, IoT technologies are particularly assured to play a pivotal role by supporting the principles of the Circular Economy (CE). These technologies enable real-time tracking and management of resources, among other use cases, which is critical for optimizing resource utilization and minimizing waste.

The concept of a CE is rooted in the minimization of waste and the maximization of resource use. Unlike the traditional linear economy, which follows a 'take, make, dispose' model, the CE emphasizes keeping resources in use for as long as possible, extracting the maximum value from them while in use, and recovering and regenerating products and materials at the end of each service life (MacArthur, 2013).

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Digital Product Passport (DPP) are emerging as a key tool within the CE context (Jensen et al, 2023). These passports serve as digital records that provide detailed information about the materials and processes involved in the manufacturing of products, their usage, and disposal guidelines, thereby enhancing transparency and accountability in product life cycles.

Requirements Engineering (RE) is a systematic process in systems development that involves the elicitation, analysis, specification, validation, and management of the various requirements (Aurum and Wohlin, 2005).

In the context of IoT systems designed to support the CE principles and strategies, RE becomes critical (Symeonidis et al, 2019; Plociennik et al, 2022). It ensures that the systems are not only functionally effective but are also adaptable, secure, and aligned with CE sustainability goals and practices. Properly engineered requirements help in mitigating risks associated with system failures and security vulnerabilities (Aurum and Wohlin, 2005), which are crucial in maintaining the availability, integrity, confidentiality, and trustworthiness of IoT systems handling DPP data and associated CE practices.

This research aims to explore the intricate relationship between IoT technologies and the CE domain to support circular practices and sustainability principles, with a specific focus on the integration and functionality of DPP applications from a RE perspective.

The primary objectives are to (1) identify the key requirements for IoT systems highlighting the critical functional, non-functional, domain-specific, and application-specific requirements, (2) develop and specify a design blueprint for IoT systems, and (3) identify key validation techniques to accurately check the compliance of IoT systems with CE principles and strategies and the integration of the DPP applications.

After the introduction of the research context, the Literature Review section presents the overview of CE, IoT, and DPP and their common requirements as well as the RE process and framework used to guide this research. Furthermore, the Methodology section outlines the research design, research questions and objectives, data collection methods, and data analytical techniques used in this paper. The research findings are presented in the Results and Discussions section with a focus on the requirements specification, system modeling, and validation techniques. The Conclusion section summarizes the main contributions of this study and recommends areas for future research.

Literature review

Circular Economy overview

The CE paradigm represents a systemic shift from the traditional linear economic model, emphasizing resource efficiency and sustainability.

At its core, the CE model promotes "closing the loop" of product lifecycles through greater recycling, reuse, and reduced resource consumption, thereby creating a regenerative economic system (MacArthur, 2013).

This approach contrasts sharply with the 'take-make-waste' philosophy of the linear economy, which has led to many of today's most significant challenges, such as climate change, environmental degradation, material scarcity and resource depletion, global biodiversity loss, vulnerability to economic and environmental shocks, and the uneven distribution of benefits along globalized value chains (MacArthur, 2013).

CE principles

According to MacArthur (2013), the CE model is underpinned by three core principles: (1) design out waste and pollution, (2) keep products and materials in use, and (3) regenerate natural systems.

These principles aim to build a sustainable, equitable and resilient holistic system for people, businesses, and the environment and can be visualized in the Figure 1.

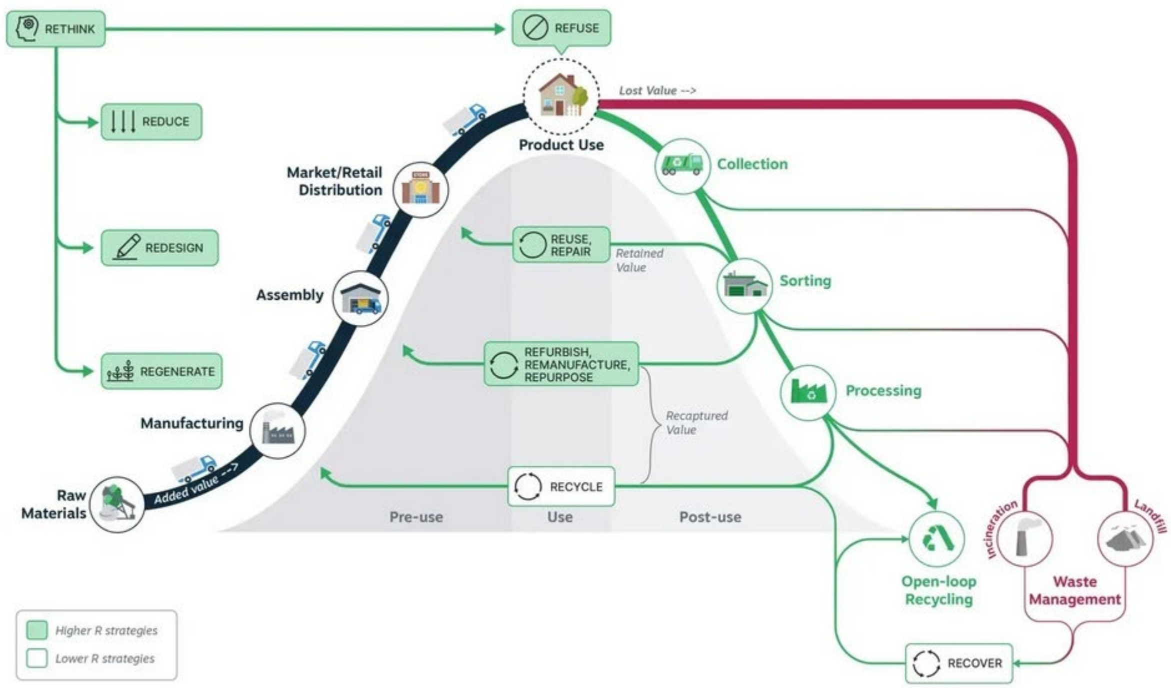

Figure 1. Value Hill model with the "R" circular strategies

Source: One Planet Network (2023).

The “Value Hill” model depicted above illustrates the full life cycle of any given product, from extraction and manufacturing through use and eventual disposal (One Planet Network, 2023). Value accumulates as the product ascends 'uphill' in the supply chain, with circular strategies aiming to maintain the product at its peak value (situated at the top of the hill) for the longest possible duration. In this circular supply chain model, products are designed to be durable and suitable to maintenance and repair, thereby decelerating resource loops and extending the product's use-phase. As a product begins its 'downhill' journey, the decline is managed as gradually as possible to ensure that its valuable resources continue to serve others.

CE strategies

In the context of the CE, the "Rs" circular strategies, often referred to as the "R" circular practices, aim to maintain, increase, or restore the value of products and materials during their lifecycle (Morseletto, 2020).

The Table 1 presents the most used "Rs" circular strategies. These circular strategies represent a broad and integrative approach to implementing circular economy principles across the lifecycle of products and materials.

Each plays a role in preserving or enhancing the value of resources, reducing environmental impact, and promoting sustainability (Morseletto, 2020).

Table 1. "R" circular strategies

Circular Strategy	Brief Description	Circular Principle
Rethink	Reconsider the need, design, ownership, use, and maintenance of products to prevent waste.	Design Out Waste and Pollution
Reduce	Minimizing the use of materials and energy in products and processes.	Design Out Waste and Pollution
Redesign	Altering the design of products and systems to improve sustainability and efficiency.	Design Out Waste and Pollution
Refuse	Opting not to use or purchase unnecessary or environmental harmful products.	Design Out Waste and Pollution
Reuse	Using products repeatedly in the same form or slightly modified forms to extend their life.	Keep Products and Materials in Use
Repair	Fixing and maintaining products to prolong their use.	Keep Products and Materials in Use
Refurbish	Restoring and improve products to like-new condition to extend their life.	Keep Products and Materials in Use
Remanufacture	Breaking down products into parts and using these to create products with same function.	Keep Products and Materials in Use
Repurpose	Modifying a product or discarded parts to be used for a different function than it was originally designed for.	Keep Products and Materials in Use
Recycle	Transforming waste materials into new materials or products to prevent waste of useful materials.	Regenerate Natural Systems
Recover	Recovering energy or other resources from waste materials that cannot be reused or recycled.	Regenerate Natural Systems
Regenerate	Enhancing and restoring natural systems through sustainable products and practices.	Regenerate Natural Systems

Source: Adapted from Morseletto (2020).

Research gaps

The Circular Economy (CE) paradigm represents a fundamental shift from the traditional linear economy, offering numerous advantages across environmental, economic, and social dimensions (MacArthur, 2013).

Environmental benefits include waste reduction, lower carbon emissions, and biodiversity conservation, contributing to long-term sustainability.

Economic benefits arise from new business models, reduced production costs, and enhanced supply chain resilience, fostering innovation and resource efficiency.

Social benefits include the creation of jobs in sustainability-focused industries and greater consumer awareness regarding responsible consumption and ethical production practices.

Despite these advantages, several challenges hinder CE adoption, including:

Lack of standardization – Many industries lack unified guidelines for sustainable product design, material reuse, and lifecycle management.

Data and transparency issues – The absence of robust data-sharing mechanisms makes it difficult to track materials across lifecycle stages, reducing supply chain traceability.

Technological barriers – CE implementation often depends on advanced technologies, such as IoT, Blockchain, and AI, which require significant investment and interoperability frameworks.

Several studies have explored how digital technologies, particularly IoT, can enable CE practices (Askoxylakis, 2018; Bressanelli et al., 2022).

Han et al. (2023) identify IoT as a key enabler of CE, emphasizing its role in real-time resource tracking, predictive maintenance, and lifecycle management.

However, while these studies highlight IoT's potential, they do not provide a structured methodology for defining IoT system requirements within CE – a critical gap that this research aims to address by exploring Digital Product Passports use case and using RE framework.

Internet of Things overview

The IoT represents a global infrastructure that integrates physical and virtual entities – "things" – to deliver advanced, context-aware services enabled by interoperable technologies (Al -Fuqaha et al, 2015).

According to ITU (2012), IoT adds a new dimension – any THING communication – to the existing Information and Communication Technologies (ICT) capabilities of communicating any TIME and any PLACE.

In this paradigm, physical things (e.g. industrial robots, appliances, environmental sensors) and virtual things (e.g. software, multimedia content) are uniquely identifiable and integrated into communication networks.

At its core, the IoT leverages devices: equipment with mandatory communication capabilities and optional sensing, actuation, data capture, storage, and processing functions. These devices may communicate directly, via local networks, or through gateways over traditional TCP/IP-based networks as well as next- generation networks.

The interactions occur not only among physical devices, but also between their virtual counterparts and across the two realms. According to ITU (2012), all IoT devices must at least support communication capabilities and they fall into four main categories:

Data-carrying devices: attached to a physical thing to provide an indirect link connecting the physical world with the communication networks.

Data-capturing devices: read and optionally write information directly or indirectly (via *data-carrier devices*) to things via various interacting technologies (e.g. radio frequency, infrared, optical and galvanic driving, etc.).

Sensing and actuating devices: measure environmental data or perform operations based on received digital signals, typically organized in local networks and linked to broader communication networks through gateways.

General devices: embed both processing and communication capabilities (e.g. smart appliances, smart phones, industrial machines) and connect over wired or wireless networks to support various IoT application domains (e.g. smart homes, smart cities, smart factories, etc.).

The overall vision of IoT system is to integrate emerging technologies – machine-to- machine communication, autonomic networking, data mining, cloud computing, an d advanced security/privacy measures – into a cohesive infrastructure that fully exploits the potential of connected "things."

IoT System Common Non-Functional and Functional Requirements

The Internet of Things (IoT) encompasses a wide range of requirements critical for the successful implementation and operation of IoT systems considering the various system, devices, and applications' characteristics. These requirements can be categorized into non-functional and functional areas (Paldês et al, 2020).

Non-functional requirements deal with general system characteristics such as scalability and reliability, while functional requirements are more specific to the actions and interactions within the IoT ecosystem, involving application support, service, communication, device management, data management, and security (Paldês et al, 2020).

According to ITU (2014a), the common IoT non-functional and functional requirements of the, which are independent of any specific IoT application domain are summarized in Table 2 and Table 3.

Table 2. IoT Non-Functional requirements (NFR)

IoT-NFR	Description
Interoperability	Necessary for seamless operation among diverse IoT systems.
Scalability	Essential to handle increasing numbers of devices, users, and applications
Reliability	Critical for ensuring dependable communication, service, and data management.
High Availability	Important for consistent service provisioning and data management.
Adaptability	Important for integrating future technological advancements
Manageability	Needed for maintaining normal operations and management of the system.

Source: Adapted from ITU (2014a).

Table 3. IoT Functional requirements (FR)

IoT-FR	Description
Application	Focuses on user interaction capabilities, including standardized interfaces and group management.
Service	Involves prioritization and management of services to meet diverse user needs and ensure robustness.
Communication	Encompasses various modes and types of communication essential for device interaction and data transfer.
Device	Includes requirements for device connectivity, monitoring, and management.
Data Management	Involves the storage, processing, and security of data within the IoT system.
Security and Privacy	Ensures secure and private communication, data management, and service provisioning.

Source: Adapted from ITU (2014a).

IoT Applications Common Requirements

IoT applications span a wide range of domains – such as industry, environment, society, and home – and frequently combine features across multiple domains ("inter-domain" applications).

Table 4 outlines common requirements for IoT applications as per ITU (2014b), where depending on the IoT application domain some requirements might be more critical than others.

Table 4. IoT Applications common requirements (App)

IoT-App	Description
Identification & Connectivity	Ensuring each device has a unique ID and connectivity approaches that handle heterogeneous identifiers in a unified way.
Interoperability & Autonomics	Enabling seamless integration across diverse systems, with self-managing (self-configuring, self-healing) networks and automatic service delivery.
Location, Security & Privacy	Balancing location tracking needs with robust security (confidentiality, authenticity, integrity) and privacy protections throughout data handling.
Ease of Use, Manageability & Compliance	Facilitating plug-and-play setups, allowing oversight of automated processes, adhering to legal requirements, and ensuring user awareness of IoT services.
Mobility & Scalability	Supporting roaming devices and large-scale deployments without service disruption, handling high connection demands and data volumes.
Reliability & Self-Healing	Maintaining stable operation under changing conditions, with capabilities for re-organization and automatic recovery in case of failures.
Energy & Data Exchange	Minimizing energy consumption (especially for battery-powered devices) and promoting a common data format for efficient sharing and interoperability.

Source: Adapted from the ITU (2014b).

IoT Architecture Unified Requirements

In addition to the common IoT system and application requirements, the analysis of the Internet of Things Architecture (IoT-A) Unified Requirements (IoT-A, 2024), which outlines a robust framework for developing IoT systems that are secure, efficient, and capable of operating within diverse and dynamically changing environments, reveals additional functional, non-functional, and design requirements essential for the architecture of IoT systems, further summarized in Table 5.

Table 5. IoT Architecture Unified Requirements (IoT-A)

IoT-A Category	IoT-A Unified Requirements
Functional	Data handling, Interoperability, Privacy, Security, Manageability, QoS, Reliability
Non-Functional	Scalability, Performance, Resilience, Availability, Adaptability, Maintenance
Design Constraints	Compatibility, Integration, Standardization, Semantics

Source: Adapted from IoT-A (2024).

IoT System Requirements for Circular Economy

The deployment of IoT technologies within the framework of the CE has gained increasing attention for its potential to revolutionize resource management and waste reduction.

IoT, with its network of interconnected devices capable of generating real-time data, plays a pivotal role in enhancing the transparency and efficiency of resource flows of the CE ecosystem (Askoxylakis, 2018).

The integration of IoT technologies into CE practices is underpinned by several key theoretical frameworks that not only guide the conceptualization of such integrations but also inform their practical implementations, as mentioned in CE-IoT (2020a) and depicted in Figure 3.

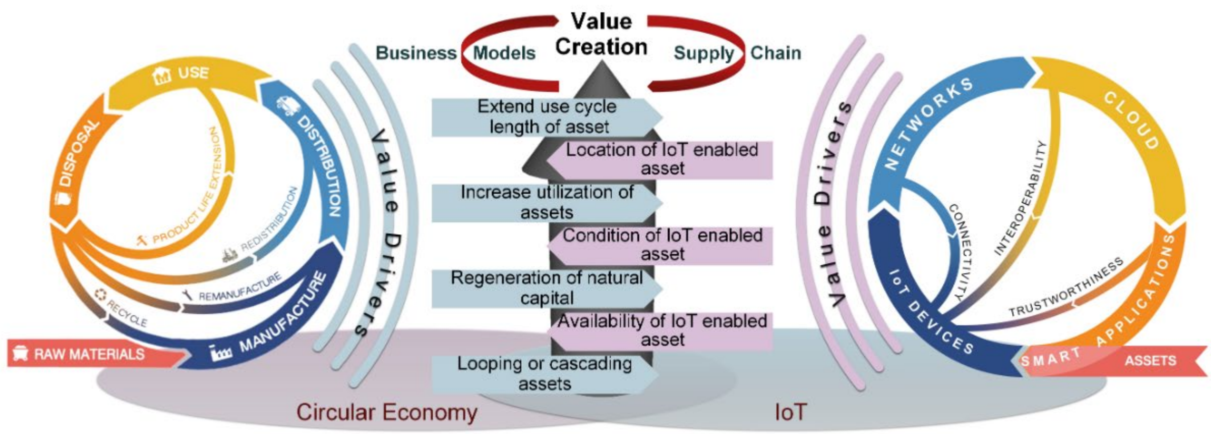

Figure 2. The IoT – CE ecosystem

Source: CE-IoT (2020a).

One of the central theoretical constructs is the *smart digital circular economy*, which utilizes IoT technologies to enhance resource efficiency, extend product lifecycles, and improve waste management through the strategic collection and analysis of data (Bressanelli, 2022).

According to CE-IoT (2020a), the integration of IoT systems in CE initiatives (CE-IoT systems) outlines multi-dimensional system requirements focusing on *Location, Condition, and Availability* (LCA) as well as *Connectivity, Security, Privacy, Dependability, and Interoperability* (CSPDI) further presented in Table 6.

Table 6. CE-IoT Requirements

.	Description
Location	The ability to track the real-time and precise location of IoT devices and assets.
Condition	Monitoring the state of devices to assess their operational readiness or maintenance needs.
Availability	Ensuring devices are operational and accessible when needed, critical for system reliability and effectiveness.
Connectivity	Robust network connections among IoT devices, supporting various communication protocols to ensure continuous data exchange
Security	Strong safeguards to protect data integrity and prevent unauthorized access, ensuring the confidentiality, integrity, and availability of data.
Privacy	Measures to protect individual and corporate data, adhering to regulations like GDPR, and ensuring that data usage is consented and transparent.
Dependability	Reliability of IoT devices and networks, including fault tolerance and the ability to perform under expected conditions.
Interoperability	Seamless interaction between diverse systems and devices, enabling effective communication and function across different technological platforms.

Source: Adapted from CE-IoT (2020a).

Research gaps

The integration of IoT into CE practices is not without challenges. According to Rajput and Singh (2021), the vast amounts of data generated by IoT devices necessitate robust data management and security measures to protect sensitive information. Moreover, there are concerns about the interoperability of IoT systems, as different devices and platforms often lack standardized communication protocols, complicating the integration process across various stages of the supply chain.

Despite these challenges, the potential of IoT to support CE initiatives remains significant, with ongoing research focusing on overcoming these barriers to harness IoT's full capabilities (Han et al, 2023; Gheorghe, 2024).

For instance, Rajput & Singh (2021) explore Industry 4.0 challenges in implementing CE, noting that IoT interoperability and security are key concerns; however, their work lacks a structured RE approach for designing IoT-driven CE systems. Paldês et al. (2020) identify common functional and non-functional requirements for IoT, but do not consider CE-specific constraints, such as regulatory compliance and material traceability. Compagnucci et al. (2024) discuss IoT-aware business process modeling but do not focus on the specific requirements needed for CE integration. The CE-IoT framework (CE-IoT, 2020a) outlines generic system requirements but lacks practical implementation models.

Indeed, IoT applications in CE focus on resource efficiency, product lifecycle tracking, and waste reduction, where interconnected smart devices can collect and process data for automated decision-making (Al-Fuqaha et al., 2015) and while many existing studies focus on IoT applications in CE, they lack a structured, requirements-driven approach for ensuring system reliability, security, and regulatory compliance. This study addresses this by introducing a systematic RE methodology for IoT-DPP integration in CE.

Digital Product Passports overview

The DPP was first mentioned in general terms as an instrument in the EU Green Deal of 2019 and Circular Economy Action Plan (CEAP) pillar which identifies DPP as a solution to mobilize the potential of product information digitalization as part of a sustainable product policy and it was further specified in the proposal of the EU Ecodesign Regulation in 2022 (Voulgaridis, 2019).

The European Union (EU) is set to introduce the DPP as part of its Ecodesign for Sustainable Products Regulation (ESPR) (European Commission, 2022). This initiative aims to enhance product transparency across the value chain and set a new standard for sustainable products within the EU market (Neligan, 2023).

A DPP is a structured collection of product related data with pre-defined scope and agreed data management and access rights conveyed through a unique identifier and that is accessible via electronic means through a data carrier (CIRPASS, 2024).

The intended scope of the DPP is information related to sustainability, circularity, value retention for re-use, remanufacturing, and recycling.

Under the EU Ecodesign Regulation, the DPP is defined as digital records and system aimed at collecting, sharing, and managing product-related information throughout its lifecycle, from production to disposal (CIRPASS, 2024).

According to Jansen et al (2023), we distinguish between the DPP and the DPP system. The DPP itself seen as digital records is comprised of the data and information contributed by various stakeholders involved in the product's lifecycle. In contrast, the DPP system refers to the foundational hardware and software infrastructure that aggregates this necessary data.

Furthermore, the DPP system not only facilitates communication and data exchange among different stakeholders, but also links the physical product to its corresponding digital passport and, according to Gligoric et al (2019), the IoT can be further used as a digital infrastructure for the integration of the DPP applications.

ESPR ecodesign requirements

The proposal for the ESPR encompasses a broad spectrum of ecodesign requirements aimed at enhancing product sustainability across various stages of the product lifecycle (European Commission, 2022).

These requirements, further presented in Table 7 are designed to develop products that are environmentally friendly, economically viable, and socially responsible.

They align with global sustainability targets and consumer expectations for greener products, enhancing environmental performance and extending product usability, contributing to the EU's broader sustainability goals and supporting the CE.

Table 7. The ESPR Ecodesign Requirements for Products

Category	ESPR Ecodesign Requirements
Durability and Reliability	Durability, Reliability
Usability	Reusability, Upgradability, Reparability, Maintenance
Safety and Compliance	Presence of substances of concern
Efficiency	Energy use, Resource use, Energy efficiency, Resource efficiency
Sustainability	Recycled content, Remanufacturing, Recycling, Material recovery
Environmental Impact	Environmental impacts, Carbon footprint, Waste generation
Product Identification	Unique product identifiers, Global Trade Identification Number.
Manufacturer Identification	Manufacturer details, unique operator identifiers, etc.
Material and Composition	Substances of concern, their locations, and concentrations.
Product Design & Service Info	Safe usage instructions, disassembly info, user manuals.
Compliance and Circularity	Compliance documents, ecodesign information, EU Ecolabel.
Substances of Concern	Classification of hazardous substances, impact on recycling.

Source: Adapted from CIRPASS (2024).

DPP system requirements

The DPP system, as outlined in the text of the ESPR, encompasses a range of requirements aimed at ensuring sustainability, traceability, and accessibility of product information through digital means (Jansen et al, 2023).

Therefore, the DPP system requirements outlined in Table 8 are crucial for creating a transparent, efficient, and user-friendly system that supports the lifecycle management of products in an eco-friendly manner.

Table 8. Digital Products Passports System Requirements

Category	Requirements
Legal Obligations	ESPR Compliance, EPR Compliance, GDPR Compliance
Functional Suitability	Industry Specific, Responsibility Statements, Decentralized Data Storage
Security, Confidentiality, IP Protection	Nonrepudiation, Data Verification, Data Sovereignty and Secure Storage
Interoperability	Semantic Clarity, Standardized Data Schemas, APIs for Data Interaction
Modularity and Modifiability	System Flexibility, International Scalability
Accessibility	Access Rules Implementation, Inclusive Participation
Availability and Responsiveness	Reliable Access, Real-time Data Capability
Portability	Transferability of Identifiers, Avoid Central Registers, Harmonization

Source: Adapted from Jansen et al (2023).

Research gaps

Despite their potential, the implementation of DPPs faces several challenges, including technological hurdles related to the integration of DPPs with existing IoT infrastructures, the need for standardized data formats to ensure interoperability, and concerns over data privacy and security (Neligan, 2023).

Furthermore, the effectiveness of DPPs relies heavily on the accuracy and completeness of the data they contain, which can be compromised by discrepancies in data entry or updates.

Current research in this area focuses on developing standardized frameworks for DPPs that ensure compatibility and security while promoting ease of use across different sectors and regions (Voulgaridis et al, 2024).

For instance, researchers are exploring innovative ways to use IoT and Blockchain to secure product data and maintain its integrity throughout the product's lifecycle (Jum'a et al, 2024).

While DPPs enable traceability, circularity, and sustainability compliance, aiming to improve material tracking and sustainability reporting, several research gaps remain in existing studies examining their implementation.

CIRPASS (2024) defines the DPP standard but lacks technical implementation guidelines for IoT integration. Jansen et al. (2023) identify key DPP system requirements, such as security, interoperability, and compliance, but do not propose a structured IoT system design. Neligan et al. (2023) highlights the challenges of DPP adoption in industry, including standardization issues and data privacy concerns, but lacks a practical approach for overcoming these barriers.

While previous studies primarily focus on DPP system requirements, they do not provide a comprehensive IoT-based design framework to ensure seamless integration and validation of DPPs within digital infrastructures.

This research addresses this gap by: proposing a layered IoT system architecture that ensures secure, scalable DPP integration within CE ecosystems and by defining a structured validation process using scenario-based modeling to assess system reliability, compliance, and performance.

By bridging these gaps, this study contributes to the technical standardization and practical deployment of IoT-driven DPP solutions enabling a smart digital circular economy model.

Requirements Engineering overview

RE is fundamental in developing systems that effectively meet user and stakeholder expectations, particularly for complex and dynamic environments such as the IoT systems designed to support CE initiatives, where these systems must align complex technological solutions with circular strategies and sustainability goals, a task that requires robust and adaptable RE methodology (Aurum and Wohlin, 2005).

RE process

The RE process helps in clarifying the purposes and functionalities of the system, setting up the groundwork for its design, development, and subsequent maintenance, and it typically involves several distinct phases (Aurum and Wohlin, 2005).

Requirements elicitation (or gathering): This is the initial phase where requirements are collected from various stakeholders, including users, customer representatives, engineers, and managers. Techniques such as interviews, questionnaires, user observation, and workshops are commonly used. The goal is to gather a comprehensive list of needs and constraints from all parties that will influence the system's development.

Requirements analysis: Once requirements are gathered, they need to be analyzed to resolve conflicts between differing requirements, understand the feasibility of requirements, and determine their necessity and priority. This phase helps in refining and clarifying the requirements. It may involve partitioning large requirements into smaller, manageable segments or modeling the requirements to check their correctness and completeness.

Requirements specification: In this phase, the analyzed requirements are documented and transformed into a detailed specification document that serves as a guideline for system developers. The specification is typically written in a clear, precise, and unambiguous language to avoid misunderstandings. It often includes use cases, functional requirements, non-functional requirements (like performance, usability, reliability), and design constraints.

Requirements validation: This step involves reviewing the requirements specification to ensure that it accurately reflects the needs and conditions as stated by the stakeholders and that all requirements are testable and feasible. Validation can involve stakeholders reviewing the document or using techniques like prototypes or models to validate assumptions. The key is to catch and correct errors before the development process begins.

Requirements management: Throughout the development process, requirements can change due to various factors such as market changes, technological advancements, or changes in stakeholder needs. Requirements management is the ongoing process of tracking and managing changes to the requirements. It involves maintaining traceability of requirements throughout the project lifecycle, prioritizing requirements, and keeping documentation up to date.

RE framework for IoT-CE-DPP

The design and implementation of IoT systems within the CE and DPP context are heavily reliant on robust RE frameworks that ensure these systems are not only effective but also adaptable and sustainable (CE-IoT, 2020a; CE-IoT, 2020b; Wenning et al, 2024).

Furthermore, adapting RE to the development of IoT systems that support DPP involves several specific considerations given the specific innovative nature of the CE practices and DDP applications, designed to enhance product lifecycle transparency with detailed information such as product composition, origin, usage, and recyclability (Aguilar-Calderon, 2022).

Key approaches are *FURPS+* and *MoSCoW* models, which provide a structured way to capturing and prioritizing IoT system requirements (Kozlowski et al, 2023; Farhat et al, 2022).

FURPS+ categorizes requirements into *functionality*, *usability*, *reliability*, *performance*, and *supportability*, with additional considerations for *design constraints*, *physical requirements*, and *quality standards* (Kozlowski et al, 2023).

This approach is particularly useful in the IoT context, where multifaceted system attributes such as sensor accuracy, system reliability, data security, and user interface design are critical.

The adaptation of FURPS+ in the CE and DPP context might emphasize usability and supportability to ensure that the systems are accessible to a wide range of users, from consumers to regulators, and can adapt to evolving regulatory requirements around product sustainability reporting.

The MoSCoW approach, which stands for *Must have*, *Should have*, *Could have*, and *Won't have*, is crucial for prioritizing requirements in environments characterized by rapid technological changes and limited resources (Farhat et al, 2022).

In the development of IoT systems for the CE, this method helps stakeholders focus on essential features that drive immediate value, while identifying others that can be introduced over time as part of continuous improvement processes.

In contrast, when developing IoT systems for DPP, this method prioritizes functionalities that are critical for compliance with environmental legislation (Must have) – such as accurate tracking of material sources and disposal methods – over more advanced features like predictive analytics for product end-of-life (Could have), which can be added as the technology matures.

By leveraging FURPS+ and MoSCoW in the RE process, the development of IoT systems to support of CE practices, particularly through applications like DPP, can be significantly improved. These IoT systems not only meet the immediate operational needs, but also align with broader sustainability goals considering the fit-for-use and fit-for-purpose of the CE domain and DPP applications.

Research gaps

While the RE plays a critical role in developing IoT systems that align with CE principles and DPP compliance by ensuring that the system requirements are systematically defined, analyzed, and validated (Aurum & Wohlin, 2005), prior studies apply RE to general IoT development, but do not focus on CE-DPP integration.

Current research efforts are increasingly focuses on addressing these issues by examining how traditional RE methods can be adapted to meet the specific demands of IoT-driven CE (CE-IoT) systems (Symeonidis et al, 2019).

For example, researchers are exploring RE frameworks that incorporate environmental impact assessments, lifecycle analysis (LCA), and environmental, social, and governance (ESG) factors to more effectively integrate CE sustainability considerations into the development of digital technologies and systems such as IoT (Fatimah et al, 2023). This paper contributes to this research gap by adapting FURPS+ and MoSCoW for IoT-DPP requirement prioritization and defining validation techniques (scenario-based modeling) for ensuring IoT-DPP compliance.

Methodology

Research design

This study employs a *Systematic Literature Review* (SLR) methodology, chosen for its comprehensiveness and rigor in synthesizing existing knowledge on the topic (Snyder, 2019).

SLR are particularly effective in fields like RE, as they allow for a structured requirements elicitation and thorough analysis of published literature to identify trends, gaps, and consensus in the research landscape as well as standards and reference models and common or specific catalogue requirements (Kitchenham et al, 2009).

As seen in Figure 3, this research design mirrors the RE process: data collection gathers relevant literature akin to requirements elicitation, data analysis using a thematic analysis correlate to requirements analysis, while synthesizing research findings and aligning them with research questions resembles requirements management. Furthermore, the research questions itself provide a structured approach similar to RE focus on specification, modeling (analysis), and validation.

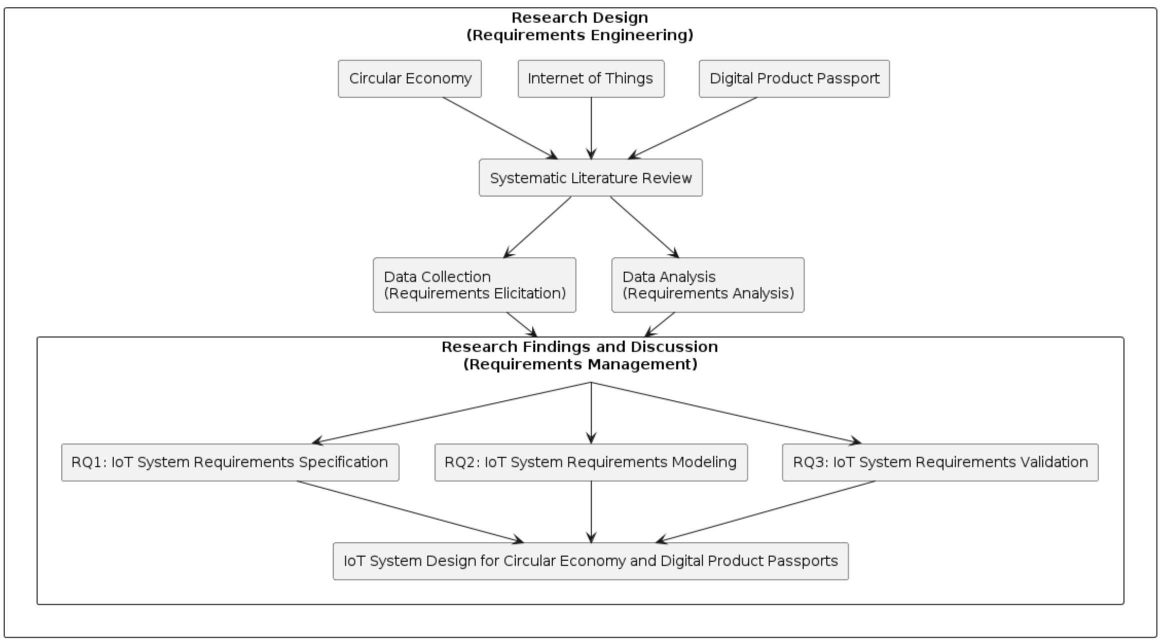

Figure 3. Conceptual Research Design Diagram

Source: Authors' own research.

We appreciate that this design is well-suited to address the complex interdependencies and multifaceted nature of IoT systems in the CE and DPP context, where understanding the breadth and depth of requirements is critical for successful implementation.

The systematic literature review also ensures that the study is grounded in empirical evidence, providing a solid foundation for identifying best practices and innovative solutions in the field.

Research purpose

The purpose of this research is to systematically explore how Internet of Things (IoT) systems, when engineered with specific requirements, can serve as enablers of Circular Economy (CE) and Digital Product Passports (DPPs).

By applying a structured Requirements Engineering (RE) approach, this study identifies the necessary system specifications and evaluates their role in sustainability-driven digital transformation. This research aims to bridge the gap between IoT-enabled circular economy strategies and real-world digital passport implementations by introducing a validated framework and system architecture.

Unlike previous studies that analyze IoT applications in isolation, this paper contributes a structured RE methodology that ensures CE and DPP compliance. It extends the theoretical underpinnings of CE-IoT frameworks and provides a reference model for future research and industrial adoption.

Research questions

The research questions guiding this study are the following:

*[**RQ1**] What are the key requirements for IoT systems to support Circular Economy principles and strategies with the integration of Digital Product Passports?*

*[**RQ2**] How can IoT systems be designed to optimally support Circular Economy principles and strategies and seamlessly integrate Digital Product Passports?*

*[**RQ3**] What validation techniques can be used to ensure that IoT systems meet the requirements for supporting Circular Economy principles and strategies with the Digital Product Passports?*

Research methodology

Systematic literature review method

The research methodology for this study is structured around a *SLR* method, a rigorous approach designed to aggregate, synthesize, and analyze existing scholarly work on IoT systems within the context of CE domain and DPP applications.

According to Kitchenham (2009), this methodology is particularly well suited for extracting detailed insights about the state-of-the-art, identifying prevailing gaps, and understanding the breadth of software engineering such as applying the RE process to the specific domain of CE and use case scenario of DPP applications.

Data collection

Data collection focuses on sourcing and aggregating relevant literature that discusses the RE and integration of IoT systems within CE domain, particularly emphasizing the application of DPP. This step is critical for ensuring a comprehensive understanding of the existing body of knowledge and the state of practice. The data collection steps are presented below:

Database Search: The primary sources for collecting data include prominent academic and industry databases such as *Web of Science*, *Scopus*, *IEEE Xplore*, *ScienceDirect*, *Springer Link*, *Emerald Insight*, and *Google Scholar*. These platforms are chosen for their extensive repositories of peer-reviewed scientific and technical literature.

Search Queries: The search queries are crafted using a combination of relevant keywords and phrases derived from the research objectives. Examples include "*Internet of Things*" "*Circular Economy*" "*Digital Product Passports*", "*Requirements*", "*Sustainability*", while Boolean operators ("*and*", "*or*", "*not*") have been applied to combine and refine the search results. These queries help in retrieving articles that directly relate to the focus of the review.

Inclusion Criteria: Publications must focus on IoT systems and/or IoT applications within CE domain and/or study the implementation and impact of DPP applications and/or have references to the RE process. Only articles published in English within the last 15 years are considered to ensure the review's timeliness and relevance.

Exclusion Criteria: Studies that do not explicitly address IoT systems in the context of CE or DPP, as well as non-peer-reviewed articles like opinion pieces and editorials, are excluded.

Screening and Selection: The initial screening involves reviewing titles and abstracts to assess their relevance based on the inclusion and exclusion criteria. This is followed by a detailed examination of the full texts to confirm their applicability and to ensure they provide valuable insights into the study's domain.

Data Extraction: For each selected publication, pertinent information is extracted and recorded in a structured template. This includes details such as authors, publication year, research aims, methodologies employed, key findings, and specific contributions to understanding the RE process for the IoT systems.

Data analysis

In this study, the data analysis process is meticulously designed to align with the stages of the RE process, particularly focusing on the tasks of requirements specification, analysis, and validation.

The method for data analysis is an adapted form of *thematic analysis* structured to integrate the RE process steps more effectively:

Requirements Specification: Specify the IoT functional, non-functional, domain-specific, and application-specific requirements for supporting CE domain and DPP applications using FURPS+ and MoSCoW approaches,

Requirements Analysis (Modeling): Identify broader patterns, themes, or models relevant to the design and architecture of IoT systems.

Requirements Validation: Explore and define validation techniques to ensure that the specified requirements meet the necessary criteria for supporting CE domain and DPP applications.

The adapted thematic analysis – requirements engineering data approach not only aligns with traditional qualitative data analysis methods, but also integrates the structured steps of the RE process, making it particularly suitable for developing comprehensive and robust IoT system designs that support CE domain and DPP applications.

Results and discussions

The research findings are further presented following the structure of the research questions.

[RQ1] What are the key requirements for IoT systems to support Circular Economy principles and strategies with the integration of Digital Product Passports?

According to the insights found and analysed from the literature review (Aurum and Wohlin, 2005; ITU, 2012; ITU, 2014a; ITU, 2014b; CE-IoT, 2020a; Jansen et al, 2023; IoT-A, 2024; CIRPASS, 2024), we distinguish between IoT functional, non-functional, domain-specific (CE), and application-specific (DPP) requirements.vThese requirements are further presented in Table 9, Table 10, Table 11, and Table 12, respectively.

IoT functional requirements specification

Table 9. IoT Functional requirements

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
FR01	Data Acquisition	IoT devices must be able to accurately capture and transmit real-time data related to the location, usage, and condition of products.	Functionality	Must Have	Rethink, Reduce, Repair	Product lifecycle management, Regulatory compliance
FR02	Data Processing	IoT system must process and analyze data to forecast maintenance needs and predict product lifecycle endpoints.	Functionality	Should Have	Repair, Refurbish, Remanufacture	Maintenance optimization, Product as a Service
FR03	Modular Design	IoT system should be designed with modular components to facilitate easy repair, refurbishment, and upgrades.	Usability	Must Have	Repair, Refurbish, Remanufacture	Product design for circularity
FR04	Dynamic Configuration	IoT system must adapt its operation based on feedback from their environment and usage patterns to optimize energy and material use.	Performance	Should Have	Reduce, Reuse	Energy and resource efficiency
FR05	End-of-Life Management	IoT system should provide notifications and options for end-of-life processing, including recycling, refurbishing, or disposal instructions.	Supportability	Should Have	Recycle, Refurbish	End-of-life processing
FR06	Maintenance Alerts	IoT system must automatically alert users and service providers when maintenance is required or likely to be required soon.	Performance	Must Have	Repair, Maintain	Proactive maintenance
FR07	Remote Diagnostics	IoT System should enable remote diagnostics to assess product health and diagnose issues without the need for physical inspections.	Functionality	Should Have	Repair, Maintain	Remote service provision
FR08	Lifecycle Assessment	IoT system must be able to assess and report on the	Functionality	Should Have	All Relevant Rs	Sustainability reporting

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
		environmental impact of products throughout their lifecycle.				
FR09	Resource Optimization	IoT system must utilize algorithms to optimize resource use (e.g. energy) based on usage patterns and operational conditions.	Performance	Could Have	Reduce, Rethink	Resource management
FR10	Product Updates	IoT system must support over-the-air updates to firmware and software to extend the product's life and add new features without needing physical modifications.	Supportability	Could Have	Maintain, Upgrade	Product upgrades and maintenance

Source: Authors' own research

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IoT non-functional requirements specification

Table 10. IoT Non-Functional requirements

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
NFR01	Scalability	The IoT system must scale to handle increased data volume from a growing number of IoT devices without performance degradation.	Performance	Must Have	Not Specific	All
NFR02	Reliability	Ensure IoT system reliability to perform under specified conditions over a defined period, minimizing downtime and errors.	Reliability	Must Have	Not Specific	All
NFR03	Security	IoT system should implement robust security measures to protect data integrity, confidentiality, availability, and prevent unauthorized access.	Security	Must Have	Not Specific	Consumer data protection, Secure system integration

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
NFR04	Interoperability	IoT system must be compatible with various other IoT devices and network communication protocols, adhering to international standards to ensure seamless integration.	Usability	Must Have	Not Specific	System integration and operation
NFR05	Performance	The IoT system should maintain high performance under varying load conditions, ensuring timely processing and responsiveness.	Performance	Should Have	Not Specific	All
NFR06	Maintainability	IoT system should facilitate easy maintenance and upgrades of the system and its devices to extend its operational life and improve its environmental footprint.	Supportability	Should Have	Maintain, Upgrade	Maintenance optimization
NFR07	Adaptability	IoT system must adapt to changes in environmental conditions and user patterns without manual intervention.	Usability	Could Have	Rethink, Adapt	System flexibility
NFR08	Fault Tolerance	IoT system should continue operating properly in the event of individual component failures.	Reliability	Should Have	Not Specific	High availability
NFR09	Environmental Resistance	IoT devices must be resistant to environmental factors such as moisture, temperature variations, and physical shock to ensure longevity and reduce waste.	Reliability	Could Have	Rethink, Reduce	Product durability
NFR10	Compliance	IoT system must ensure compliance with all relevant CE and DPP regulations, facilitating certification and standardization.	Supportability	Must Have	Not Specific	Regulatory compliance

Source: Authors' own research.

IoT domain-specific requirements specification

Table 11. IoT Domain Requirements for Circular Economy

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
CE01	Lifecycle Data Tracking	IoT system must track detailed lifecycle data for products, including pre-use (e.g. manufacturing), use, and post-use (e.g. disposal) phases.	Functionality	Must Have	All "Rs"	Product lifecycle management, Regulatory compliance
CE02	Material Health Monitoring	IoT system must implement sensors to monitor the health of materials used in products to determine optimal recycling times and methods.	Functionality	Must Have	Recycle, Recover	Material traceability
CE03	Repairability Support	IoT system should provide diagnostics and repair guidelines digitally to support maintenance and extend product lifespan.	Usability	Should Have	Repair, Maintain	Maintenance optimization, Proactive maintenance
CE04	End-of-Life Strategy Implementation	IoT system must include functionalities to support end-of-life strategies, such as automated sorting and identification for recycling or reuse.	Functionality	Should Have	Recycle, Refurbish	End-of-life processing
CE05	Product as a Service Enablement	IoT system could support models where products are offered as services rather than sold, facilitating return and reuse or recycling.	Usability	Could Have	Reuse, Repair	Product as a Service
CE06	Environmental Impact Monitoring	IoT system should actively monitor and report on the environmental impact associated with the product throughout its lifecycle.	Functionality	Must Have	Regenerate	Environmental impact analysis
CE07	Feedback Loop Mechanisms	IoT system should include mechanisms for feedback from end-users and recyclers to	Usability	Should Have	Rethink, Redesign	User feedback, Design improvements

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
		manufacturers to inform product design improvements focused on CE.				
CE08	Smart Contract Capabilities	IoT system could integrate smart contract functionality to automate parts of the circular process, such as payments for recycling or the return of leased products.	Functionality	Could Have	All "Rs"	Smart leasing systems
CE09	Interconnectivity with Circular Databases and/or Digital Product Passports	IoT system must interconnect with global CE and/or DPP databases for sharing and accessing data on material health, product design, and end-of-life processing.	Performance	Must Have	Recycle, Recover	Material traceability, Regulatory compliance
CE10	User Education and Engagement	IoT system should include functionalities to educate users on sustainable practices and the importance of participation in the CE.	Usability	Could Have	Rethink, Reduce	Consumer engagement

Source: Authors' own research.

IoT application-specific requirements specification

Table 12. IoT Application Requirements for Digital Product Passports

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
DPP01	Unique Identifier Implementation	IoT apps must be able to implement a unique digital identifier that corresponds to the DPP, ensuring traceability of products from production to end-of-life.	Functionalit y	Must Have	Not Specific	Traceability and transparency
DPP02	DPP Data Integrity	IoT apps must ensure the integrity and accuracy of data within the DPP, using technologies like blockchain for secure, tamper-proof data logging.	Security	Must Have	Not Specific	Secure system integration

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
DPP03	DPP Accessibility	DPP must be easily accessible by authorized stakeholders through secure IoT apps/system, both online and offline as needed.	Usability	Must Have	Not Specific	Consumer data protection, Regulatory compliance
DPP04	Real-Time (LCA) Data Sync	IoT apps must provide real-time data updates to the DPP to reflect current product location, status (availability), and usage (condition).	Performance	Must Have	Not Specific	Product lifecycle management
DPP05	End-of-Life Data Recording	IoT apps must record and update DPP with end-of-life processing information, including recycling, refurbishing, or disposal details.	Functionalit y	Must Have	Recycle, Recover	End-of-life processing
DPP06	Multi-Lingual Support	IoT apps must offer multi-lingual support to ensure DPP accessibility and usability by international users and stakeholders.	Usability	Should Have	Not Specific	User engagement and interface
DPP07	Data Privacy Compliance	IoT apps must comply with international data protection regulations (e.g. GDPR) in the management, storage, and dissemination of data in DPP.	Security	Must Have	Not Specific	Consumer data protection
DPP08	Environmental Impact Information	IoT apps should be able to read and write DPP detailed information on the environmental impact of the product, including carbon footprint, resource use, and disposal options.	Functionalit y	Should Have	Regenerate	Sustainability reporting, Environmental impact analysis
DPP09	Modular Information Access	IoT apps should structure DPP data (e.g. using graph) so that information access can be modular, with stakeholders accessing only the data relevant to their role or interaction with the product.	Usability	Should Have	Not Specific	System flexibility
DPP10	Standardized Data Formats	IoT apps must use standardized data formats and protocols to ensure that DPP information is consistent	Usability	Must Have	Not Specific	Material traceability, Regulatory compliance

ID	Requirement	Requirement Description	FURPS+	MoSCoW	CE Rs Strategies	DPP Use Case(s)
		and interoperable across different systems and geographic jurisdictions.				

Source: Authors' own research

[RQ2] How can IoT systems be designed to optimally support Circular Economy principles and strategies and seamlessly integrate Digital Product Passports?

According to the literature review (Aurum and Wohlin, 2005; Compagnucci et al, 2024), this includes designing system blueprint artefacts such IoT system architecture models.

Based on the various functional, non-functional, domain-specific and application-specific requirements found and analysed from the literature review and according to the insights from Gligoric et al (2019) and Wenning et al (2024), we are further presenting two such architecture models: a system context diagram and a layered system architecture diagram.

IoT system context model

IoT system architecture is represented using the *C4* modeling (Brown, 2021), which is a lean graphical notation technique for modeling the architecture of systems based on a structural decomposition of a system into containers and components and relies on existing modelling methods such as Unified Modeling Language (UML) for a more detailed decomposition of the architectural building blocks (Richards and Ford, 2020).

The C4 model documents the architecture of a system, by showing multiple points of view that explain the decomposition of a system into containers and components, the relationship between these elements, and, where appropriate, the relation with its users (Brown, 2021). The viewpoints are organized according to their hierarchical level: context, container, component, and code diagrams.

In order to depict the IoT generic use case model and the system in scope for CE and DPP and its relationship with users and other systems, a system context diagram is being used and depicted in Figure 4.

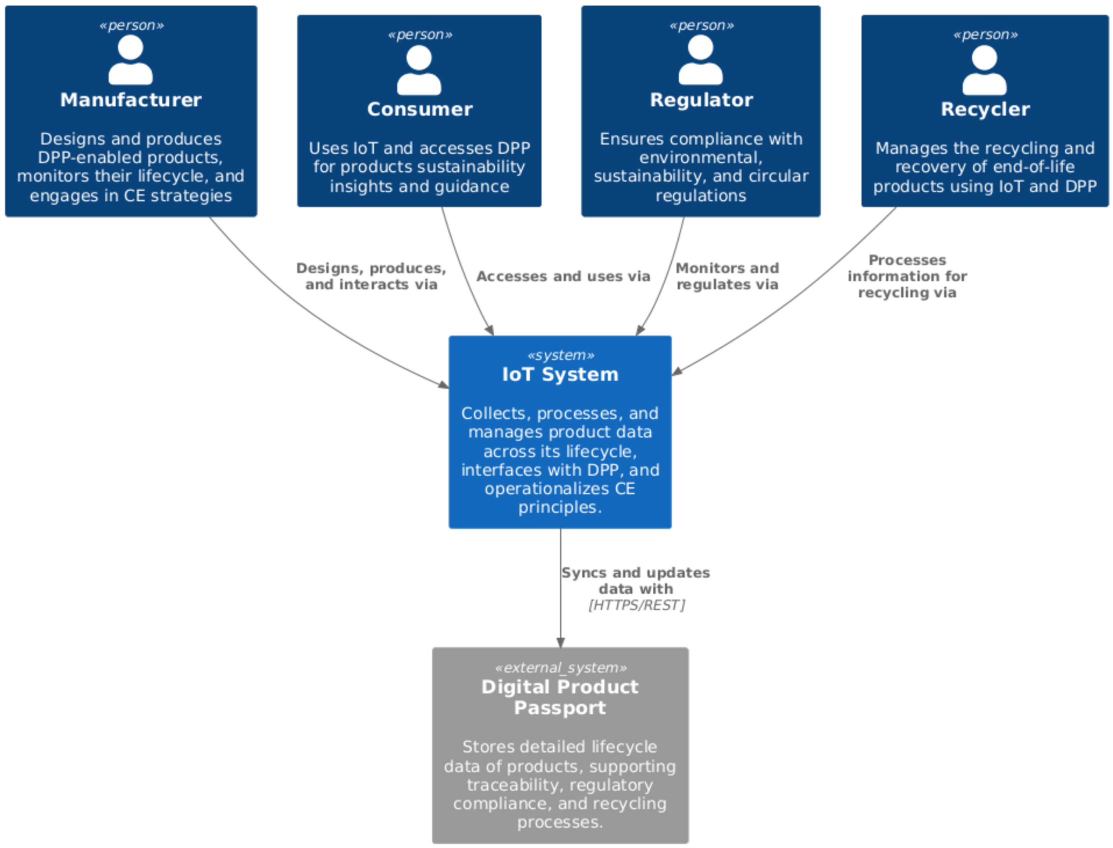

Figure 4. IoT system context model for CE and DPP

Source: Authors' own research.

This IoT system context diagram provides an model for the high-level overview of the entire system showing the main software systems (IoT and DPP), people (actors), and their interactions.

Manufacturer: Directly interacts with the IoT system to design, produce, and monitor DPP-enabled products, integrating CE strategies such as sustainable material use, efficient design, and extended product lifecycle management.

Consumer: Engages with the IoT system to access real-time and historical data on product use, maintenance, and end-of-life options through the DPP information, fostering informed decisions that align with CE principles.

Regulator: Ensures that the physical products adheres to environmental and sustainability regulations as well as data privacy standards, utilizing the IoT system and DPP's data to verify compliance.

Recycler: Uses the IoT system to efficiently manage the end-of-life processes of products, leveraging data to optimize recycling, refurbishment, and the recovery of materials.

The IoT system serves as a critical link, providing a detailed record of each product's lifecycle, which supports traceability, enhances regulatory compliance, and facilitates efficient recycling processes. This design highlights the synergies between IoT technologies, CE principles, and DPP sustainability goals, offering a holistic view of a smart, sustainable product lifecycle management system in line with the smart digital circular economy paradigm.

IoT layered system architecture model
The IoT layered system architecture is using best practices from software architecture engineering (Richards and Ford, 2020) and the model is structured into distinct five layers: *perception*, *network*, *processing*, *service* and *application*, where each layer is potentially addressing specific requirements identified in the previous analysis.

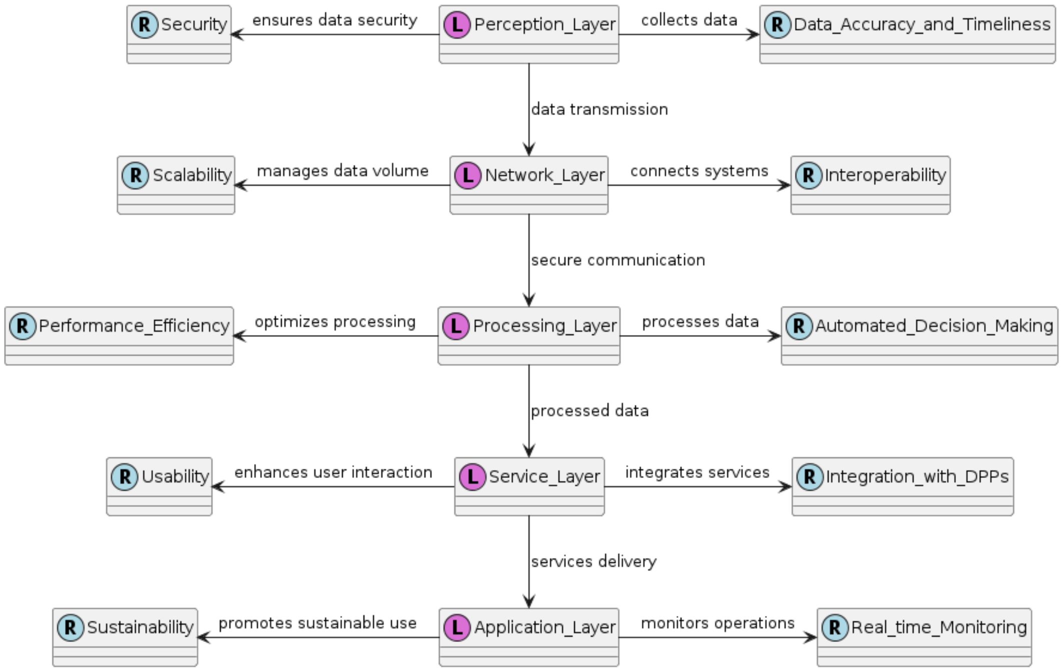

Figure 5. IoT Layered System Architecture Model for CE and DPP
Source: Authors' own research.

This multi-layered architecture model depicted in Figure 5 ensures a comprehensive design, accommodating both broad (cross-layer) and detailed (layer-specific) IoT system various requirements.

Perception: this layer collects data from the physical world via sensors, RFID tags, barcodes, and similar devices. These tools capture real-time product identity, condition, and environmental parameters critical for CE and DPP use. In a CE context, such data supports proactive maintenance, resource optimization, and reduced material waste. Also, DPP efforts depend on accurate, continuous data input from this layer to maintain an up-to-date record for each product. An example might be a smart warehouse using sensors to monitor inventory conditions, notifying operators when items need refurbishment.

Network: this layer transmits captured data to processing systems, using technologies like Wi-Fi, Bluetooth, 5G, or LPWAN. Connectivity choice depends on range, power consumption, data volume, and cost considerations. Reliable data flow enables prompt detection of inefficiencies, ensuring various CE targets such as sustainability are met. For DPP, continuous connectivity updates each product's digital record whenever it changes location or ownership. An example might be a logistics firm using IoT 5G for real-time cargo tracking, feeding condition data back into DPP records.

Processing: this layer turns raw sensor data input into actionable insights through cloud or edge computing and data analytics. Algorithms and machine learning reveal patterns in product usage, facilitating better resource allocation in a CE framework. Early detection of anomalies or wear can extend product life, minimizing waste and environmental impact. In DPP, this layer ensures data integrity, flags inconsistencies, and enriches each product's passport with verified updates. An example might be an IoT analytics platform predicting the optimal time to refurbish industrial machinery, updating relevant DPP automatically.

Service: this layer provides specialized functionalities such as environmental validation, compliance checks, and lifecycle assessments. It orchestrates data flows from the processing layer into various business operations and software services. For CE domain, automated alerts can schedule repairs, collect returns for remanufacturing, or trigger recycling processes. DPP applications rely on this layer to maintain regulatory standards, verify product certifications, and share lifecycle milestones. An example might be a service portal automating product recall workflows based on sensor-detected defects, updating the DPP to reflect repair actions.

Application: this layer interfaces directly with users and stakeholders through dashboards, mobile apps, or web platforms. It presents processed data in user-friendly formats, enabling informed decisions and clear oversight of CE initiatives. Relevant metrics, like carbon footprint or material usage, guide more sustainable consumption and product handling. For DPP, this layer displays complete product histories, compositions, and compliance records in an accessible manner. An example might be a mobile application for field technicians can instantly pull up a product's DPP, streamline repairs, and log updates in real time.

[RQ3] What validation techniques can be used to ensure that IoT systems meet the requirements for supporting Circular Economy principles and strategies with the Digital Product Passports?

According to the literature review (Aurum and Wohlin, 2005; Paldês et al, 2020; Guerrero-Ulloa et al, 2023; Darwish and Megahed, 2016; Aguilar-Calderon et al, 2022; Symeonidis et al, 2019), validation techniques in the context of IoT system designed for CE and DPP are crucial to ensure that the system meets all specified requirements and operates effectively under real-world conditions.

In Table 13, we present the key validation techniques for IoT system requirements that are fit-for-use and fit-for-purpose for the CE and DPP context.

Table 13. Key validation techniques for IoT system requirements

Requirements Validation technique	Short Description	Context Application
Simulation Testing	Simulations are used to create virtual models of the IoT system to test how it performs under various conditions with CE and DPP context without the need for physical prototypes.	This method is particularly useful for testing the system's response to different CE scenarios in resource management and DPP updates without incurring the high costs and complexities of real-world testing.
Expert Review	Involves sessions where domain experts review the system's designs and specifications to ensure they align with both DPP technical standards and CE principles.	Experts in IoT technology, CE practices, and DPP regulatory compliance are engaged to scrutinize the system for any potential oversights or improvements.
User Acceptance Testing (UAT)	Real end-users test the system in a controlled environment to provide feedback on its usability and effectiveness.	This testing is critical to ensure that the system interfaces are intuitive, and that the system effectively integrates CE and DPP functionalities as intended for end-users.
Field Trials	Deploying the system in a real-world environment on a limited scale to	Field trials help validate the system's performance in actual CE and DPP operational conditions,

Requirements Validation technique	Short Description	Context Application
	observe its operation and gather practical insights.	particularly its ability to handle real-time data collection and processing as required for effective lifecycle management and sustainability practices.
Scenario-Based Modelling	Creating theoretical scenarios in which the IoT system operates within a CE and DPP context. This method helps in visualizing how the system would perform under different conditions.	Although practical testing might be limited, scenario-based modeling allows for a theoretical examination of the system's functionality and effectiveness in supporting CE and DPP goals under various hypothetical conditions.

Source: Authors' own research.

Considering the limited availability of practical, hands-on validation methods, this paper focuses on theoretical validation techniques – specifically, scenario-based modeling.

Through requirements analysis (functional, non-functional, domain-specific, and application-specific), categorization (using the FURPS+ approach), prioritization (using the MoSCoW approach), and system modeling illustrated previously with various diagrams, we consider that the IoT system requirements specifications are both fit-for-use and fit-for-purpose for supporting effectively the CE principles and strategies and the integration of DPP applications.

Conclusion

This research has explored the intersection of IoT technologies with CE principles, emphasizing the crucial role of well-defined and carefully modeled requirements in building effective systems.

The study demonstrates how a structured RE approach can be used to define, design, and validate IoT systems that support sustainability initiatives and regulatory compliance.

Through a detailed RE process, combined with theoretical validation techniques, we have showed how IoT systems can be designed to support CE goals effectively, particularly through the integration of DPP applications.

The findings highlighted the potential of IoT systems to enhance resource efficiency, improve sustainability, and ensure compliance with environmental regulations. Also, by integrating DPP applications, these IoT systems not only track product lifecycle data, but also foster transparency and accountability across the supply chain. Our scenario-based modeling has shown that when designed with precision, IoT systems can significantly contribute to sustainable practices, aligning with both industry needs and environmental goals.

This study advances the field by:

Establishing a requirements framework for IoT supporting CE and DPPs, categorizing requirements into functional, non-functional, domain-specific, and application-specific needs.

Proposing a structured methodology using FURPS+ and MoSCoW to prioritize IoT system requirements, ensuring practical feasibility and implementation scalability.

Designing a scalable IoT-DPP system architecture (C4 modeling and layered system model), providing a blueprint for real-world deployments within the CE domain.

This study provides actionable insights for:

Manufacturers and policymakers aiming to integrate DPPs into IoT-enabled circular supply chains while ensuring compliance with the EU Ecodesign for Sustainable Products Regulation.

System architects and IoT developers who require a structured methodology for designing sustainable, secure, and interoperable IoT systems.

Supply chain stakeholders and CE practitioners, facilitating transparent product lifecycle tracking and efficient end-of-life management.

While this systematic review provides valuable insights for both academics and industry practitioners, certain limitations must be acknowledged:

Rapidly evolving research landscape – The literature review may not cover all relevant studies due to the continuous advancements in CE, IoT, and DPP research.

Lack of empirical validation – Although this study offers a strong theoretical foundation, further research is needed to validate its findings through real-world implementation.

Future research should explore:

Empirical Testing – Developing and deploying real-world prototypes of IoT-DPP integration to evaluate performance, reliability, and compliance.

Advanced Data Analytics & AI – Investigating how predictive analytics, machine learning, and AI-driven automation and more sophisticated data analytics techniques can enhance IoT system requirements for performance and decision-making.

Human-Centric Design – Improving user interfaces and accessibility, ensuring IoT systems are intuitive and beneficial to both technical and non-technical stakeholders.

Longitudinal Studies – Conducting long-term evaluations of IoT-driven CE and DPP implementations to measure sustainability impact and economic feasibility.

Integration of Emerging Technologies – Exploring Blockchain, AI, and Digital Twin technologies to enhance security, transparency, and automated decision-making in CE ecosystems.

By leveraging the structured RE approach outlined in this study, future research can further enhance the effectiveness, reliability, and scalability of IoT-DPP systems, contributing to the global transition toward a Smart Digital Circular Economy.

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